NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

DEPARTMENT OF
COMPUTER SCIENCE

AUGMENTED REALITY SERIOUS GAMES TOWARDS INTRODUCING AND PROMOTING CHEMISTRY TO PRETEENS

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Master in Entertainment Technology

DOCTORATE IN DIGITAL MEDIA

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Augmented Reality Serious Games Towards Introducing and Promoting Chemistry to Preteens

To my daughter Nicolle Sophia Câmara Olim

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“The only source of knowledge is experience.” (Albert Einstein)

Abstract

Science education, particularly physics, and chemistry, remains unpopular among students. Children's perception of chemistry as a complex and strenuous subject starts at a young age, even before their first contact with the discipline, and these perceptions can affect the students' achievements and future career choices in this domain.

As a result, teachers and educational stakeholders acknowledge the need for innovative tools to reach the children and motivate them in these areas. This intervention should be applied to reach students earlier to demystify negative perceptions and encourage children to invest in these areas.

Augmented Reality (AR) and Serious Games continue to be used as tools to engage students with learning content perceived as less engaging or challenging. However, in chemistry, the vast majority of AR educational tools are designed for older students (15 and older) and mainly focus on the potential of AR to provide the visualization of scientific phenomena. Our research revolves around AR multimodal Serious Games as an opportunity to explore different pedagogical methods to facilitate scientific content learning while incorporating game elements to engage preteen children (9 to 13 years old) with chemistry.

This thesis systematically investigated the effectiveness of three Augmented Reality serious games designed around the chemistry learning experience. In the scope of this thesis, three novel AR serious games were created, namely: "Periodic Fable Discovery," "Periodic Fable An Augmented Journey," and "Periodic Fable in The Wild." These games were iterated, tested, and refined employing Research through Design methodology.

The thesis contribution is centered around the design and lessons learned while producing three novel AR serious game artifacts. The outcomes of this research will establish the underpinnings for developing guidelines that can be implemented by game designers and developers who aim to create educational Augmented Reality (AR) Serious Games.

keywords: Augmented Reality, Serious Games, Learning, Chemistry, Periodic Table, Children

Resumo

A educação científica é fundamental para o desenvolvimento da sociedade, especialmente nas áreas da física e da química. No entanto, muitos estudantes demonstram pouco interesse nestas disciplinas, particularmente em relação a química, sendo frequentemente vista como complexa e exigente. A conotação negativa em relação à química pelas crianças começa desde cedo, antes mesmo de terem contato com a disciplina a nível curricular, sendo que esta percepção pode condicionar o seu percurso acadêmico e mesmo a futura escolha da carreira profissional.

Consequentemente, professores e agentes educativos reconhecem a necessidade de ferramentas inovadoras para cativar as crianças, apoiando intervenções para motivar os alunos mais cedo, desmistificando percepções negativas e, finalmente, levar as crianças a investirem na química. São necessárias estratégias educacionais que enfatizem a aplicabilidade da química no quotidiano e na resolução de problemas, de modo a tornar o conteúdo mais relevante e interessante. Além disso, é importante adotar abordagens didáticas inovadoras, como a utilização de tecnologias interativas, jogos e atividades práticas, que possam ajudar a envolver e motivar os alunos.

A Realidade Aumentada (RA) e os jogos continuam a serem utilizados como ferramenta que ajudam a cativar o interesse dos estudantes para disciplinas consideradas mais difíceis ou menos interessantes para os jovens. Contudo, na área da química, estudos sobre esta ferramenta continuam a focar-se num público alvo acima dos 15 anos de idade, habitualmente só oferecendo benefícios no que concerne à visualização de fenómenos científicos.

A investigação presente nesta tese, visa o estudo da eficácia de três jogos educativos em Realidade Aumentada: A Descoberta da Fábula Periódica, A Fábula Periódica uma Viagem Aumentada e, por último, a Fábula Periódica na Floresta. Estas ferramentas lúdico-didáticas procuram facilitar a aprendizagem, cativar o interesse e motivar jovens para a área química.

A contribuição desta tese está centrada no desenho e aprendizagem obtida durante a produção de três novos artefatos de jogos sérios de realidade aumentada (RA). Os resultados desta pesquisa estabelecerão as bases para o desenvolvimento de diretrizes, que podem ser implementadas por designers e criadores de jogos educativos em Realidade Aumentada (RA).

Palavras-chave: Realidade Aumentada, Jogos Educativos, Aprendizagem, Química, A

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flow State of complete absorption or engagement in an activity as to lose the sense of time of what is around 22, 25

immersion Feeling of being fully engrossed or actually part of the Imaginarium environment in the virtual world or game 24

Presence Psychological sense of "being there" 25

research through design Research approach using design and artefact to generate knowledge and understanding of a problem or phenomenon 52

self-determination Sense of being in control. Ability to make choices based on one's own values, belief and goals, rather that external factors 35

tangible interfaces Interactions that involved physical objects or environments 23

Acronyms

AR	Augmented Reality vii, 2, 4, 5, 21, 38
ARCS	Attention, Relevance, Confidence, and Satisfaction 85
CPK	Corey, Pauline, Koltun 61
GPS	Global Position System 20
HCI	Human Computer Interaction 53, 57
HMD	head-mounted display 22
IMMS	Instructional Materials Motivation Survey 85
ITI	Interactive Technology Institute 59
MARs	Mobile Augmented Reality 21
MDA	Mechanics, Dynamics and Aesthetics 28
MRT	Mental Rotation Test 129
PANASC	Positive and Negative Affects Scale for Children 125
PF	Periodic Fable xi, 6, 9, 53, 57, 59, 60, 61, 63, 65, 67
PFT	Paper Folding Test 129, 132
Rtd	Research Through Design xiii, 4, 52, 53, 54
SDT	theory of self-determination 35
SPSS	Statistical Package for the Social Science 129
STEM	Science, Technology, Engineering and Math 1, 2, 4, 13, 14, 23
SUS	System Usability Scale 87
TI	Tangible Interfaces 23
TPACK	Technological Pedagogical Content Knowledge 35

UI	User Interface 28
UNESCO	United Nations Educational Scientific and Cultural Organization 18, 53

CHAPTER 1

INTRODUCTION

This chapter describes the motivation for this research, an overview of the research process, and the contributions to the research community.

1.1 Motivation

Abstract and spatial reasoning are crucial cognitive abilities that are closely associated with the successful academic performance of preteen children [228]. Abstract reasoning, as a component of executive functions, calls for analyzing and manipulating information about situations, things, and ideas not present in the individual's immediate environment. The acquisition and development of abstract reasoning are essential in the learning process of school subjects from a young age, especially regarding sciences, since these subjects involve inquiry, experimentation, evidence, evaluation, and analysis of ideas, problem-solving, creative thinking and overall understanding of information by making connections with the real world. Spatial reasoning, on the other hand, is a cognitive ability linked to children's understanding and manifested through their capacity to retain, generate, and manipulate visual information to solve problems. Spatial reasoning includes tasks such as mentally rotating objects, comprehending spatial relationships, interpreting maps and diagrams, and recognizing patterns in complex images. These skills are commonly referred to as spatial skills or spatial abilities.

Science, Technology, Engineering and Math (STEM) relies on many concepts that don't have physical references visible to the naked eye in the real world, such as molecules, covalent and ionic bonding, and electromagnetism. As a result, it is difficult for students to connect the content of these subjects to real-life situations. Due to its involvement in abstract reasoning and spatial cognitive thinking, chemistry, among other STEM domains, is regarded as a particularly complex and demanding subject. This perception, which according to Michela Lurachi [200] starts early on (preteens), builds up, and continues to persist until secondary school, contributes to the lack of interest, and influences students' future career choices [219, 299, 11, 301]. Moreover, previous research identifies perception and motivation toward chemistry subjects as important factors in students' performance and learning processes.[342, 110, 270] Consequently, educational stakeholders have acknowledged the need to incorporate tools that can enhance students' emotional engagement (interest and enjoyment) and improve their behavior and cognitive engagement in STEM subjects, including the field of chemistry [152].

There is a need to engage preteen students with chemistry using child-friendly pedagogical approaches, as many of them lose interest in this subject before encountering it in junior high school (7th grade - 11 years old) and college [327].

Games have proven beneficial for encouraging active learning and boosting student motivation since they are interactive, engaging, and fun tools [66]. According to research, introducing games into the classroom can increase student learning outcomes, such as knowledge retention, critical thinking skills, and problem-solving aptitudes [367]. Children learn by using their senses, playing, and engaging in activities, thus intuitively assimilating concepts [181]. Games designed and developed for education, training, and simulation to support specific learning objectives are typically called Serious Games. Serious games can provide a more engaging and immersive experience than traditional teaching methods by simulating real-world scenarios, especially useful in high-risk or dangerous situations. They allow learners to work at their own pace, provide immediate feedback and reinforcement, and support learning content developed in various settings and contexts [316]. Additionally, when combined with other mediums like tangible interfaces (such as physical objects) and immersive technologies, Serious Games can provide further layers to the learning experience, supporting a lasting and effective learning experience.

AR and Serious games can potentially create entertaining and innovative experiences for children. Moreover, if the game tackles daunting and complex concepts in a fun and engaging manner, the experience can benefit their education [49]. By allowing the superimposition of virtual objects into the real world, AR facilitates students' understanding of difficult concepts through spatial reasoning. It enables the training of spatial visualization skills by making scientific phenomena visible. Furthermore, AR allows users to discern and interact with the real environment while simultaneously receiving additional digital information into their field of perception [42], showing great potential as a pedagogical tool.

AR experiences are increasingly being studied in the chemistry learning and teaching context [99, 245] because it allows the visualization of abstract concepts and phenomena that otherwise would not be possible. This technology can provide the visualization of three-dimensional AR models facilitating the microscopic, macroscopic, and symbolic dimensions of chemistry. AR intertwined with other mediums like 2D information visualization, 3D modeling, animations, and Tangible Interactions (TI) can also engage students with the microscopic and the representational chemical world, which are considered challenging for students [281, 52, 161]. Furthermore, Mobile Augmented Reality (MAR) is gaining prominence in chemistry because of the continued technological advancements, affordability, and proven benefits in promoting students' engagement with learning content [65].

While AR has been explored in different fields with a broad target audience, in chemistry, the effectiveness of the technology as a learning tool has been chiefly studied with high-school and colleague students (15 years and older), with few reports on a younger population [120]. Its application to preteens has not been sufficiently studied. There is a need to engage and explore friendly pedagogical approaches that engage and leverage the natural enthusiasm of young science learners to keep up with the accelerating pace of discovery and technological innovation,[120]. There is an opportunity to fill this gap by approaching immersive learning experiences according to the complexity of chemistry understanding (symbolic, microscopic, and macroscopic) [160] and the student's characteristics to design and develop effective and engaging tools for chemistry while gathering the interest of a younger and broader population in this domain.

This research explores the potential of Augmented Reality Edutainment as a pedagogical and ludic tool that provides, facilitates, and improves the understanding of abstract concepts, motivating and engaging preteens toward chemistry. However, while focusing on chemistry its findings can be implemented to other STEM subjects. This research started in the year of the UNESCO celebration of the 150th anniversary of the discovery of the Periodic System by Dimitri Mendeleev, several formal and informal educational activities were taking place, and chemistry was chosen as the context for this research. The Periodic Table is one of the most significant achievements in the modern sciences for chemistry, physics, medicine, earth sciences, and biology. We took this opportunity to reflect on the Periodic Table and its elements and introduce them to preteens who might have yet to experience them in their school curricula. The research aims of this proposal are multi-folded and will articulate in several Research questions (RQs) expressed in detail in the research questions section later in this document. As an orienting statement, this research proposes to investigate an edutainment approach to learning the Periodic Table; Can AR apply to edutainment encourage children to appreciate science, improve and contribute to abstract reasoning and chemistry in particular?

To investigate these issues, the project designed, developed, and studied serious AR games centered around the Periodic Table of Elements. The game prototypes will be evaluated with the preteens' target audiences of 9 to 13 years old children, and its findings will form the basis for creating guidelines that game designers and developers can apply to educational AR serious games. We aim to evaluate game design principles (aesthetics, mechanics, story) and pedagogical methods when using AR as a platform to assess the limitations, benefits, and efficiency of this technology when delivering educational content knowledge. By identifying methods and tools when conducting our research, we envision the findings from this specific research work to be transferable to other STEM domains (such as physics, biology, mathematics, and others).

We produced three AR serious games with this aim: 1. Periodic Fable Discovery; 2. Periodic Fable and Augmented Journey; and 3. Periodic Fable in the Wild that can be interconnected or played individually, each one with a specific set of goals in mind. We briefly describe the games below:

Periodic Fable Discovery uses an exploratory/ constructive learning approach and tangible interface to introduce content knowledge of the chemical elements: oxygen, hydrogen, carbon, chlorine, and nitrogen. By rotating and scanning images/patterns on each facet of the physical cube (dedicated to one of these elements), preteens can gather information about properties, their location within the Periodic Table, objects/products that contain such elements within their compositions, short animations about possible covalent bonding, and through a game activity can create chemical reactions and view its chemical molecular structure. We tested the game to evaluate the adequacy of the pedagogical method, efficiency when delivering the content, the usability of the AR tangible system, and game elements: enjoyment and motivation towards the game and domain. We also assess its efficiency and engagement compared to a more traditional method of teaching chemistry (using a textbook).

The second game, **Periodic Fable An Augmented Journey**, is an adventure game that utilizes a narrative approach to convey learning content. The game adopts an expository and consolidating approach (closer to a traditional pedagogical method). At the beginning of the game, preteens are invited to help the protagonists (Oxygen, Hydrogen, Carbon, Chlorine, and Nitrogen) to solve an incident (crash of their spacecraft) by exploring a 3D AR map and using chemical reactions. The game was evaluated to test the efficiency of the delivery and retention of the educational content, usability, and cognitive overload of the system, game elements balance (gameplay and content), the persuasion potential of the aesthetics and storytelling, enjoyment and affects of the user towards the game and domain.

And finally, a third game, **Periodic Fable in the Wild** follows a situated learning approach by integrating everyday routine products and the participant context to deliver the learning content. The game evolves around the scanning of real products containers located on a space (shelves) to gather atoms that are part of such a substance. The player can then recreate or create substances by joining the atoms collected. The game was developed to assess the incorporation of real-world elements into the mechanics of augmented reality gameplay to provide educational content and foster a connection to enhance learning. The game was evaluated based on the same factors as the PF Discovery and PF An Augmented Journey, such as game elements balance, usability, motivation, and engagement.

This thesis adopts a Rtd method [368] to study and better understand the learning effectiveness of the AR Serious Games in the STEM educational context, understanding best pedagogical methods, the adequacy of game design principles (immersive narrative, role play, mechanics, aesthetics and the technology) in learning activities, keeping a balanced combination of scientific content and storytelling. This thesis aims to understand whether AR Serious games can motivate and engage students with scientific concepts, particularly in chemistry.

1.2 Research aims, Contribution, and Questions

This thesis's research aims and contributions were developed through the design, development, and study of three interconnected serious AR games for STEM domains, leading to a focus on the domain of chemistry and the Periodic Table. The game prototypes were evaluated with the target audience of 9 to 13 years old children and its findings formed the basis for creating guidelines that can be applied by game designers and developers targeting AR educational games. We aimed to use game design principles (aesthetics, mechanics, story) and pedagogical methods using AR as a platform to evaluate this technology's limitations, benefits and efficiency in delivering educational content knowledge.

We contribute to this field of study by:

- Providing guidelines for designing AR serious games that integrate: Learning content according to Alex Johnstone's theoretical approach [161]; human factors (participatory design approach, with teachers and experts to select and validate the content and pedagogic aspect through a user-center approach), and AR technology with game-based learning (see Figure1.1).

- Designing and Developing three novel AR serious games artifacts: Periodic Fable Discovery, Periodic Fable An Augmented Journey, and, finally, Periodic Fable in the Wild, developed to facilitate the learning of abstract concepts about the Periodic Table while engaging preteens with chemistry.

- Providing insights on the benefits and limitations of AR Serious Games to facilitate and engage preteens children (9 to 13 years old) in learning abstract scientific content.

To this end, my research was guided by the following questions:

RQ1 *How can Augmented Reality game design balance: aesthetic, story, gameplay, technology and pedagogical methods facilitate the learning process of abstract scientific concepts encountered in the Periodic Table?*

RQ2 *What design considerations-guidelines should be taken into account in the development of Augmented Reality (AR) serious games to effectively support science education?*

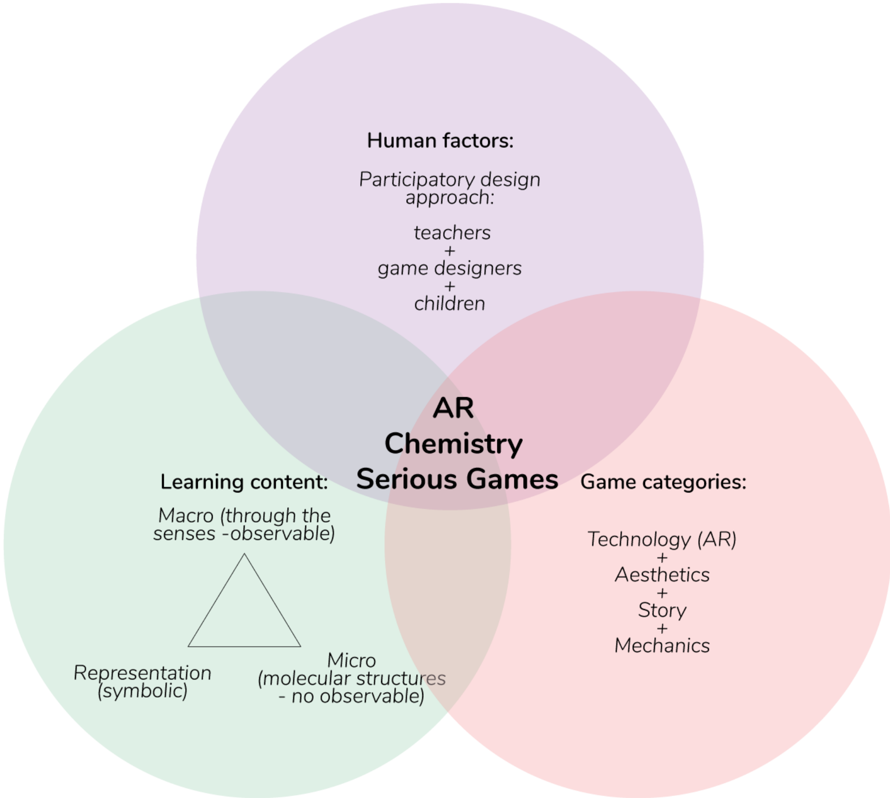

Figure 1.1: Chemistry AR Serious Games Research Approach

RQ3 *Can AR Serious Games improve children's affects on chemistry and facilitate the learning of abstract content about the Periodic Table?*

1.3 Research Process Overview - Methodology

In this context, my doctoral research process relies on:

1. Participatory design approach – reflects on the contributions of teachers and game designers in the different stages of our game design process regarding content and pedagogical methods.

2. Research Through Design using PF AR Games developed with different pedagogical approaches embedded within the game mechanics to introduce concepts about the Periodic Table to preteens.

3. Children's interactions with Periodic Fable Discovery, Periodic Fable An Augmented Journey and Periodic Fable in the Wild allowed us to systematically test theoretical interventions in the active context of educational environments.

4. Conducting and sharing insights from the results of several studies in a formal and informal learning context.

To accomplish this objective, we provide a concise overview of our process (see Figure 1.2). While in the illustration, Stages 1, 2, and 3 are on different levels; this was a continuous process.

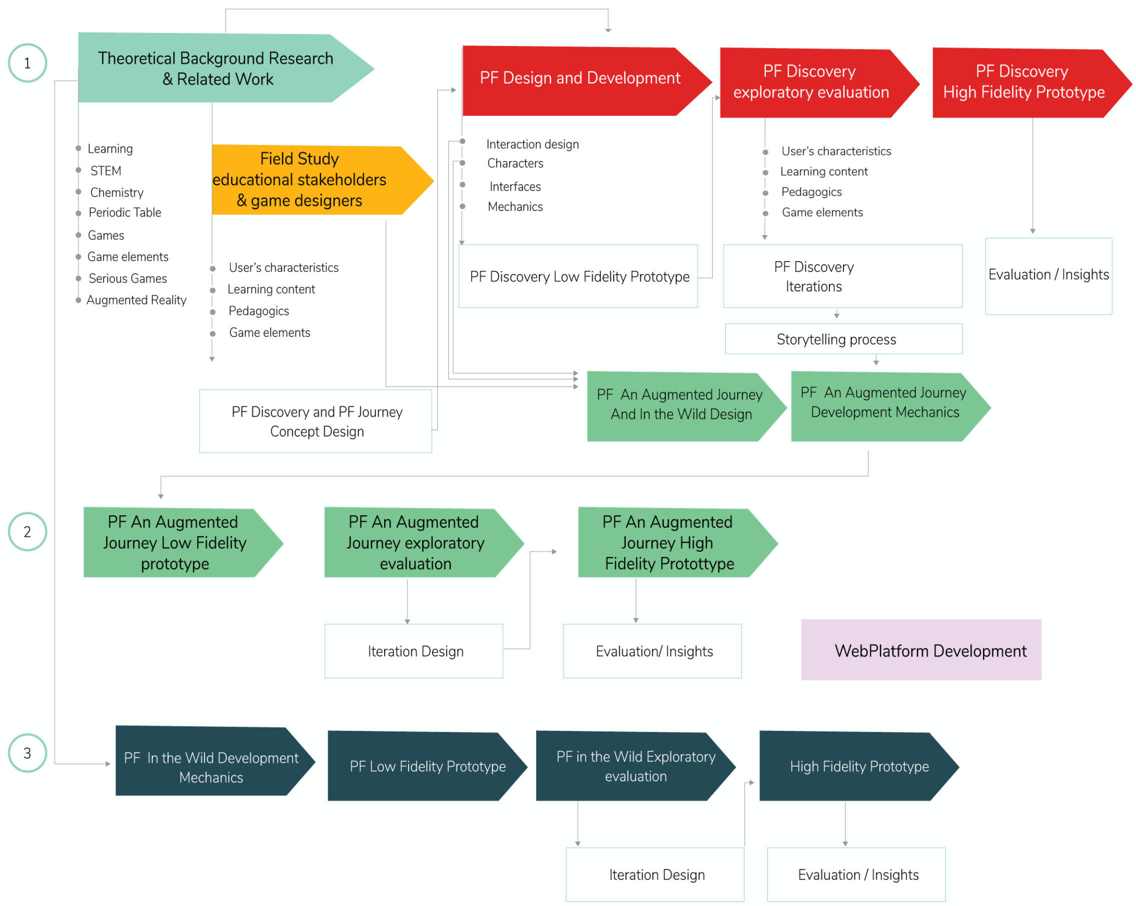

Figure 1.2: Overview of the iterative research process documented in this manuscript

1.4 List of Publications

Most of the work presented throughout this thesis has been published at international conferences in the field of Human-Computer Interaction.

Camara Olim, S. M., Nisi,V., & Romão, T. (2023). Periodic Fable Discovery: an Augmented Reality Serious Game to Introduce and Motivate Young Children Towards Chemistry. Journal of Multimedia Tools and Applications, 2023. Doi: 10.1007/s11042-023-17526-9

[235].

Camara Olim, S. M., Nisi, V., & Rubegni, E. (2023, February). "Periodic Fable Discovery"Using Tangible Interactions and Augmented Reality to Promote STEM Subjects. In Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (pp. 1-15) [55].

Câmara Olim, S. M., Nisi, V., & Rubegni, E. (2022, June). Periodic Fable Augmenting Chemistry with Technology, Characters and Storytelling. In Interaction Design and Children (pp. 123-136) [56].

Olim, S. C., Nisi, V., & Romão, T. (2021, August). Towards Identifying Augmented Reality Unique Attributes to Facilitate Chemistry Learning. In Human-Computer Interaction–INTERACT 2021: 18th IFIP TC 13 International Conference, Bari, Italy, August 30–September 3, 2021, Proceedings, Part V (pp. 513-516). Cham: Springer International Publishing [237].

Camara, S., Nisi, V., & Romão, T. (2021, October). Enhancing Children Spatial Skills with Augmented Reality Serious Games. In Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play (pp. 94-100) [54].

Olim, S. C., & Nisi, V. (2020). Augmented reality towards facilitating abstract concepts learning. In Entertainment Computing–ICEC 2020: 19th IFIP TC 14 International Conference, ICEC 2020, Xi'an, China, November 10–13, 2020, Proceedings 19 (pp. 188-204). Springer International Publishing [236].

In Review

Camara Olim, S. M., Nisi,V., & Romão, T. (2023). Augmented Reality Interactive Experiences for Multi-level Chemistry Understanding. Journal of Child-Computer Interaction.

Other Publications, not directly related to the subject of this thesis

*Vasconcelos, F., Dionísio, M., **Câmara Olim, S.**, & Campos, P. (2023, November). Game ON! a Gamified Approach to Household Food Waste Reduction. In International Conference on Entertainment Computing (pp. 139-149). Singapore: Springer Nature Singapore.*

*Freitas, A., Fernandes, F., Dionísio, M., & **Olim, S.** (2023, November). Mystery in the Ecological Park: An Interactive Narrative to Promote Interaction with Biodiversity. In International Conference on Entertainment Computing (pp. 360-364). Singapore: Springer Nature*

Singapore.

Ferreira, M. J., Oliveira, R., ***Olim, S. C.,*** *Nisi, V., & Paiva, A. (2020, November). Let's Learn Biodiversity with a Virtual "Robot"?. In International Conference on Social Robotics (pp. 194-206). Springer, Cham.*

Cesário, V., ***Olim, S.,*** *& Nisi, V. (2020, November). A Natural History Museum Experience: Memories of Carvalhal's Palace–Turning Point. In International Conference on Interactive Digital Storytelling (pp. 339-343). Springer, Cham.*

*Cesário, V., Trindade, R.,****Olim, S.,*** *& Nisi, V. (2019, September). Memories of Carvalhal's palace: haunted encounters, a museum experience to engage teenagers. In IFIP Conference on Human-Computer Interaction (pp. 554-557). Springer, Cham.*

*Bala, C. S., Trindade, R.,****Olim, S.,*** *Dionisio, D., Bettencourt, A., & Texeira, D. (2018). 6 FFragmentns of Laura & HA-VITA. Looking Forward, Looking Back: Interactive Digital Storytelling and Hybrid Art Approaches, 71*

1.5 Thesis Structure / Document Organization

The rest of this document is organized in the following manner: **Chapter 2.** Describes the Theoretical Background that supports the research framework. **Chapter 3.** Presents the Related Work around Serious Games in the context of STEM domains, AR games, and finally, Augmented Reality Serious Games in the context of chemistry. **Chapter 4.** Describes our methodology starting with our game design process, PF, which included the participation of educational stakeholders and HCI and game designer experts. In this chapter, we also provide the initial Interaction Design process starting with the aesthetics and technology, since these elements are common to all the games, and finally, we provide a brief description of the games. **Chapter 5.** Describes Periodic Fable Discovery according to its mechanics, pedagogic methods, and storytelling. The chapter continues with a pilot test, an iteration that leads to a High Fidelity prototype, and the description of several studies to evaluate the system. The results of this evaluation provide us with the final insight and lessons learned. **Chapter 6.** In this chapter we describe PF an Augmented Journey, our second game. The chapter describes the gameplay mechanics, pedagogic, and storytelling game approach used within the game. Afterward, we describe the iteration process and evaluation of the system resulting in some insights about its efficiency as a tool to provide information about the Periodic Table. **Chapter 7.** Addresses PF in the Wild, describing the game mechanics and pedagogical methods, the Iteration process, and the evaluation of the game. **Chapter 8.** Provides the insights and contributions of this thesis resulting from the conducted studies like guidelines, benefits, and limitations of the AR in the context of Serious Games. **Chapter 9.** We finalize this thesis with a conclusion derived by the process and studies results. We also identify some limitations in the process and studies conducted during our research and future directions and work that can complement this research.

Chapter 2

Theorical Framework

This chapter describes the theoretical research framework of this thesis, which consist of (2.1) Learning framework, (2.2) Chemistry learning, (2.3) Augmented Reality, (2.4) Tangible Interfaces, (2.5) Games, (2.6) Game Design, (2.7) Summary of the Chapter.

2.1 Learning Framework

Learning is a very complex process and term to define. Despite being part of our daily routine, many educational writers and academics are surprisingly inconsistent in the definition of learning. However, many seem to agree that it is a process that leads to a change in behavior [188, 124, 98, 181, 294]. Following this debate, Benjamin Bloom's taxonomy of educational objectives (1956) [180] argues that all learning can be described in terms of three overlapping domains of skills: Cognitive (intellectual capability of knowledge – learn by thinking), Affective (emotions and attitudes – learn by feeling) and Psychomotor (manual and physical skill – learn by doing) [180] (see Figure 2.1).

2.1.1 Learning by thinking

This learning depends on children's cognitive ability to think and reason about an object or event. A child's cognitive development is critical for their understanding of the world around them. Very young children perceive their world concretely through a bondable physical referent that can be grasped with their senses. They learn about an object's identity, function, properties and form, such as a table, by seeing and manipulating it [242]. In contrast, abstract concepts such as "freedom"and "justice"lack bounded tangible and perceivable referents in the real world, making the learning more complex and

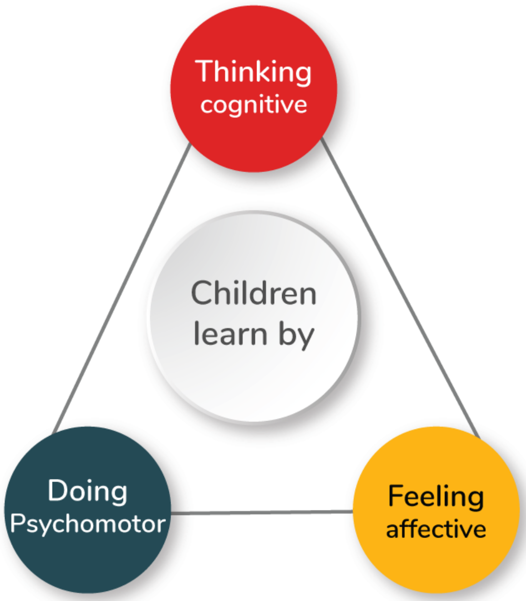

Figure 2.1: Learning Taxonomy according to Benjamin Bloom

subjective, as compared with concrete ideas that are usually visible and objective [242, 141].

Abstract reasoning is a fundamental cognitive skill that underlies children's understanding of abstract concepts. As children progress from concrete thinking to abstract reasoning, they can make connections between different concepts, solve problems using logic and critical thinking, and comprehend complex ideas. The development of abstract reasoning skills occurs gradually, persisting throughout childhood into adulthood. Recognizing the importance of abstract reasoning in children's cognitive development enables educators, parents, and researchers to foster optimal learning environments and facilitate the growth of abstract reasoning abilities.

Piaget, the founder of Cognitive Theory, classified the cognitive development of children according to their age in the "Sensorimotor"stage, from birth to 2 years of age, "pre-operational"stage, from 2 to 7 years old, children can symbolically mean that they can associate letters, sounds, and images representing objects in the real world. From age 7 to around 11, children develop logical thinking, defined as the "concrete operational stage."In the "formal-operational stage,"thinking becomes more sophisticated, and the child can create a solution to problems, beginning around 11 years old and continuing until adulthood (Piaget, 1964). Piaget's theory argues that we are innate knowledge constructors who seek a balance between the mind and the environment [23, 173]. Despite Piaget's theories being prominent in developmental psychology, some critiques included overestimating the ability of adolescence and infants. Piaget also neglected the cultural and social interactions in the development of children's cognitive and thinking ability [23]. For example, the psychologist Lev Vygotsky argues that symbolic and psychological tools such as linguistics, mathematical systems, and signs play an essential role in how humans acquire and internalize knowledge [46]. Parents, teachers, and peers help to create and alter an individual's schemata through guidance and interaction [80]. Current research also complied with Vygotsky's arguments, showcasing curiosity, active involvement, and play towards increasingly complex forms of knowledge, skills and understanding, particularly in the cognitive and social domains [359]. Research demonstrated that, at a younger age, children are capable of reasoning abstractly according to inferred rather than perceived information [296, 26, 232].

Child development studies have shown that well before formal schooling begins, children have content knowledge that aligns with the scientific disciplines of biology, chemistry, physics, and psychology, as well as emergent scientific reasoning skills [225, 44]. It has been noted that young children (preparatory to second-year students) possess an informal knowledge of mathematics that is broad and complex [2]In this line, research suggests that early exposure to STEM subjects promotes the interest and motivation of children towards these domains, which results in an increase in majoring and career choices [349, 41]. Early introduction to sciences is also a way to connect positive emotions, meet the children's natural curiosity and enhance their engagement and positive attitudes toward science [114, 327, 84].

The success and performance of students in STEM subjects are also associated with the capacity of children to manipulate and create mental /images within space, like rotating, understanding relationships between objects, and identifying shapes [199]. Spatial skills identified as spatial or visuospatial abilities might be applied according to different scientific activities and fields of studies [334]. According to Uttal, spatial skills are malleable and can be trained to lead to long-term benefits for science achievement and engagement [334]. Maria Kozhevnikow & Ronald Thorton identified a strong relationship between spatial skills and science learning in preschool to 2nd-grade children and instigated the need to deepen the study of these correlations to adapt the school curriculum design accordingly [178].

By understanding this relationship, children can benefit from the development of spatial training intervention and continued support in the more advanced stages of science education. In summary, there is a need to explicitly conceptualize pedagogical approaches for teaching Science, Technology, Engineering and Math (STEM) in the early years that embrace the maturational stages of children by inviting play and discovery, socialization, and creativity.

2.1.2 Learning by feeling

Learning by feeling relates to students' attitudes, learning, and persistence toward a domain. In this context, STEM areas are affected by the student's perceptions, motivation, and self-efficacy [266]. These findings are supported by Fredrickson 2013, who argues that emotions derived from positive affects play a crucial role in academic achievement by increasing personal resources, creativity, problem-solving, self-efficacy, and academic achievement [118]. Self-efficacy also plays a crucial role in education by causing behavioral changes, resulting in enhanced performance over the course of learning and a determinant of academic outcome [174]. Secondary research indicates that when students' self-efficacy is low (because they do not believe they can perform or accomplish a task), their anxiety level rises, affecting their productivity and output significantly [73].

The Interest and motivation of students are vital components in pursuing STEM learning and contribute toward successfully retaining its content [76]. When the learning content knowledge capitalizes on the student's context and own reality, the children are more willing to engage in the learning process [239, 331]. According to Stuckey et al., in the context of science, the relevance of the content can be achieved in three dimensions: individual, vocational, and societal. The individual dimension involves how science appears to students' personal interest and their everyday lives [319]. The vocational dimension prepares students for future careers by providing the necessary background to pursue a science career. Finally, the societal dimension develops around the comprehension of the students as members of a community and their responsibility as part of society [319]. Introducing science early on can promote positive emotions, meet the children's natural curiosity, enhance positive attitudes toward science [327, 114, 84], and lead to majoring and career choices [41, 349].

2.1.3 Learning by doing

Learning by doing is supported by Vygotsky and Piaget's theories, which agree that students achieve meaningful learning through active involvement in the teaching-learning process and, in fact, taking charge or control of their learning. They try to make meaning of a learning task through knowledge construction and understanding based on belief and previously acquired knowledge [100]. These beliefs from Piaget (building on the work of John Dewey) and Vygotsky laid empirical foundations for the learning approach and teaching methods based on constructivism [23].

In constructivism, knowledge is created by the child actively interacting with the surrounding world. Learning is a process that has to be experienced and built upon previous knowledge, meaning that children interpret the information according to his/her previous experience and knowledge [251]. Constructivism has been a powerful idea in chemistry education research. Based on this perspective, Robert Karplus proposed that young students must develop their knowledge of chemical phenomena in elementary school sciences using past knowledge and experiences [168]. For this process to be effective several factors need to be analyzed: "How much background must the children accumulate before an explanation based on structural unity makes sense to them, and how many impressions can the children retain without confusion before these are organized by a structural explanation?"[168].

Seymour Papert also envisioned a self-directed method of learning, whereby children are actively engaged in creating and constructing things rather than simply receiving information passively [244]. In contrast to imposing strict structures or curricula, Papert argues that giving kids the flexibility to explore and experiment with technology in their own ways was essential.

Other authors demonstrated that providing meaningful hands-on STEAM experiences for early and elementary-age children positively impacts their perceptions and dispositions towards sciences [50, 25, 82].

In summary, this research aims to broaden the application of tools designed to facilitate abstract and spatial reasoning in the context of education. By incorporating Bloom's theory, the study focuses on customizing learning content based on the cognitive development of preteen students, with an emphasis on the "learn by thinking"approach. Additionally, the research seeks to facilitate active knowledge acquisition through a constructivist perspective that emphasizes the "learn by doing"principle. Moreover, the study aims to explore strategies that effectively engage and motivate students towards learning content, utilizing a "learning by feeling"approach.

2.2 Chemistry Learning

Chemistry is essential for our well-being and has many unforeseen potential benefits for our future. Understanding chemistry opens an opportunity to explain the world around us and make informed decisions concerning our actions as individuals. Generally, chemistry is necessary for most science fields, such as material sciences, engineering, environmental sciences, and medicine [28]. Students opting for any of these career fields need a solid knowledge of chemistry [96]. As chemistry is vital for human well-being and the economy, it is important to encourage adolescents to choose a chemistry-related career [313, 20].

In Portugal, chemistry and physics are compulsory from 7th to 9th grade. However, by 10th grade (when students are around age 14-16 years old), students decide whether to initiate or not a trajectory in chemistry and other science domains. However, research shows that young children, some as young as 9 to 10 years old, perceive chemistry as a challenging and complex subject even before encountering this rich subject through the school curriculum ([200, 299, 68, 11]. As cited before, this perception can affect the student's academic performance and future career choices (Rivera & Li, 2020). Furthermore, previous studies link that student success in chemistry is inherently tied to motivational and other affective processes [110].

This negative perception concerns the educational community since, over the years, there has been a decline in the number of high school students who choose to major in chemistry, leading to fewer higher education graduates, which can result in an acute shortage of qualified, skilled chemists, chemist teachers, and chemical engineers [69, 310].

Furthermore, based on the results of the Portuguese Chemistry and Physics National exam with a point average of 12, 7 points (66.2%) in the year 2020, decreasing to 9.4 points (48,9%) in 2021 [1] and with similar results in Madeira Island, it is imperative to find measures that can promote children interest in this domain. To this end, empirical research reports a strong correlation between positive attitudes, the students' enjoyment, and success in chemistry [362, 341].

2.2.1 Factors for chemistry achievement

Some factors attributed to the lack of interest by the students in these domains are the use of abstract reasoning needed to understand some concepts and phenomena that do not have physical references in the real world (like molecules, covalent and ionic bondings). Abstract reasoning is critical in sciences since the learning process of these subjects involves inquiry, experimentation, evidence, evaluation, and analysis of ideas, problem-solving, creative thinking, and overall understanding of information by making connections with the real world. Teachers and experts in these areas also recognized their struggle to communicate and transfer content knowledge, especially when reaching students with low spatial cognitive skills, thus creating a barrier in the learning process. Spatial skills sometimes intertwine with spatial abilities, or visuospatial skills are the ability that an individual has to project, imagine or manipulate objects within the space [314].

The ability to manipulate the mental object can be by means of rotation, orientation within the space, or by creating relationships within objects in the space [334]. Spatial relations are critically important in chemistry, as one of the central challenges in learning chemistry is understanding spatial relations among molecules and the representation of these molecular structures [160].

Chemistry also has unique challenges, as many concepts and phenomena can be experienced in several levels of representation. The understanding of chemistry concepts depends on the symbiosis between these modes or levels of representation: macroscopic or macro, microscopic or sub-microscopic, and representational [161, 162, 121, 330], also called the Chemistry Triangle (see Figure 2.2).

Johnstone and other theorists have indicated that the interactions between these levels should be explicitly taught [138, 91, 258, 330], as some students' difficulties at one of the levels influence the other. Previous research also has indicated that understanding the microscopic and symbolic representation of chemical reactions is difficult because the representations are abstract. At the same time, students' thinking depends on more concrete sensory information [48]. These studies showed that linking one mode to another creates a better relational understanding of chemistry [151, 287].

Previous work also showcased that the use of traditional media as textbooks to display information like covalent bonds [241], molecular form, molecular polarity, and bond

[1] Direção-Geral de Estatísticas da Educação e Ciência, https://www.dgeec.mec.pt/np4/estatisticas/

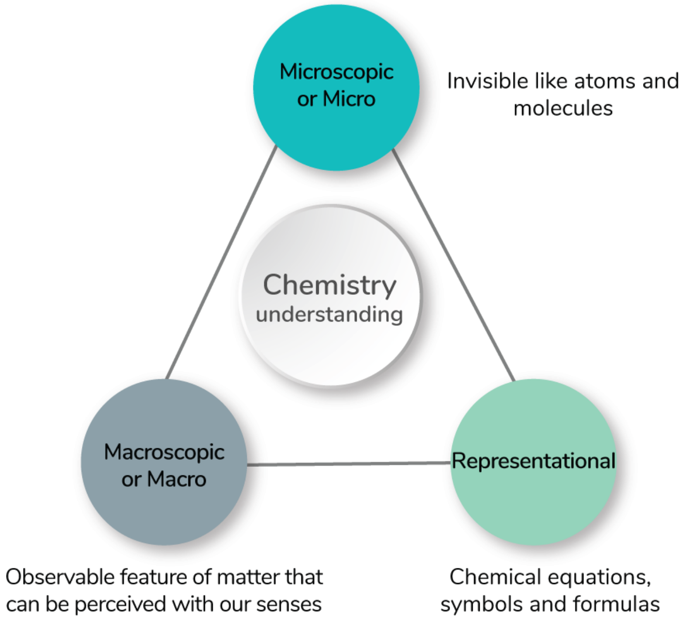

Figure 2.2: Chemistry Research Approach

polarity in a 2D format can lead to many misconceptions [333].

Chemistry understanding also demands complementing conceptual understanding in a meaningful manner by linking the content to the context of the student. This is particularly important as the more relevant the subject is for the children, the better their attitude toward the learning content. If the learning content and the scientific literacy are associated with the daily life and situations of the student, the higher their interest. The teaching of chemistry should consider the learner's psychology, meaning that the learning material should be adapted to the learner's needs and capacities.

Other factors that can affect the student's performance and predict positive student outcomes in chemistry are intrinsic (doing an activity because it is inherently interesting and satisfying) and extrinsic motivation (doing an activity because of rewards or to avoid punishment) [278]. These factors are associated with improved psychological well-being, enhanced creativity, and learning outcomes [278]. The sense of self-efficacy (belief in possession of sufficient skills to perform a task [31] and metacognition (the processes that allow one to assess and regulate one's cognition) [113] are important in the psychological constructs of children and in the process of learning chemistry [240]. As students are disappointed by their performance, their interest in the subject deteriorates [154]. A practical approach to chemistry is beneficial to understanding and developing intrinsic motivation; however, in the school context, these activities are limited by the increasing number of students within the classes, time restrictions, and lack of resources to conduct experiments.

Finally, while studies complied with providing a richer chemistry curriculum early in life, few studies have explored the benefits of immersive technologies to increase preteen interest [72]. When students develop the basic concepts early on, they can be more successful in learning advanced topics in science at later stages because each new piece of information is added to what students already know about the topic at hand [241, 317]. Children enter school eager to learn because of their natural desire and curiosity to inquire about their environment; however, research demonstrates a decrease in their motivation toward science as they advance through middle childhood and approach adolescence [194]. This lack of motivation toward science experiences may prevent many children from fully developing scientific literacy, reducing their understanding of STEM domains and environmental concerns, moreover limiting their vocational, socioeconomic, and overall life potential as adults [18, 215].

In summary, considering that chemistry understanding involves three levels of representation, our research explores the effectiveness of implementing tools capable of presenting information simultaneously at multiple levels. This approach aims to enhance students' comprehension and retention of chemistry concepts by providing a comprehensive understanding through various representations.

2.2.2 Periodic Table

The Periodic Table is one of the most significant achievements in the modern sciences for chemistry, physics, medicine, earth sciences, and biology. The Periodic Table is a fundamental tool in chemistry, allowing scientists to predict the properties and behavior of elements and their compounds.

The Periodic Table is a system whose first version (1869) was created by Dmitri Mendeleev to represent chemical elements in tabular arrangement ordered by their atomic number, electron configurations, and chemical properties. It consists of 118 elements, including 94 that occur naturally and 24 that are synthetic. The elements are organized into groups based on similar electron configurations and periods based on their electron shells. Because of its importance, in 1969, the United Nations Educational Scientific and Cultural Organization (UNESCO) declared it the International Year of the Periodic Table, and many events and activities were organized around the world to celebrate the 100th anniversary of this fundamental tool of chemistry. This anniversary was once again highlighted in 2019, with the celebration of the 150th anniversary of the continued relevance and importance of the periodic table in scientific research, education, and industrial applications, as well as the ongoing effort to discover and understand new elements and their properties.

It is important to teach children about a range of chemical elements and how essential they are in our life. However, the specific elements to prioritize may depend on the age, interests, and educational goals of the children being taught. Some chemical elements like oxygen, hydrogen, carbon, nitrogen, and calcium are introduced to children early on, while at the elementary school level, through topics like photosynthesis (oxygen and carbon), pollution (carbon dioxide), the human body – respiratory, circulatory system (oxygen, nitrogen, calcium) and the water cycle (hydrogen and oxygen). These elements are considered the most abundant in the earth's crust, ocean, and atmosphere, showcasing how crucial they are for human well-being and the environment. Moreover, children interact with various chemical elements in everyday contexts, like chlorine as a clean agent for swimming pools or household shores, carbon as part of carbonated water or soft drinks, and others.

The Periodic Table is introduced in schools in Portugal during the 8th grade (12- to 13-year-old). At this stage, the objectives of the National Board of Education for the chemistry curricular program (DGE, 2000)[2] are to develop scientific literacy, critical thinking, and problem-solving skills (through observation, formulation and using hypotheses). The content is divided into three areas of exploration– Chemical Reactions, Sound, and Light. The topic of chemical reactions starts by introducing the concept of atoms, molecules, protons, electrons, and neon. Later, students learn about the symbolic representation of the elements, properties, and chemical reactions (usually lab experiences to explore combustion) and chemical equations of the molecular structure. Lab activities used chemical elements whose properties can easily demonstrate and provide interesting reactions to captivate the students.

Introducing chemical elements to preteens is also an opportunity to reflect on the limited supplies of some of these elements and the extended use of others by industries contributing to environmental change. Since the industrial revolution and with the introduction of new technologies, there has been over-exploitation and use of different chemical elements leading to their scarcity, and some being labeled as "critical elements"and "endangered elements "[321, 209]. The critical and endangered elements are defined by their economic value, the importance of use, supply risk, and availability. In 2017, the European Union and the United States recognized at least 27 critical elements, including helium, platinum-group elements, zirconium, cobalt, phosphorus, magnesium, and borate. Even though the demand for the continuing use of elements is at its highest, it is foreseen that this problem will only increase as human life expectancy and living standards improve.

The over-exploitation of chemical usage and the impact of massively expanding industrial operations that generate greenhouse gases (contributing to climate change) [209] leads to the need for better husbanding of the critical elements, recycling and conserving available supplies with a more holistic approach to their use and recovery while searching for new and sustainable substitutes whenever possible.

In conclusion, our research emphasizes the significance of the Periodic Table as a fundamental tool in chemistry, enabling preteen students to investigate and comprehend the properties, relationships, and reactions of elements. Additionally, this topic offers an opportunity to raise awareness among children about the limited availability of specific

[2] Direção-Geral da Educação, https://www.dge.mec.pt/

chemical elements. By studying the Periodic Table, students can develop a deeper understanding of the composition and behavior of chemical elements, fostering an appreciation for the importance of sustainable resource management in chemistry.

2.3 Augmented Reality

Currently, where access to media is widely available, an opportunity emerges to augment and use our environment as a medium to acquire and share knowledge. Children can use digital technologies to create, engage, interact, connect, and communicate, amplifying their discoveries and learning possibilities. Therefore, blending the environment and children's digital capacities can augment their physical space, enhance children's access to digital educational material, and promote learning.

Augmented Reality (AR) is the perception of reality that has been enhanced through computer-generated inputs and other digital information [22]. AR interface can overlay virtual tri-dimensional models, videos, and other types of media attached to real locations and objects. AR's first prototype was developed in 1960. However, it was not until 1990 that the term Augmented Reality was conceived when scientists Caudell and Mizel from the Boeing Corporation developed an AR system [338]. The technology is not new, but its application has grown. It is being explored in new and innovative ways for medicine, manufacturing, visualization, path planning, and entertainment domains, as well as in the education fields [21]. Unlike technologies where the user's attention is exclusively oriented towards a screen, AR presents information about their real-world surroundings [21]. AR falls between a physical and a virtual reality spectrum, meaning that AR supplements reality rather than completely replacing it. This variation of ranging between the completely virtual and real is illustrated by the virtual continuum scale created by Milgram [217](see Figure 2.3).

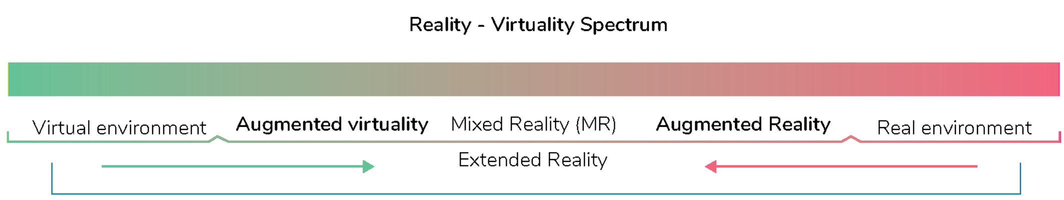

Figure 2.3: Taxonomy of Mixed Reality Displays

We can categorize AR in marker-based and markerless technology according to how the augmentation is triggered on a system. Marker-based uses unique patterns/images that cameras can recognize to render and upload digital information on the user's device. Markerless technology does not require visual cues but instead gathers information from the environment through cameras and sensors like Global Position System (GPS), accelerometer, light detection, and digital compass, or by using models of the environment and image processing to deploy the digital information. We can also identify two sub-categories within the markerless technology – Location based (ties the experience to a particular setting/context) and Projection based (projects the digital information onto flat areas without user interaction).

Since smartphones are ubiquitous, Mobile Augmented Reality (MARs) is the most common and widely used form of AR; however, other devices that support this technology are AR glasses (e.g., Google Glass, North Focals, Ry-ban Stories, Echo Frames, Snap Spectacles), AR headsets (e.g., Microsoft Hololens, Magic Leap and Snap Spectacles) and in the future, AR contact Lenses (e.g., companies investing in this technology Mjo Lens and Inwith). On this note, there has been a growing commercial interest and investment in developing applications in education targeted at children. The continuous investment in AR by some of the most prominent players in the industry (Apple, Google, Microsoft), the improvement of affordance, children's increased access to mobile devices, and the popularity of the Augmented Reality game "Pokemon Go,"with its high economic gains and extensive public engagement, have contributed to the increasing development of AR applications in many fields, including education.

Studies show that Augmented Reality has great potential in Edutainment (education and entertainment) [189]. As a pedagogical tool, AR enables critical thinking and develops creativity[370]. Many AR experiences have explored the benefits of using this technology as a form to provide learning content while engaging the students in the process and have proven especially powerful for STEM subjects [343, 166]. AR can create compelling, collaborative, and participatory experiences to enhance the user's engagement and learning. These experiences can provide alternatives to a real-world environment for situated learning, allowing the user to experience a sense of presence (being there) while applying acquired knowledge [89]. AR has also been shown to be a powerful tool in developing spatial skills, such as student understanding of structures that can be either invisible to the naked eye or spatially complex [337, 354].

Augmented Reality uniqueness enables the connection between content knowledge and the user context, given the possibility of transporting the knowledge to other settings, thus making the learning more effective. The simulation of real-world problems and contexts can be obtained by near transfer. This assimilation of knowledge can then be transferred to other situations, allowing for the construction of more knowledge. Examples of this process can be found in in-game simulations for flight and surgical training, whereby the user can practice and develop specific skills, making mistakes and getting positive feedback when the task is performed in a low-risk environment before transferring this knowledge to real-world situations. AR affords users to visualize otherwise inaccessible representations and experiment in a low-risk and low-cost platform [169]. Finally, Augmented Reality (AR) has been shown to be a powerful tool for students' affects by increasing student motivation in the learning process [37].

However, the research on AR in education is still ongoing, and several challenges must be addressed before it is widely adopted daily. Firstly, the power of AR is severely limited by technical aspects such as robust internet services and robust mobile devices [246], which does not correspond to the reality of the Portuguese educational context. Moreover, although the tracking process (that allows for synchronizing virtual objects and real environmental settings) is robust, it is still susceptible to lag and tracking errors; the system requires continuous tracking of the user and environment not to introduce computational errors and break the user experience flow[279]. Considering head-mounted displays head-mounted display (HMD) for AR are heavy, costly, and still improving technical issues (inaccurate depth of field; unrealistic fixed focus; slow real-time) [79], it is not suitable in the school context. Teachers' lack of technical skills, training and support can affect their confidence, making them uneasy about introducing AR within the classroom [304]. Limited authoring tools for teachers and students to create appropriate learning content have also been reported [304]. Other problems include the high cost of creating interactive 3D experiences through specialized engineering skills, better internet connections, infrastructures on school grounds, and the acquisition of equipment and devices that support the technology [255, 256]. There is also a lack of pedagogic knowledge regarding the off-the-shelves AR applications [304]. In addition to these concerns, research by Ann Morrison reported usability issues and identified the "attention tunneling effect"as a result of AR's higher attention demands, which led students to feel unable to perform some team tasks [220]. Moreover, it is unclear whether the students' high engagement with some educational systems in some studies is due to the novelty effect of the technology or the nature of immersive representations [255].

Furthermore, there has been limited exploration into ensuring the broader accessibility of AR applications. Some recommendations are available by Magic Leap [3] that touch on the utilization of color and audio for users with low vision or hearing impairments. Additional the work of Jaylin Herskovitz, provides an alternative to the AR visual experience, by identifying multi-modal interactions from the beginning of the design process, rather than as an afterthought [142].

Children may also encounter cognitive overload while using AR, employing much information and complex tasks, or when digital and real-world content is not well-integrated [64]. Although these technical shortcomings are relevant to the current state of the art of AR, they are expected to be solved eventually. The continued development of AR technology will explore new types of triggers/sensors (e.g., temperature, smell, and voice recognition), more input interfaces (e.g., gesture recognition, tangible interfaces), and more complex interactions.

In conclusion, this research investigates the potential benefits and capabilities of Augmented Reality (AR) as a tool to enhance student engagement with content related to the Periodic Table in chemistry. Additionally, the study explores the application of AR

[3]https://ml1-developer.magicleap.com/en-us/learn/guides/bp-for-accessibility

technology in facilitating a comprehensive understanding of chemistry concepts at multiple levels of complexity. By leveraging AR, students can interact with virtual elements and visualizations, promoting active learning and a deeper comprehension of the Periodic Table and its associated principles. The analysis of AR concerning various levels of chemistry understanding provides valuable insights into the efficacy of this medium for enhancing chemistry education.

2.4 Tangible Interfaces

Tangible Interfaces (TI) is defined by Ishii and Ullmer as "user interfaces that augment the real physical world by coupling digital information to everyday physical objects and environments"[150].

TI have been shown to facilitate learning and be an excellent alternative to traditional teaching methods [167]. One of the key aspects of TI is the opportunity for young children to learn by using, exploring, and manipulating an actual physical object connected to digital information [135]. Piaget and other developmental psychologists highlighted the importance of manipulating objects, especially for young children's cognitive development [250]. When a child rotates a cube to build a tower, he/she employs spatial reasoning, allowing his/her investigation and problem-solving skills to develop further [264]. Previous research also showcased that the interaction between AR content through a tangible interface enables an active learning process, meaning that the students are in control of the learning process [37]. Besides the visual and auditory senses addressed by some of the more traditional computer interfaces, the haptic sense can provide an extra layer to learning the content. One of TI's most prevalent theoretical accounts is constructionism, which considers manipulating an object essential to aiding children's learning processes. TI has also been demonstrated to be highly effective in supporting educational activities in several topics, including those defined as STEM [361, 166, 191]. This is the case with Digital MiMs, computer-enhanced building blocks that support learning in mathematics, probabilistic behavior, and more. Another example is ProBoNo, a software and tangible hardware prototype developed for children from four to six years of age. PrBoNo allows children to navigate virtual worlds more playfully and engagingly. A study of this system concluded that the tangible interface facilitated the transfer of knowledge acquired in a digital environment to a situation in the real world [130].

Nevertheless, while these works provide essential insights, this research explores which features of tangible interfaces design might be associated with successful learning in STEM, especially in the chemistry domain.

2.5 Games

There is no standardized definition for "game"in academia or the game industry. According to Ernest Adam (2013), a game is a type of play activity conducted in the context of a pretended reality in which the participant(s) try to achieve at least one arbitrary, nontrivial goal by acting following rules [3]. This definition is somehow shared by Carla Fisher (2014), who stated that a game could be defined as an interactive experience where one or several players need to reach a goal by taking some actions (following a set of rules) [111]. Jessy Schell has a more simplified definition "A game is a problem-solving activity, approached with a playful attitude"[292]. However, for the purpose of this thesis, we adopted Katie Salen and Eric Zimmerman, who, cobbling from previous definitions, define a game as a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome [325]. According to this definition, the system is a set of parts that, while interrelated, form a complex whole (e.g., objects, attributes, internal relationships, or the environment). The player is the participant that actively plays or interacts with the system. Artificial is the confinement or separation from the so-called "real-life"of the player; however, the artificial can become the perceived reality through immersion. The conflict is an opposing force or outcome to what one desire or a contest of power (from cooperation to competition, human vs. machines, man vs society, etc.). Rules delimited the player's action by providing a structure from which play emerges. Moreover, the quantifiable outcome is related to the goal to achieve at the conclusion of the game [325].

Playing games is also considered a crucial activity for the human development of socialization, expression, and communication skills [122]. The concept of "play,"which is commonly associated with "game,"has been defined in most modern European Languages as "a voluntary activity or occupation, executed within certain fixed limits of time and place, according to rules freely accepted but absolutely blinding, having its aim in itself and accompanied by a feeling of tension, joy and the consciousness that it is "different"from "ordinary life [126].

2.5.1 Analog Games

Analogs or physical games offer the chance to develop cost-effective and easily adaptable experiences. An example is Tug-of-War, a math game utilizing cards that allows children to engage in operations on whole numbers [157]. This game has demonstrated the potential to improve students' scores on paper-based fractions assessments. Foster and Shah use a similar method with PCaRD, a playful activity which is also used to reflect and discuss the learning content [116].

The utilization of board games extends to the promotion of diverse learning experiences. These tools have demonstrated their capacity to bring about changes in the learning process and foster engagement [315], enhance player satisfaction [289], and provide opportunities for enjoyable, social, flexible, and cost-effective experiences [218]. Some authors suggest that, in addition to facilitating knowledge acquisition, board games also contribute to behavioral change [59].

2.5.2 Digital Games

Digital games have been conceptualized as particular types of digital environments or as forms of virtual worlds. However, this term has been debated previously by game theorists leading to a broader definition by Grant Tavinor, who claims that this type of game can be best defined according to two conditions: the digital/visual medium condition and the entertainment condition – both of which should provide a rule-bound gameplay and interactive fiction [323].

Digital games benefit from studying psychological theories that can explain a specific reaction, emotion, or affect from the interaction between a game and its player. Nowadays, more and more games are designed to make the player feel like he/she is in the game. Previously authors used the theory of flow or the "theory of optimal experience", established by psychologist Csikszentmihalyi [34], to describe how a player's experience was in large part dependent on the balance between a game's challenge and its player's level of skill [61]. The flow theory (a phenomenon of becoming absorbed by an activity, even to the point of losing track of time and your surroundings) can provide insightful information to explain why certain types of activities can absorb and engage the participants to a high degree. In contrast, others quickly leave the participant bored or stressed out [34]. Csikszentmihalyi's findings lead us to believe that by following a set of criteria, the player's flow, immersion, and engagement of the player will increase:

- The player must be involved in an activity with a clear set of goals and progress. This adds direction and structure to the task.
- The activity task must have clear and immediate feedback to allow the player the adjustment of his/her performance.
- The game must balance the perceived challenges of the tasks and the player's own perceived skills.

Presence can also add to the optimal experience of the player. Presence is a psychological sense of "being there"in the environment, which is mainly influenced by the content of the digital game [309]. Presence depends on the match between sensory data and internal representation. This concept is comparable to what artists refer to as believability. We can only believe in made-up things, places, people, and stories if they mostly match our models. The presence should then be improved by making the content of video games more credible.

The theory of fun by Raph Koster examines games using a user-center approach and human psychology as the primary focus [177]. Koster's research describes fun as a sensation that arises out of the human cognitive ability to decipher the patterns of a game challenge. Games that manage to remain fun for the player for a long time are games that constantly reconfigure the patterns in the game in some way and push the player's ability to develop their understanding and mastery of the game continuously. Conversely, games that the player loses interest in quickly are the ones that either present incomplete or incomprehensible patterns or puzzles or are too easily mastered and do not throw any new configurations the player's way [177].

2.5.3 Serious Games

Serious Games emerge as practical tools for knowledge construction when they include specific learning objectives [238]. These games are sometimes described as games with a purpose that are not intended to be played solely for amusement and are often designed to make beneficial but challenging activities more fun [70]. Serious games are often designed to help cope with more complex activities intended to affect the learning process [70]. Some of the benefits associated with these tools are to provide exciting opportunities to build mental structures (Piaget, 2005), develop abstract thinking [250, 345], and improve relevant abilities such as those related to attention, memory, creativity, and imagination [19].

Playful educational experiences and games have also shown positive effects on a broad spectrum of the development of cognitive skills [143, 112]. Educational games increase concentration levels and stimulate learning in children [10], allowing for the exploration of teaching tools such as metaphors, analogies, and the spatial manipulation of 3D objects through technologies like Virtual and Augmented Reality [297].

Although serious games offer learning opportunities, the design process will affect its success. The design of serious games is a creative but complex process since it overlaps theory, content, and game design form. Brian Winn proposed that since the learning objectives are central to the core of serious games, the design should focus on the learning content and pedagogical approach in the first place. The next step is prioritizing the settings, characters, and narratives to support the learning goals adequately. Afterward, the mechanics need to be established as a medium to deliver the playable content. Finally, the designer should reflect in the user interface [356]. Jessica Hammer also identifies role-playing games as effective tools for learning when implemented with the appropriate circumstances, learning theories (e.g., constructivism and social-cultural theories), strengths of role-playing (portraying a character, manipulating a fictional world, altering the sense of reality, and supporting collaboration) supported by the learning environment [136].

Furthermore, the reported dimensions of digital games and their importance in the gaming experience rely in part on the motivational outcome of the gameplay [53, 101], the narrative, the rules of the system, the aesthetics and the technology [292].

2.5.3.1 AR Serious Games

AR games hold great potential for cognitive and motor development and represent a powerful tool to facilitate the teaching of the school curriculum and an effective way of acquiring knowledge within a formal and non-formal context. As argued by John Dewey, teaching involves "engaging children in a fun and playful environment, imparting educational content, and instigating interest in learning more ."Many virtual games and immersive simulations have been designed for training and education to motivate students by providing a more immersive and engaging learning environment to support situated learning, which builds upon social learning and development theories. According to this theory, the quality of learning depends on social interaction with the learning context [158, 274, 346]. Given these conditions, knowledge is acquired through a participatory process whereby the learner is "transformed through his actions and relations with the world"[46]. The seamless integration of virtual content with the real environment can evoke in the users a perceptual state of non-mediation, a sense of presence reinforcing immersion [265]. AR design strategies create virtual immersive experiences and games based on action and symbolic and sensory factors. Research has shown that immersion in virtual environments and games can enhance education by allowing multiple perspectives of the learning content, applying situated pedagogy, and transferring knowledge [90].

AR games allow users to discern and interact with the real environment while simultaneously receiving additional digital information in their field of perception [42]. This affordance is significant since even exceptional students in formal educational settings often find it difficult to apply what they learn in class to similar real-world contexts [90]. The simulation of real-world problems and contexts can be obtained by near transfer. This assimilation of knowledge can then be transferred to other situations, allowing for the construction of more knowledge. Examples of this process can be found in in-game simulations for flight and surgical training, whereby the user can practice and train specific skills, making mistakes and getting positive feedback when the task is performed in a low-risk environment before transferring this knowledge to real-world situations.

This research investigates the potential of Augmented Reality Serious Games as tools for enhancing children's engagement in learning activities and promoting a deeper understanding of content knowledge. We also explore immersive experiences to captivate children's attention in the content knowledge, thus helping the learning process. Furthermore, we assess the potential of using Augmented Reality Serious Games in improving preteens' attitudes toward chemistry and its potential as a "learning by feeling tool."

2.6 Game Design

A good game design is a process of creating the content and rules of a game using a user-centric approach [43]. This process creates goals that a player feels motivated to reach and rules they must follow, making meaningful decisions to pursue those goals"[43]. While the game design term is used broadly, there are many types of game design:

- Environmental/world design is the construction of the game's overarching storyline, location, and theme of the game.

- System design is the development of the game's rules and underlying mathematical patterns. Content design is the production of puzzles, quests, puzzle pieces, and characters. In the context of educational games, the content knowledge of the domains is also a predominant part of the content design.
- Game writing or game narrative is the authoring of dialogue, text, and stories for use in games.
- Level design is the process or crafting of creating a game's levels, for example, the layout of a map and the positioning of obstacles and challenges.
- User Interface (UI) is how the player interacts with the game and how they receive data and feedback from it.

Game designers follow different approaches depending on the situation and the medium that it is designed for. For example, Jessy Schell coined the term "Elemental Tetrad"to categorize four basic elements: technology, story, aesthetics, and mechanics [292](see Figure2.4).

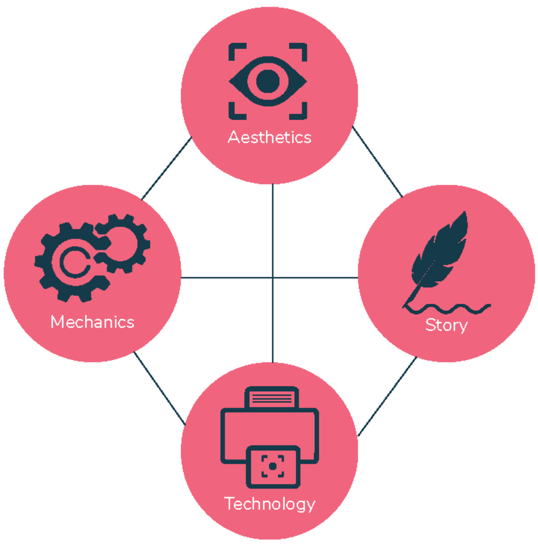

Figure 2.4: Game elements categories according to Jessy Schell – Elemental Tetrad

In his view, many factors need to be considered when designing a digital game, like understanding how specific elements and mechanics of games (rules and goals), narrative/storytelling, and fiction - can be arranged and how they affect the play experience. These elements create a specific experiential flow by being interrelated and connected and having equal importance within the context of the game. Similar to this categorization, Hunicke et al. introduced a game design framework Mechanics, Dynamics and Aesthetics (MDA) (see Figure 2.5) to help designers in the process of creating a game [145].

There are many similarities between Hunicke et al. (2004) framework and Jessy Schell's game categories, except for the dynamics, defined as the emergent behavior of

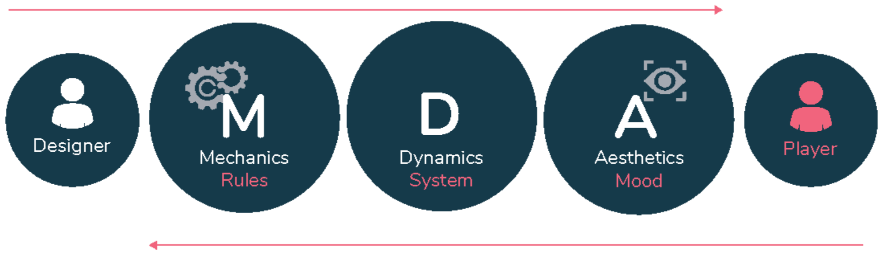

Figure 2.5: Game Design Framework according to Hunicke, Leblanc & Zubeck

both the game and the player(s) during the game interaction. Dynamics include artifact behavior (usability issues like lag), player-player interaction (e.g., cooperation), and artifact-player interaction (e.g., explosion). Some mechanics can lead to specific dynamics, like feedback or particular abilities, that a game avatar can develop. Games can be framed as designed artifacts that generate behavior through interaction with the developed systems. At all levels of research and development, these interactions can provide a more precise design decision and analysis.

Likewise, George Kalmpourtzis's approach follows the four basic elements identified by Jessy Schell; however, when designing games for education, a fifth element needs to be part of this balance: the pedagogics (Kalmpourtzis, 2018b). All the game elements are interrelated with learning aspects as part of the design that is being implemented, leading to an extension of the elemental Tetrad to Elemental Pentad [165](see Figure 2.6).

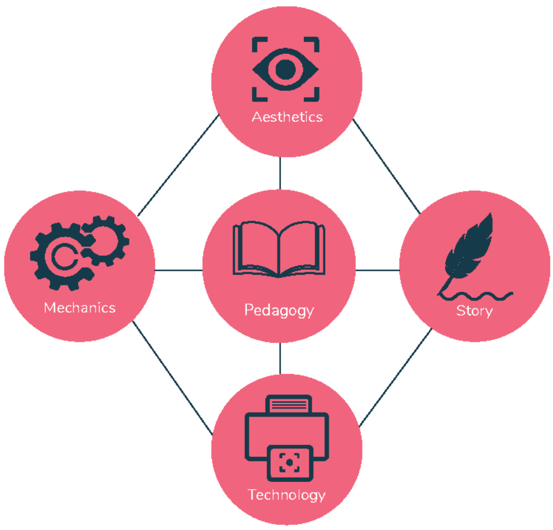

Figure 2.6: Representation of the elemental Pentad according to G. Kalmpourtzi

Based on this body of work and our design process, this thesis uses a framework that, while balancing game elements (Jessy Schell) and pedagogics (Kalmpourtzi), iterates according to game dynamics (see Figure 2.7).

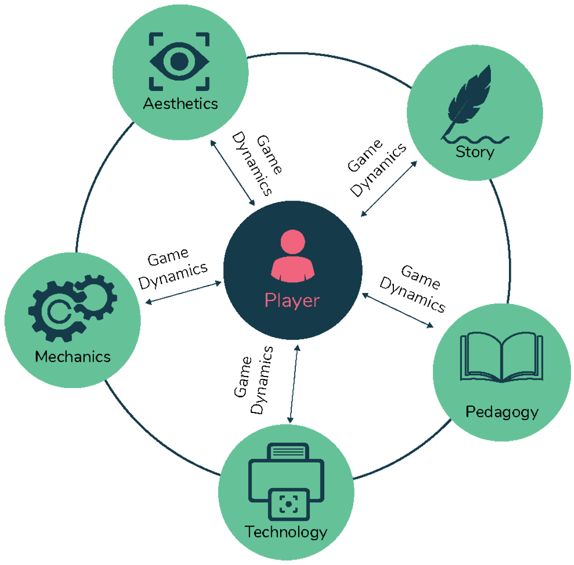

Figure 2.7: Periodic Fable Game Design Framework Approach

2.6.1 Aesthetics

The aesthetics of a game is defined as "the desirable emotional responses evoked in the player when he/she interacts with the game system"[145]. The aesthetics are also considered as having the most direct relationship with the user since it provides the visuals and tone of the game (Schell, 2008). Influenced by MDA and the Tetrad, some of these tones or atmospheres are fantasy, discovery, and expression. While the aesthetics in the domain of digital games is related to the emotions and specific to a player, it emerges from the player-game interaction dynamics [145]. A game's aesthetics also depend on its style, resulting from numerous interwoven micro-design choices related to the game's visual presentation, gameplay, balancing, and level design [257].

2.6.2 Aesthetics for children

Designing aesthetics for children involves creating visual and sensory elements that are appealing, age-appropriate, and creates a positive and engaging experience. According to Green [133], who introduced the concept of "aesthetic relevance," users engage, behave and react emotionally according to the aesthetic experiences. Several authors have tried to identify specific design features that offer a positive aesthetic experience to users, however there is a lack of studies that involved children experiences [187]. In a study conducted by Andrew Large et al., involving seven children, the creation of an aesthetically attractive experience for children was explored through a visualization taxonomy. The study suggests that incorporating elements such as unity, balance, equilibrium, symmetry, rhythm, and economy is essential [187]. Jolley and Zhi's research asserts that the focus on illustrations varies according to the child's age. For instance, four-year-olds tended to pair illustrations more frequently based on color compared to participants in other age groups [163]. The findings also revealed that seven-year-olds more frequently paired illustrations based on subject matter than both the four-year-olds and the ten-year-olds [163]. Another investigation conducted by Reinecke and Gajos (2014) delves into the effects of the visual complexity of images [262]. The experiment revealed that 12-year-olds exhibited a preference for a moderate level of visual complexity when interacting with websites. These findings were supported by a study conducted by Wang, Hsiu-Feng, and Lin, Chia-Hsiung, where 7-12 year-olds displayed a preference for web pages with a moderate level of visual complexity. The authors emphasize the significance of considering simplicity, diversity, and colorfulness in website development for children, as these factors, akin to adults, significantly influence aesthetic preferences [348]. However, as per Birgit Cold et al. biological, emotional and cultural aspects can influence a person's aesthetic preference and can change during the course of development [75].

2.6.2.1 Character and environment design

Character design is fundamentally the process of developing a brand-new, unique persona for a medium, like a movie, comic book, or digital game [231]. The characters serve as a window allowing the viewer to witness a variety of places and events, so stories are perceived via them. In order to elicit emotion and investment in the plot, characters must establish a relationship with the audience. A character designer must be proficient in designing likable and believable characters to produce stories that connect with the audience [29]. Because of this, both in written and visual media, strong character design is crucial. While the character design commonly focuses on visually appealing characteristics, the mental world and story are also important.

Understanding what methods of approach are needed to create a visual emotionally educe Virtual characters can be used to promote the discovery and exploration of educational content. The character design process needs careful development, which involves choosing the visual characteristics and aspect of the characters, their purpose, and how to create a connection to its audiences, evoking the audience's emotion and investment [231]. Design for the demographic and target group to whom the character is developed, such as age, gender, socioeconomic status, interest, and faith. In children's case, character designs are usually designed as being colorful, made from basic shapes, with exaggerated facial expressions, showing evident changes in mood, behavior, and social interaction [329]. According to Tillman, the criteria for this selection is that children prefer simple character design that optimizes the information necessary for their processing ability [329]. According to Disney animators Ollie Johnston and Frank Thomas in 1991, the exaggeration of movement and visual expressions also appear pleasant to viewers of all age groups [328]. Besides, a designer needs to consider how the character moves (body language), speaks (voice), makes facial expressions, and interacts to provide a social impression [148].

Designers must also consider the medium that evolves the character to optimize the character (style and purpose) according to such application or target media [30]. In the case of digital games, this means some restrictions to visual traits; for example, heavily detailed characters can compromise the equipment's image processing system and provide a different perspective according to the view screen – mobile vs. computer screen. Designing recognizable characters depends heavily on the silhouette and shape. In contrast, the silhouette can promote user interest, and the basic shape can draw attention and contribute to the overall feel of a character [329]. Circles, for example, are perceived as being friendly forms and, because of their lack of sharp edges, considered not threatening.

Color is also an essential element when projecting a character's personality. Because color has cultural symbolism (either from individual to individual or across cultures), it is essential to underlying the associated meaning of the colors according to the cultural context. However, some colors have standard symbolic connections, like red, a vibrant, energetic, and aggressive color.

Likewise, the environment or the digital world creation of the game can be used to inform the player about the setting, characters, and conflict. Environmental storytelling creates the necessary conditions for a fully immersive narrative experience in at least one of four ways: spatial stories can evoke previously experienced narrative associations; they can act as a stage for the performance of narrative events; they can incorporate narrative information into the scene; or they can provide the raw material for emergent narratives [329]. Through the character's story, the audience can reflect on a similar experience they had in their past, which causes the character to seem more believable. It will also motivate the audience to follow a character's adventure to get to know them [329]. Arie W. Kruglanski's research argues that the human need for cognitive closure, or gain a resolution in the world, is based on a need to feel in control [182]. The need to avoid ambiguity can motivate and lead an audience to follow a character's story.

In conclusion, a well-developed character serves as a medium through which the audience can experience various emotions and encounters. When a character establishes an emotional bond with the audience, invoking empathy and similar sentiments, it prompts the audience to become invested and actively engage with the overall experience. In this context, we seek elements of character empathy and emotional impact to indirectly allude preteens to the educational content.

2.6.3 Storytelling

Storytelling has been used in every civilization throughout history to understand and express human experiences. The educational psychologist Jerome Bruner defines narratives as a primary method by which individuals can organize and interpret reality [19]. Storytelling within the game context is considered a vital element of the overall gameplay experience [292]. The game narrative is described as the sequence of events which unfolds in a game [292]. Digital game storylines, especially those in serious games, are vast and diverse, ranging from those in a fantasy setting to those in real-world settings. Significantly, game stories differ from narratives in other media types since the audiences have more control and interact with the story [254].

Narrative game learning environments that combine stories and pedagogical support strategies to deliver effective, engaging educational experiences have been shown to be influential in teaching science and arouse interest and promote positive attitudes toward learning science in the early years [292]. A gamified storytelling approach can immerse children in the narrative, positively affect their attitudes, and raise their interest in learning science in the early years [198, 213]. According to Ermi and Mäyrä, immersion is attributed to sensory factors, challenge-based experiences, and imagination – which they call imaginative immersion. Imaginative immersion is when players become absorbed in the world and stories or begin to empathize or identify with game characters [211]. At the same time, Tuomas Harviainen distinguishes imaginative immersion between "character immersion"and "narrative immersion,"depending on if the story or the character is absorbing the player [139].

Readers experience emotions in response to stories and entertainment in general; education can exploit this mechanism to foster learning. Transportation into a story world makes narrative events seem closer to a personal experience, and the impact of the lesson to learn can be strengthened [224]. Moreover, attitudes based on cognitive and emotional foundations are more persistent over time [272]. Emotionally rich stories are more likely to be remembered [195]. Digital games can give life to incredibly engaging fictional worlds in which learning takes place as part of the game's mechanics in addition to the incidental content learning [58].

The effectiveness of this method of teaching and learning depends on factors like contextualizing the learning content within the narrative plot, which implies pedagogical planning and identifying goals according to the student's cognitive development and cultural reality [305]. Our focus lies in examining the utilization of storytelling to offer pedagogical assistance and inspire children's engagement in chemistry. Our objective is to envelop our targeted audience within a narrative universe that establishes links to the educational material, fostering curiosity and reinforcing their grasp of the subject matter.

2.6.4 Mechanics

Game mechanics is another concept without a generally accepted definition in the industry and academics; however, research agrees that there is an interrelationship between mechanics and player behavior [302, 153]. Several authors have made several tentatives to define game mechanics, namely: "the means that guides the player into a particular behavior by constraining the space of possible plans to attain goals"(Järvinen, 2007); "the method (behavior) invoked by agents, designed for interaction with the game state"[302]; finally, the process, which includes rules that are needed to achieve an identified game goal [292]. We can conclude that game mechanics are crucial in differentiating games from other mediums as they determine interactivity through the rules and procedures.

Game mechanics are associated with specific players' demands like the desire for autonomy, relatedness, or to fulfill a sense of competence [335]. To achieve this demand, game designers use game mechanics that include compelling and believable characters, challenging tasks, or interactions that allow users to explore and make their own decisions.

2.6.4.1 Gameplay mechanics for educational games

When designing educational games, the game's mechanics are directly related to the learning objectives [6]. Serious Games Mechanics (SGM) makes design decisions that prioritize content learning practice/goal into a mechanical element of gameplay [13], which leads to the need for a clear understanding of the gameplay according to the relevant educational strategy. A serious game's learning outcomes and motivational potential will depend on implementing the mechanics within the learning situation where the game is integrated. Implementing learning theories and pedagogical principles with gameplay mechanics will result in the player's need to correctly understand game dynamics and find and synthesize the educational message. Constructivism learning theory is the predominant approach in this type of game, where the players can construct their own knowledge by being proactive in the learning process [311].

Some gamification elements while providing feedback can enhance students' motivation towards the learning content, like badges (for achievement, completing a specific task, or acquired the desired skill, understanding a concept, or finishing a game level); leaderboards (ranking players by comparing their achievements relative to others), and rewards (points for each correct answer) [183].

This research delves into the exploration of game mechanics applied to the learning of chemistry, recognizing their close association with learning objectives, theories of learning, and the equilibrium of game elements.

2.6.5 Technology

Game technology is the medium or modus operandi used on a game [292]. Each technology provides different affordance, potentials, limitations, and constraints that make them more suitable for specific tasks and activities than others [172]. Understanding the affordances and constraints of a specific technology influences the overall experience of a game. Digital game technologies are volatile, dynamic, and unpredictable elements of game design because technology advances rapidly (facial and voice recognition, gesture control, high-def displays, virtual reality, augmented reality, and wearable – mobile -cloud on-demand gaming).

In education, the choice of technology affordance constrains the content that can be taught. Similar to how some content choices can restrict the available technologies. Technology might limit the kind of feasible representations, but it can also make it possible to create new and varied representations. Creating a technology-rich environment needs to bring together learning content and pedagogy while supporting game mechanics, storytelling, and the aesthetics of a game [172]. In this regard, Mishra and Koehler introduced a framework using Technological Pedagogical Content Knowledge (TPACK) that is based on the effective integration of the technology by taking into account the complexity of teaching and the unique permutable nature that interplays between the pedagogy (learning theories like constructionism), the content (science concepts) and the affordance of the technology (game-design software)[172].

To conclude, by identifying interaction design factors according to the target group and the elements that are part of the game design process, we can use this knowledge to improve and adapt the design of serious games, improving its potential and effectiveness towards education. The user experience can improve by balancing the technology, which is any medium that permits the game's construction, allowing or restricting certain learning activities. The story is a sequence of events or situations that unfolds within the game. The aesthetics have the most direct relationship with the user since it provides the visuals and tone of the game. Finally, the mechanics are the process and rules needed to achieve the game goals. Besides these elements, serious games' pedagogical strategies within the game mechanics are critical to facilitate learning a domain. Moreover, understanding norms and assumptions behind different methods and approaches of game design can provide us with some strategies to motivate students, like the reinforcement of challenges to achieve skills such as problem-solving, content, and active learning, leading to overall better learning performance of students. Interaction design factors can lead to emotional connections promoting the continuity of serious games and further exploration of learning content.

2.6.6 Gamification

Serious games can benefit from gamification factors, which involve identifying, extracting, and applying individual game elements intended to encourage a behavior or attitude in a non-game environment [137]. Related work agrees that game components can provide users with motivational affordances like autonomy, relatedness, a sense of competence, and self-determination [81, 137]. The theory of self-determination (SDT) is particularly interesting to serious games and gamification, as it explains the user's psychological and behavioral engagement, helping provide more profound and more long-lasting experiences for players. According to SDT, intrinsic motivation (doing an activity because it is inherently interesting and satisfying) and extrinsic motivation (doing an activity because of rewards or to avoid punishment) [81] are factors that can potentially anticipate and predict positive student outcomes, such as academic achievement, learning, and skill development [261].

However, despite the influence that game elements used in educational gamification can have on student engagement [83], previous research also claims that gamification (focusing on extrinsic game elements) impacts decrease over time (e.g., the novelty effect) [71, 286, 267]. To avoid these pitfalls, Michael Sailer and Lisa Hommer pinpoint the inclusion of fictional and competitive-collaborative elements (social interactions) as possible positive moderators to impact users' behavioral outcomes [283]. From a theoretical point of view, including relevant game fiction throughout game intervention can influence students to invest more effort in completing tasks [282]. Also, creating a game environment that allows learners to engage in both competitive and collaborative interactions (working together in teams to compete against other teams) can help to improve learners' quality of performance and skills [282]. Other factors that can promote performance gains and sustain engagement are context factors like pedagogy and the feeling of competence (which enhances intrinsic motivation) [214, 184].

We seek to explore gamification as a method that can promote autonomy, confidence, and self-determination to preteens while interacting with immersive technologies and disclosing learning content. As gamification promotes intrinsic and extrinsic motivation

2.6.7 Game Dynamics

Game Dynamics is defined by Hunicke as the behavior and actions that emerge from a game's rules and gameplay mechanics [145]. According to the author, game designers must anticipate patterns of behavior and actions to determine how players will engage with the game to motivate them to keep playing. There are four critical components of game dynamics: sensation, fantasy, challenge and fellowship. Sensation refers to the emotional and sensory experience of the player, like excitement, tension, relaxation, and satisfaction. Fantasy involves the theme or imaginative elements of the game, like the story, settings, and characters. A compelling fantasy can motivate the players to explore and engage with a game's world. The challenge refers to the difficulty level and skills required by a player to succeed in a game, which requires to be well-balanced. Finally, the fellowship is the social component that reflects on cooperation, communication, and competition between other players' dynamics to create fun and engaging experiences that lead to the continuing desire to play.

2.6.8 Immersion

The success and enjoyment of an entertainment experience, such as a game, are significantly influenced by the degree of immersion. Immersion pertains to a state of complete absorption or profound involvement in a specific activity, signifying a deep engagement with the experience. This phenomenon implies a heightened sense of focus and concentration, often to the extent that the individual loses awareness of the external surroundings [357]. The work of Agrawal et al. more recently defines immersion as "a phenomenon experience when an individual is in a state of deep mental involvement in which their cognitive processes cause a shift in their intentional sate such that one may experience disassociation from the awareness of the physical world"[5]. In the other hand, Nilsson et al, claims that immersion can derive from the individual surrounding in three dimensions: technology, narrative and challenges [233]. The technology is related to technical system and its properties, which in the case of a video game implies the hardware to play it. The narrative content involves the story line or plot, the characters (characteristics, interactions, relationships with other characters), and the environment where the story develops. The challenges suggest conditions or context in which the experience is taken place (fatigue of the player, emotional state - relax or not, etc). A systematic review by D Beck et al. provides insights on the need for evaluation, design and development of immersive learning environments [33]. According to the authors, there is a need to research "what works, how it works, and the contextual aspect, but also understand how to design and developed the experiences, including deployment, monitoring, assessment and outreach"[33].

2.6.9 Usability effects and evaluation

Usability factors are also link to the engagement and effectiveness of a app or game. The design and implementation of usability features in an application or game can significantly impact how users interact with the product, affecting their overall engagement and the effectiveness of the experience. User-friendly interfaces, clear navigation, and efficient interactions contribute to a positive user experience, fostering greater engagement and enhancing the overall effectiveness of the app or game.

In the educational context, according to Mayes and Fowler, “educational effectiveness is greatly affected by perceived usability” [210]. The usability assessment provides information which can help in improving serious game overall dynamics.

There are several different usability testing methods for kids that have been documented, which include children being asked about bugs in the software, providing simple feedback about the success or not of the software, to analyzing a story [87]. According to Allison Druin, children can be “incredibly honest and at times harsh in their assessment of technology”, and ready to be part of the testing of an app [87]. However, children who participate in usability testing must do much more than just test the use of the technology; they also need to adapt to the testing environment, interact with the facilitator, adhere to certain procedures, and, most often, contribute to the evaluation by reporting on their experiences [205]. Druin recommends that usability testing sessions, need to be short and precise to gather useful and important input [87]. Furthermore, many methods like surveys are sometimes questioned about their readability and validity, since children’s cognitive development abilities may not be anticipated leading to a misinterpretation of the questions. Using a usability scale allows us to test several elements within the games like if the mechanics were intuitive and adequate to our target group, meaning if the rules, tutorials, and language used were effective towards guiding the children through the game. Also provides information about the feedback mechanism (visual, audio cues, messages), which is important in the dynamics of a serious game helping children understand how their actions impact the game and the learning outcomes. The data collected from this instrument can also provide information about engagement, challenges of the game-play and self-efficacy of the player. Overall, the usability study of serious games (interplay between the game mechanics, feedback and challenge) can help to explain the dynamics of the games (patterns of behavior and actions to determine how players will engage with the game).

There are several usability scales, some evaluating specific aspects of usability like the ease of use, engagement and feedback, while other measures various aspects of the experiences such as the ease of use, learning, and satisfaction of the users [344]. The Game User Experience Satisfaction Scale (GUESS), also evaluates user satisfaction by assessing several factors, one being the Usability /Playability of a system [249]. However while there are usability scales that allow to gather important feedback into the redesign of a game, presently there is a scarcity of research focused on tailoring new standards and validating usability metrics specifically for Mixed Augmented Reality (MAR). While it is crucial to formulate usability models tailored to MAR, it is equally imperative to substantiate them through the application of well-established metrics relevant to usability studies.

2.7 Summary of the Chapter

Serious games, designed with specific learning objectives in mind, have been proven effective tools for knowledge construction and can positively impact cognitive skills. The careful design and implementation of gamification factors can enhance engagement and sustain learning outcomes. AR games have great potential for teaching in formal and non-formal contexts, providing immersive and engaging learning environments that support situated learning, social interaction, and immediate transfer of knowledge. Overall, AR Serious Games represent innovative and effective approaches to education and training that have the potential to transform the way we learn and teach.

The body of work presented in this chapter also focuses on the various elements that work together to create engaging and effective games, whether for entertainment or educational purposes. These elements include aesthetics, interaction design, storytelling, game mechanics, game technology, and game dynamics. Immersion and usability factors can also contribute to the involvement and efficiency of an app or game. We must consider in our design the target audience, including cognitive (spatial and abstract reasoning), physical (active learning using a constructivism approach and other senses-tactile, visual, and audio), and emotional states, to create safe, enjoyable, and effective games. For an educational game in chemistry, linking game mechanics directly to learning objectives and implementing learning theories and pedagogical principles into gameplay is essential. Furthermore, there is a need to investigate how to implement a multi-level understanding of chemistry concepts. The Periodic Table allows us to introduce fundamental concepts related to chemical elements, their significance in our daily lives, their properties, and their potential effects on the environment. To conclude, gamification and game dynamics are critical in motivating players to engage and continue playing. These findings will be used as informative guidelines in this research to describe the design process and development of AR serious games for chemistry (see Figure 2.8).

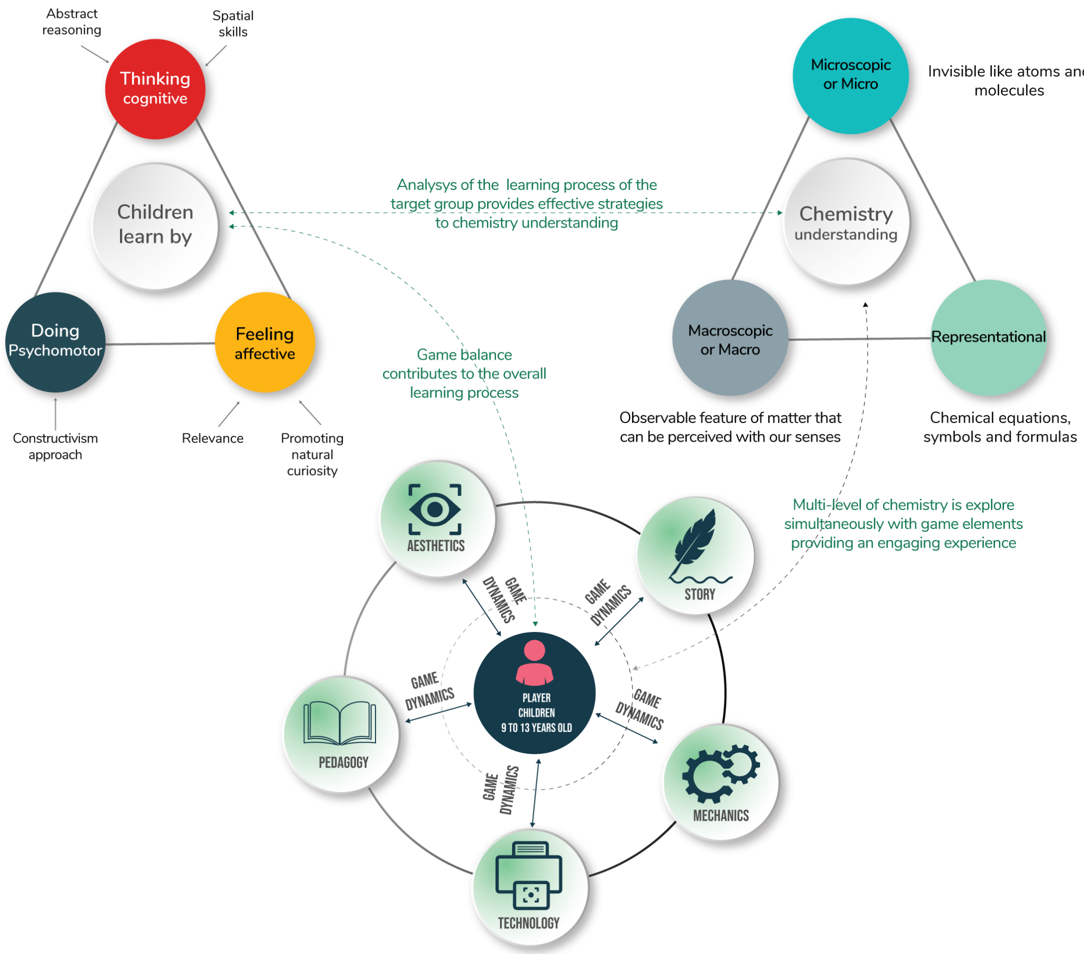

Figure 2.8: Research Theoretical Framework

CHAPTER 3

State of the Art

Serious Games and Augmented Reality (AR) have emerged as an exciting field of research and development. In this chapter, we examine the current state of the art to comprehensively understand how Serious Games and AR are integrated into formal and informal learning contexts, fostering engagement and improving learning outcomes.

3.1 Serious Games and STEM

The utilization of serious games has been extensively studied in educational settings, and its potential continues to be increasingly recognized. Researchers, school boards, and teachers have tried to capitalize on innovative tools and the benefits of technologies to create appealing and engaging content for youth. According to Nicola Whitton, educational games can motivate students by creating an experience in which they are out of their everyday setting, immersed in challenges, and rewarded for their achievements [353].

Serious games have exhibited considerable potential as a medium for promoting the comprehension of abstract concepts in domains like Science, Technology, Engineering, and Mathematics (STEM), facilitating its understanding and fostering student engagement. In Math, for example, *"Math City"* a simulation game targeting kindergarten to 12th-grade students, aims to teach children how to add and subtract using the mechanics of the gameplay [253]; *"Curious George and the Odd Squad"* is a transmedia narrative-based intervention which includes arithmetics within the game mechanics [212]. The experience with this game showed that students' overall knowledge of mathematics in numbers, operations, and algebraic thinking increased significantly, as well as their competency with mathematics vocabulary and the concept of fact families [212].

More recently, *"Math is magic"* was developed for 4th-grade students, using learning content (based on the Math school curriculum) that changes according to the participant's performance during the game. The Role-playing story infuse game asks the user to help save the world by using a spell book (which requires solving some Math problems) [271]. *"Dragonboxs 12+"* by Siew et al. using an interactive game mechanics of drag and drop, allows students (12 to 17 years old) to understand the order in which equations are solved[303]. The results from a conducted study using this system drastically improved the learning rate, retention, and overall satisfaction of the students [303]. In Madeira, *"Clash of Wizardry"*[1] is a game that was developed through a European project called E-MaGIC (Education in Mathematics in Game-based Immersive Context), and recently tested with 200 students (9 to 16 year) and respective teachers, demonstrating that the participants were excited to explore Math using the game within the context of the classroom, especially since it provided an engaging experience in an area that some considered difficult.

"Crystal Island" is another experience using a narrative-centered learning environment, where eighth-grade students have to solve a science mystery while better understanding microbiology. After interacting with the game, the authors claimed that the participants had an increase in the learning gains [275].

In Computer Science learning, many games have been created that focus on computer programming. Developing logical thinking and problem-solving skills is crucial for students learning to program. Programming demands a very practical approach (learning by doing), which involves reading and understanding the syntax of a programming language [129].To address this challenge, MIT Media Lab[2] used a visual blocks-based programming language called Scratch. This medium emerges as an innovative tool to introduce programming to students due to the ability to provide visualization to complex concepts and ease of use mechanics with the drag-and-drop technique [351]. *"NoBug's SnackBar"* promotes the development of Computational Thinking (process required to provide solutions that can be represented as computational steps and algorithms) by using the same method as MIT Lab (blocks), allowing students to focus on the logic and structure of programming instead of the method of writing textual programs [336]. The authors provided guidelines based on the results of these experiences to support introductory computer programming learning for novices, starting with using rewards points and leaderboards, avatar customization, locked areas (only achievable by finishing a task), and sound. Furthermore, the author's advice for feedback and customize support allow the users to freely select the next mission within a game and organize the task according to the learning goal [336].

Serious games can help students' performance by providing methods that allow them to understand scientific phenomena in chemistry better. A study conducted in Thailand showed that remembering the Periodic Table was part of an exam necessary to pass a

[1] https://funchalnoticias.net/2019/05/30/jogo-digital-volta-as-aulas-de-matematica-na-escola-dos-louros/

[2] https://www.media.mit.edu/projects/scratch/overview/

university entrance examination in their scientific program. However, many students struggle to achieve good results due to time restrictions, large classes, and a lack of economic resources. As such, Saksrisathaporn et al. developed three mini-puzzle games: one to remember the names and symbols of elements, the second to remember the group and period, and the third stage allowed students to apply elements to form chemical compounds. The interaction with the games increased the scores of retaining the information, engagement, and satisfaction of the participants. Furthermore, the authors advocate for using game-based self-learning tools to be effective, convenient, and fast for students to complement their formal studies [284].

"Al-Kimia" is a role-playing, graphical adventure Mobile game where users can experiment with chemical reactions in a virtual world as a medium to acquire knowledge and generate positive attitudes towards chemistry. The game was developed by two teams from different Universities (Vigo and Santiago de Compostela) to tackle chemistry which, according to the authors, is an area undervalued by the general population of students [190]. The study conducted in several High Schools in Spain provided only insights about the student's lack of knowledge about chemistry as a subject and how it can affect their lives. However, the design and development process of "Al-kimia,"which included teachers and designers, allowed them to gain an appreciation of their counterpart's area of expertise [190].

To summarize, by using Serious games, students can have a hands-on approach to the learning content, leading to a better understanding and more effective recollection of the content. Serious games, and interactive and simulated environments, can harness problem-solving and critical thinking skills with real-world applications.

Students' interest in games and their tech-savvy skills suggest that their adoption in the classroom context could effectively facilitate learning and engagement. It is necessary to adapt the content to children's interests, make it appealing, and include mechanisms that provide a chance to explore, develop hypotheses and actively participate in the learning process. Using game settings to provide scientific content, students developed another level of skills by discovering new rules and ideas rather than memorizing learning materials others created. However, serious games implementation are influenced by the particular learning context in which the game is deployed and by the objective and learning goals the educator wants to adopt [94]. Educators are concerned with the roles, strategies, and pedagogical approaches that games may provide, leading to avoiding their use on a regular basis [60]. Furthermore, teacher support can expand to the informal learning context by providing pedagogical expertise.

To conclude, while serious games in the field of chemistry showcased promising results, their implementation within the classroom continues to showcase some resistance by teachers. Frequently, the educational content of these tools is not designed for the context and learning goals that need to be achieved according to the school curriculum. Also, there needs to be more research on the process and effects of these tools when implemented to introduce new topics in chemistry to younger students. We contribute to this field of study by including educational stakeholders in our design approach to create serious games customized to our users, their needs, and the content delivered. Furthermore, our research objective is to evaluate the effectiveness of these tools in facilitating the understanding of abstract content in chemistry when provided to a younger audience.

3.2 AR Games

In 2016, an AR game *"Pokémon Go"* captured the attention of the whole world, from young to old. In just over two weeks, it secured the participation of 20 million active users, making a substantial gross income over the years [366]. The same company has launched other AR games, like, *"Ingress"*[3], developed two years prior to Pokémon Go, the game uses narrative base gameplay, which takes place in the context of a sci-fiction environment giving it a cyberpunk feel. In the game, the Earth has come in contact with an alien force, giving the player the task of saving it. *Ingress* uses the mobile GPS to interact with "portals,"usually coinciding with landmarks.

"Pickmin Bloom"[4] with game mechanics similar to *Pokémon Go*, where the player needs to move within the real space to collect digital items like AR seeds and flowers, eventually growing into a Pikmin. *"Peridot"*[5], it is an AR pet game to bond with a character pet and collaborate with other players to diversify their species. This game, recently launched, relies upon high-quality and cute characters and animations, which evolve along the game according to the player's choices.

The game application called *"AR Dragon - Virtual Pet Game"*[6] is a simulator game that uses Augmented Reality technology to display a virtual pet, a Dragon to enhance the users' experience. The result from an evaluation of the app showed that it was well-liked by users.

"Minecraft Earth"[7] is a game intertwined with the ideas and mechanics of the original Minecraft game of using pieces shaped like cubes to create a world, in this case, an AR virtual world. The game uses storytelling, treasure hunting, and animations to engage the user. The game also provides a collaborative feature, where several players can change and add elements to the digital world.

"Zombie Run"[8] is an AR game that focuses on enhancing the physical activity of users. The game mirrors the movement of the player's real-life movements. It provides a narrative (an apocalyptic world scenario where the player runs from Zombies while collecting items to help save the world) to incentive the player to execute the activities proposed in the game and, as such, work out.

[3] https://www.ingress.com/
[4] https://pikminbloom.com/
[5] https://playperidot.com/
[6] https://www.data.ai/en/apps/ios/app/ar-dragon-virtual-pet-game/
[7] https://www.minecraft.net/en-us/article/minecraft-earth-coming-end
[8] https://zombiesrungame.com/

"Jurassic World Alive"[9] displays AR prehistoric dinosaurs in modern cities (based on real maps). The game reveals Prehistoric creatures and stumbles upon competitive fights by exploring the area around the user. The game was evaluated according to its usability, revealing participants' enjoyment of its mechanics; however, the developers also indicated that robust and constant GPS recognition is needed for the game.

The above foremost games were selected in the AR entertainment industry by being considered some of the most popular. To summarize, the use of AR for gaming and entertainment is vast and continues to grow. Some common features across this entertainment system are the elaborated use of graphics, characters, and animations, providing an immersive experience. Game mechanics that use the player's movement within the space to collect virtual items that will help within the game's objective. Used of Gamification elements like leaderboards, improvement of the character (more robust, customization), punctuation, and more skills is provided to keep the player interested in finishing the game objectives. Finally, these games have strong collaborative and community game features, using rewards to encourage teams to get together, fight, or exchange items. However, due to the Covid pandemic, many games have had to follow different strategies (primarily online), and some even had to discontinue the game, like Minecraft Earth.

3.2.1 AR in the Field of Education

Besides being used for entertainment, this technology also shows promise for changing the landscape of industries such as medicine, education, and workforce training. Augmented reality has the potential to be used as a tool of edutainment since it allows the combination of entertainment (play) and learning (education) to develop the children's mental and cognitive abilities [280]. Augmented Reality also has excellent potential as a pedagogical tool since previous studies have demonstrated its extreme usefulness for increasing the student's motivation in the learning process [24]. New possibilities in the use of this tool have been increasingly recognized by educational researchers because of the uniqueness of Augmented Reality of allowing the superimposition of virtual objects within our real world, thus creating new settings for active learning, whereby children can learn from real-life situations and experiences [15, 42] .

One early example of AR application is the *"Magic Book,"* which combined narrative elements with a physical textbook. Although it offered limited educational content, this experience showcased the potential of AR for scientific visualization [38]. Building on this idea, the work of Jiang-Jie Chen et al. uses paper text information with AR to teach design principles and visual art elements to university students of an art and design course [62]. *"Magic Boosed"* uses AR with tridimensional geometry to emphasize the understanding of volume and surface areas to elementary school students providing positive results in the learning of shape and geometry formulas [8]. In a study by Cathy Weng, where 80 participants from eighth-grade school were involved, the results revealed

[9] https://jurassicworldalive.com/

that using mixed reality (augmented reality and virtual reality) as a learning supplement to the printed book to teach children about the solar system and how Earth moves in space, could improve students' learning outcomes, particularly for those with low spatial ability students[352]. Moreover, the author claims that the 3D objects displayed in the Mix reality platforms with animated learning materials are more effective than using the reading material (book). Supporting this claim, other authors indicated that Mix reality technologies integration with learning content provided in a book format could provide significant benefits for science learning and other areas. Mix realities bring the possibility to entertain and provide better results in the autonomy, self-efficiency, and intrinsic motivation of students than static pictures and text used in formal school domain [247, 97, 27, 352].

Combining tangible, physical interfaces with tridimensional virtual imagery allows children to play, engage, and have fun as they learn.[37, 52]. Tangible interfaces can ease the communication of abstract concepts. This is the case of *Digital MiMs*, computer-enhanced building blocks that support learning in mathematics, probabilistic behavior, and more. Another example is *ProBoNo*, a software and tangible hardware prototype developed for children from four to six years of age. *PrBoNo* allows children to navigate virtual worlds more playfully and engagingly. A study of this system concluded that the tangible interface facilitated the transfer of knowledge acquired in a digital environment to a situation in the real world [130]. *Ambient Wood*, a large-scale learning activity targeting 11-12- year-old children, aims to teach children about the nature of scientific inquiry employing tangible discovery, reflection, and experimentation. A study of the system highlighted that, while tangibility per se is not enough to engage children in a task, it is crucial to have the appropriate tangible system [268].

"Merge Edu"[10] is a platform that combines augmented reality (AR) technology with a physical object (a cube), offering an immersive, hands-on learning experience that can make complex concepts more engaging and accessible. Researchers of the University of Maryland, USA, claimed that having used *"Merge Cube"* within a school class of K-12 students had a significant impact, especially STEM areas [159]. The authors suggested including embodied movement or movement that mirrors the content taught in 3D learning environments. They also claim that manipulating objects in three-dimensional space gives a learner unprecedented personal control (agency) over the learning environment [159].

"ARQuest", is a collaborative mobile augmented reality game for developing the computational thinking skills of primary school students. The game combines a physical board, storytelling, and tangible tokens with animated 3D content used by children to create and solve challenges in a gamified environment. The exploratory study indicates that mobile AR combined with tangible activities is a promising path for early STEM education, as it can engage and motivate children with the proposed activity [123].

[10]https://mergeedu.com/?cr=5136

To contribute to raising children's awareness about air quality and pollution, a team designed and implemented a serious augmented game with physical sensor nodes that provided an educative and playful experience. The results of a study from a sample of 27 children between 7 and 11 years showed improvement in the children's knowledge about indoor air pollution derived from playing the game. The game was also perceived as easy, useful, and engaging [107].

Dunleavy and Dede [89] see Mixed reality applications primarily aligned with situated and constructivist learning theory, as they position the learner within a real-world physical and social context while guiding, scaffolding and facilitating participatory and metacognitive learning processes such as authentic inquiry, active observation, peer coaching, reciprocal teaching, and legitimate peripheral participation with multiple modes of representation [89] [130, 51, 35, 105].

In Physics, where most principles are based on Math, Optics, Electricity, Magnetism, and other abstract concepts, students often struggle to grasp and understand phenomena without referent or visual connections. *"ARLE"* is an AR-based environment that improved the understanding of concepts like a magnetic field, electromagnetic waves, Maxwell's equations, and Fleming's rules for electromagnetism [105]. The students can interact with virtual components by simply drag, drop, grab, and flip operations, which overcome the limitations of the conventional teaching system. The experimental results suggest that *ARLE* positively impacted students' learning gain and critical thinking abilities compared with the conventional teaching approach due to the student's interaction with 3D virtual content, which provided a visualization of different concepts of Physics. The authors conclude that AR can help students understand the core concepts easily, enhancing their knowledge retention capabilities and practical learning abilities in this domain [105]. *AR-SaBEr*, is also an AR simulation tool developed by a team of researchers to discover the principles of electricity. Analysis of the data showed a positive learning performance of the students. These results were attributed to the participant's attitude towards the activity, showing engagement while interacting and manipulating three-dimensional objects [146]. Furthermore, research has shown that digital simulations and visualization tools have helped students to learn challenging concepts like Bernoulli's principle, a science concept that states that there is an inversely proportional relationship between fluid speed and pressure [365]

Cai et al. used AR and Kinect (a system that tracks the body movement in the field of view) to convey knowledge about magnetic fields in real-time [51]. The study participants (eight grade students) could trigger the magnetic field with the wave of their hand in front of a depth camera (using sensing technology to infer the distance). The results stated that the system promotes learning more extensively and intuitively [51].

MaR-T project uses a mixed-reality (MR) system with tangible representation to teach children ages 3 -to 5-year-old math content about conceptual understanding and judgment between quantities, called non-symbolic numbers. The result supports that AR can provide active learning, engaging, and social learning skills [35].

Shaping Watersheds is an interactive 3D exhibit at the National Science Foundation, developed through a participatory design methodology involving scientists, science educators, and designers. It aims to improve public understanding of freshwater ecosystems. This AR tangible experience with real-time projections allows users to move water across a landscape, displaying engagement and understanding of earth science concepts. The activity also incentivizes young children's curiosity, allowing them to participate and inquire about this type of content. Other exhibitions in formal and non-formal settings have used the same approach to teach other science-related topics, such as geology, topographic map reading, planetary science, and hydrology, to children from different schools [260].

The comprehension of microstructures is regarded as difficult for beginning students of chemistry. Low-achieving students benefit considerably by interacting with 3D models of micro-particles, understanding the composition of substances much better [52]. Using this system, the allowance of Inquiry-based learning also helps students be active in the learning process [52]. Students make observations, collaborate with others, ask questions, and investigate and interpret data when engaging with the AR system [89]. As research in the domain of chemistry has increased, the next section is dedicated to this field.

3.3 Augmented Reality Serious Games in the Context of Chemistry

AR has been accepted as an effective learning method for chemistry and continues to be explored because of its affordances. AR can facilitate the understanding of the spatial processes and structures of the molecules, which are more difficult for students to grasp through conventional teaching methods [106]. This technology provided the opportunity for the 3D visualization of structures of atoms, molecules, and chemical bonds [364, 281], topics that are essential for understanding the chemical behaviors and properties of matter [203]. For instance, Argüello and Dempski deployed AR tools to visualize protein structures for an undergraduate biochemistry course [12]; Eriksen and their team developed an Augmented Reality app to visualize any chemical 3D model based on crystallography data [102]; and Rubilar Melino research with university-level participants shows the potential of AR to facilitate student' transitions among macro, micro and symbolic levels of chemistry [277]. *"StereoChem"*, a mobile AR app, is used to understand Stereochemistry helping students in the perception of 3D molecules [171]. This system studies stereoisomers (molecular formulas that differ in spatial orientation) to help perceive the 3D molecules [171].

Chemistry also demands student imagination to comprehend abstract concepts without visible or physical referents in the real world (atoms, molecules, chemical bonds, biochemical processes). This process is highly challenging; translating external representations like 2D visualization into 3D mental models can lead to cognitive overload, especially if the content itself is highly complex [360]. According to David Palmer, misconceptions among students must be tackled because they can interfere with learning scientific principles and concepts [243]. Physical models, for example, have been used in the past (ball and stick molecular kits) to facilitate the learning of molecular transformation [32]; however, because of their structural rigidity, it is difficult to adequately represent the difference of bond angle, and size of the atoms. In this context, visualization technologies, like AR, have exciting potential for facilitating understanding and preventing misconceptions in the scientific domain [140]. Moreover, it provides the opportunity for the understanding of more complex content like the analysis of different molecular characteristics (form, geometry, and nature of molecular structures and chemical interactions) [1], bond distances, dihedral angles [108], calculation of electrostatic potentials and vibrational modes [134], visualizes and manipulate the 3D structure of the potassium channel [229] and the different ways in which a molecule itself moves in space [1].

Other examples of AR systems to facilitate the microscopic understanding of molecular structures are *Augmented Chemistry*, which allows students to obtain and understand information about the spatial relations between molecules by using the input of keyboards and tangible interaction. *Augmented Chemistry* represents the molecules in a 3D environment, providing multiple viewpoints and control of the interactions [307]. The system was designed to teach elements of the Periodic Table through a Head Mounted Display and hand motion control (touch, grab, drag, drop, and rotate). The participant uses the hand to select a chemical element from a virtual Periodic Table, and the system responds with a 3D visualization of an atomic model of the element [103]. While this system provides an interesting research approach, there is no evidence regarding learning outcomes.

Mobile AR applications like *"Chirality-2"* and *"Elements 4D"* by DAQRI studio is designed to simulate how elements of the Periodic Table react in real life [164] [364], and *"Biochem AR"* [320], and "ARMET (Metabolic Pathways) [339] have shown to facilitate the interaction with virtual 3D information within the classroom context.

Chemistry in public schools with large size classes suffers from limited resources and time available, and, as a result, some students do not have the opportunity to conduct experiments. AR simulation helps bridge this gap, contributing to observing some reactions on a one-to-one basis[93]. An example is the simulation of chemical laboratories using AR technology, which can provide freedom for experimentation while avoiding cost and safety hazards. Besides, students can also conduct experiments with minimal use of liquid chemicals resulting in lower negative impacts on the environment [324]. Children can explore different scenarios without compromising their safety and knowledge transfer to the real-world [226]. For example, *"ARiEL"* provides the opportunity for connecting information in general Lab chemistry with chemistry instruments [7]. On the other hand, Naese et al. created *"HP Reveal"* an AR app to support instruction of analytical instrumentation [223]. The Mix Reality (MR) *"Chemistry Lab"* and *"HoloLAB Champions"* aim to familiarize students with experimental procedures, safety, and protocol knowledge while conducting experiments [88].

Previous studies also provided positive insight into combining AR and storytelling to teach Chemistry. *"Table Mystery"* is an AR game explicitly developed for the Science Centre in Oppland County, Norway. The game serves as an interactive educational tool, aiming to provide information about the elements of the periodic table. By incorporating a narrative backstory and a large printout of the periodic table, players are encouraged to read and scan elements to unravel mysteries and overcome challenges while deepening their understanding of chemistry [39]. Soares and colleagues implemented *"World of Chemistry"*, a virtual reality SG with narrative elements meant to motivate students to study chemistry [312].

AR's edutainment approach to learning and education is still relatively new and challenging, and even though we start to see more investment in this area, most of these immersive experiences and simulations that produce unique educational affordances have been carried out in a high school and university educational context neglecting the preteens users. Previous research conducted by Britt Lindahl shows that the period between 10 – 14 years old is a critical time for developing a young person's attitude toward science [194]. This is a concern since by the time students reach the age of 14, their attitudes towards science are fairly fixed on whether they wish to pursue science as a career choice.

A few examples of the success of earlier interventions using AR in the chemistry domain for young scientists are *"LiCo.STEM "* created by Lilia Midak and co-authors to showcase the chemical structure of water for learning natural cycle subjects and performance of laboratory experiments in the elementary school [216]; *"Atomik-3D"* is an AR market base app that allows children to view 3D materials of some chemical elements [57], likewise Ahmed Eway and Olga Troyer, used a marker base AR system to represent atoms: Oxygen, Zinc, Hydrogen, Sodium, Chlorine, and Copper; and two molecules: Ammonia and Hydrochloric [103]. *"Mad City Mystery"*is a location base AR game that uses storytelling to promote scientific thinking. While using, an off shelve- app in another study conducted at a science center in Finland, 146 participants (11 to 13 years old) used the tool "Merge Cube"to observe the 'Doppler Effect' and 'Molecule Movement in Gas' phenomenon [285]. The data, which consisted of cognitive tasks and self-report questionnaires, showed that AR-technology experience was beneficial for all, but especially for the lowest-achieving group and the girls. Other claims by the author are that the results showed evidence that interest in school science is enhanced by situation motivation in the science exhibition context; autonomy experience support learning; and AR benefits students who are below average in traditional school success and achievement level [285].

Finally, there are off shelve apps that explore AR in the chemistry domain, like: *"ModelAR Organic Chemistry"*[11], which allows the user to explore chemical structures (3D models) and interact with virtual objects in real space. *"Arloon Chemistry"*[12] teaches students how to write inorganic formulae and chemical compounds, thus facilitating

[11] https://www.alchem.ie/

[12] http://www.arloon.com/apps/arloon-chemistry/

learning nomenclature. *Happy Atoms*[13] is a Physical Magnetic Molecular Modeling and AR app that introduces Atoms, Molecules, and bonding activities to children. Printed material to trigger the AR information is also used to aid the learning process, like *"360ed Elements AR"*[14], *"ANSTO XR"*[15], *"Aumentifylt AR Elements -The Periodic Table of Me"*[16], *"AR VR Molecules Editor AR"*[17], *"Popar Periodic Table of elements 4D smart chart"*[18], and *"Dáskalos Chemistry"* [19].

Despite research on AR technologies and education during the last decades, a common criticism that has prevailed is that while educational games improve the learning interest of youth, there is little scientific design in the games, insufficient application of educational and pedagogical methods, and lack of assessment tools to analyze its efficacy and impact on students [36, 295]. Our research explores this gap by applying scientific and pedagogical methods within the development of AR serious games, intending to assess its efficacy in learning and engaging preteens with chemistry.

3.4 Summary of the Chapter

There are many examples of the implementation and benefits of serious games in STEM, with many focusing on intended target lessons or the entertainment and immersion factors to retain the learning information. Many of these solutions also favor the participant's autonomy when using these tools, with minimum interaction by the teacher. However, teachers are vital in implementing and adapting these technologies within the formal class scenario. As such, it is necessary to promote a collaborative space where teachers' inputs can provide strategies to increase these tools' effectiveness and use.

When used for entertainment and engagement, Augmented Reality game strategies follow the use of appealing graphics, characters, and animations to provide an immersive experience. Game mechanics that most prevailed are the player's movement within the space commonly used to explore, discover and gather items. The use of the external mechanism of gamification promotes the progression in the game: leaderboards, punctuation, improvement of the character skills, increasing number of items and power, and customization. AR and tangible interfaces can benefit students with diverse learning styles. Visual learners can benefit from the visualizations and interactive elements in AR, while kinesthetic learners can engage with tangible objects. Furthermore, the use of tangible interfaces and embodied movement gives the learner a sense of control over the learning environment.

[13] https://schellgames.com/portfolio/happy-atoms
[14] https://www.360ed.org/products/elements-ar/
[15] https://www.startbeyond.co/case-studies/ansto-xr
[16] https://augmentify.myshopify.com/collections/frontpage/products/augmentifyit-ar-elements-the-periodic-table-of-me
[17] https://appagg.com/android/education/ar-vr-molecules-editor-28960491.html?hl=en
[18] https://popartoys.com/products/popar-periodic-table-of-elements-smart-chart
[19] https://epsonmoverio2.devpost.com/submissions/34524-daskalos-chemistry

There is no doubt that AR technology has the potential to complement traditional teaching methods by providing visualizations, simulations, and interactive elements that make abstract concepts more tangible and relatable, diminishing the gap between the real world and theoretical knowledge. In the chemistry domain, where understanding abstract concepts is critical, AR provides the opportunity for visualization and interaction with phenomena facilitating its understanding. Furthermore, the immersive nature of AR experiences captures students' attention. It encourages active participation in the learning process and makes learning more fun and stimulating, thus fostering a positive attitude towards STEM subjects. Finally, AR's social component can be explored as a tool allowing children to engage in collaborative activities, contributing to creating dialogues, knowledge, practice concepts, and improving communication and literacy.

To this end, this thesis is based on the development and study of AR Serious Games centered around preteens (9 to 13-year-old) in the context of the Periodic Table of Elements to fill the identified gap, described at the end of section 3.3, as general lack of scientific approach and in-class assessment of AR serious games. We envision the creation of serious games with the collaboration of educators shaping the content to complement the school curriculum and the student's needs. We want to create an Augmented Reality edutainment experience, adapted to a younger population, that provides visualization and interaction with content about chemistry. Following other works, we project the use of character, storytelling, and gamification elements to gather interest and immerse the users with the Periodic Table content, thus facilitating its understanding.

Finally, we aim to use these edutainment systems to evaluate game design principles and pedagogical methods when using AR games as platforms. We aim to evaluate AR technology's limitations, benefits, and efficiency when delivering educational content knowledge in chemistry.

Chapter 4

Overview of the Methodology

This chapter explains in detail the rationale of the research approach. It also describes the participatory design process leading to the development of three game prototypes: PF Discovery, PF and Augmented Journey, and finally, PF in the Wild.

This research aims to advance the field of game design, design methods, or games as created things. Nigel Cross defines design research as the "creation, articulation, and sharing of design knowledge"[77]. This author also argues that design knowledge is on the people, processes, and artifacts, which leads to three different domains of design knowledge: design phenomenology (the study of the form and function of the produced artifacts; design praxiology (the study of design practices and processes) and finally design epistemology (study of design methods of knowing) [77]. On the other hand, the phrase "game research"is used to refer to all types of research that examines games (as artifacts), play, or players [185]. Both approaches agree that research is a systematic endeavor with multiple phases leading to knowledge.

Some authors advise that organizing design research into categories based on the objectives and methods adopted in the studies is a helpful strategy for making sense of the field's complexity [117, 115]. To this end, Coulton and Hook proposed three categories for design research: research on design (understanding design as a specific human activity), research for design (developing theories and knowledge to be applied in the practical design work), and research through design (outputs are developed through actively engaging with the designed artifact) [186]. According to Zimmerman, research through design Research Through Design (Rtd) also requires deep introspection as researchers work to comprehend the people, issues, and context sounds. The author also defined Rtd as the process by which researchers create new knowledge by comprehending the current state and suggesting a design for a better future state [368]. With the need for deep introspection, an apparatus is created to comprehend the people, issues, and context surrounding a situation they believe they can improve. As such, the method is constructing a research prototype that effectively communicates a research contribution while striking a balance between research and creation. As a result, the product prototype serves as a tool for investigating design knowledge [368]. The approach taken during this research is Research through design Rtd, where the developed games take the role of the product prototype used as a tool of design knowledge inquiry. The prototypes are used to generate, develop, and validate design knowledge.

4.1 Periodic Fable Design Process

The Periodic Fable games were inspired by the UNESCO 150th anniversary of the creation of the Periodic System of chemical elements by Dmitry Mendeleev. Using the Periodic Table as our topic of exploration, we followed an iterative participatory design process involving a team of three chemistry and science teachers, a Ph.D. student in chemical biology, and four Human Computer Interaction (HCI) and game design experts. The teacher's collaboration was secured after the leading researcher presented the project to the Regional Secretary of Education, and at the Science Centre in Lisbon in Portugal.

The design and development of Periodic Fable (PF) games followed different stages: the framing of the hypotheses based on input from related work, concept design (a multistage iteration plan process to identify several solutions), a paper prototype (paper representations of digital games to test the concept and design ideas), and interactive mockup or low-fidelity prototype (early stages of the digital games without final assets) and finally a completely functional or high-fidelity prototype (digital games with final assets). This process involves several iterations using realistic user settings to inform interaction issues, design choices, and validation of tested formularized hypotheses(see Figure4.1). We further describe in this chapter each stage of the process.

4.1.1 Participatory design approach

The term "participatory design"was initially used in Scandinavian literature to describe a method of including consumers and designers in the actual technical development process [16]. By considering other people's viewpoints, participatory design implicitly and overtly aims to produce artifacts while changing people as a whole [176]. The practice of participatory design (PD), which is on the rise, incorporates a variety of non-designers in diverse co-design activities throughout the design process.

Today, PD draws on a wide range of tools and methodologies and is used in various industries and situations, including research. Participatory action research engages both researchers and practitioners in the process of design, analysis, reflective inquiry, and iterative design [300]. A PD approach leads to mutual learning between users, researchers, and developers as they bring their expertise and voices to the design process

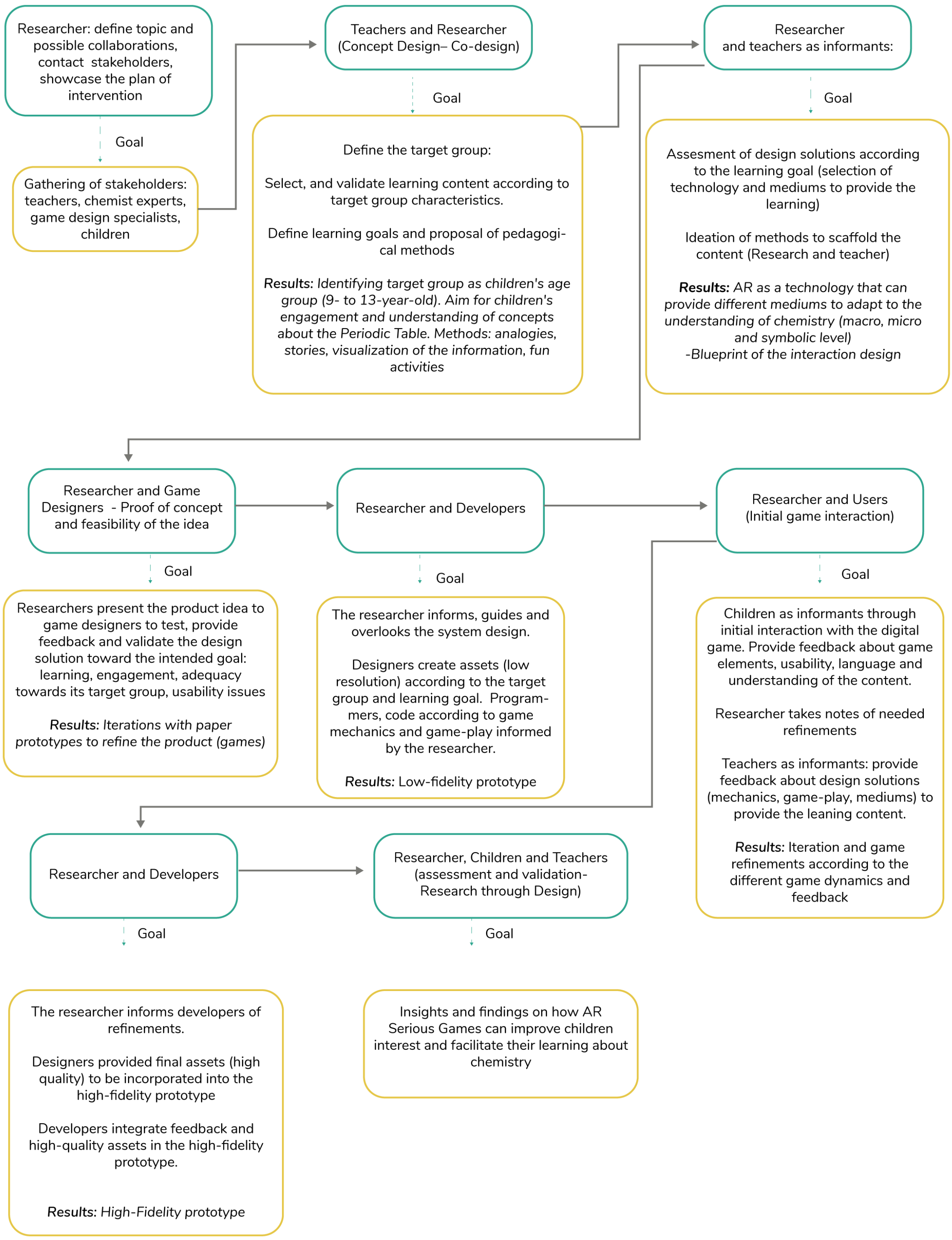

Figure 4.1: Summary of the main interactions with the stakeholders and a detailed explanation of the Periodic Fable experience's initial design and iterations, which correlate to the Rtd stages, where three prototypes/artifacts are created and tested.

by considering together how and under what circumstances a tool will be most beneficial to users.

The practice of participatory design is well-established in human-computer interaction, but it has only recently drawn interest from the educational community. By involving end users as partners in design, participatory design in educational research settings aims to create an educational product (such as a curriculum) and ensure its use, usability, and utility in these contexts. Teachers can create activity sequences that are relevant to their students and flexible understanding of the relationship between instructional goals, student activity and desired learning outcomes by taking part in the creation of a learning environment. Their intervention allows for exploring forms of research that are deeply informed by the reality of classroom practice and content knowledge while contributing to improving that practice. As a result, participatory design can allow teachers to design educational materials better aligned with their students' expectations and their own teaching needs. Since the ultimate purpose of education is for students to learn, teacher opinions should not be disregarded, particularly when introducing new technologies or learning settings.

When designing interactive experiences, Allison Druin et al. emphasized the importance of understanding the child's environment by considering them as consumers and providers of critical feedback to evaluate a product [87]. However, serious games' design process must consider pedagogical theory, domain content, and game design principles to be successful [356]. This process also needs to be endogenous, meaning that the content needs to be intertwined with the context, rather than exogenous, where the content and the context are independent, leading designers to couple domain content to the game mechanics [149].

As this process demands some knowledge of content familiarity and game design literacy, Michael Scaife et al. proposes that children should be involved in the design of learning environments as informants rather than co-designers. Children's lack of knowledge of a domain area, primarily if the game aims to provide this knowledge limits their abilities to offer pertinent ideas [291]. The authors also provided some consideration for involving children in the design of serious games, like including them only during the middle stages of the game design process or later in the design cycle. At this point, designers are better positioned to create boundary objects with the essential theoretical foundations and scaffolding to aid kids in developing good ideas. Also, as a result of growing up with constant access to games, children have a high level of game literacy, making them able to harness their ability to procedural thinking to acquire and understand new content. As a result, designers can draw on their flow to facilitate the game interactions [78].

After extensive research and identifying the factors that needed to be overlooked (see Figure 4.2), it was imminent that the interdisciplinarity of the research needed the collaboration of educational stakeholders, experts in game design, and children.

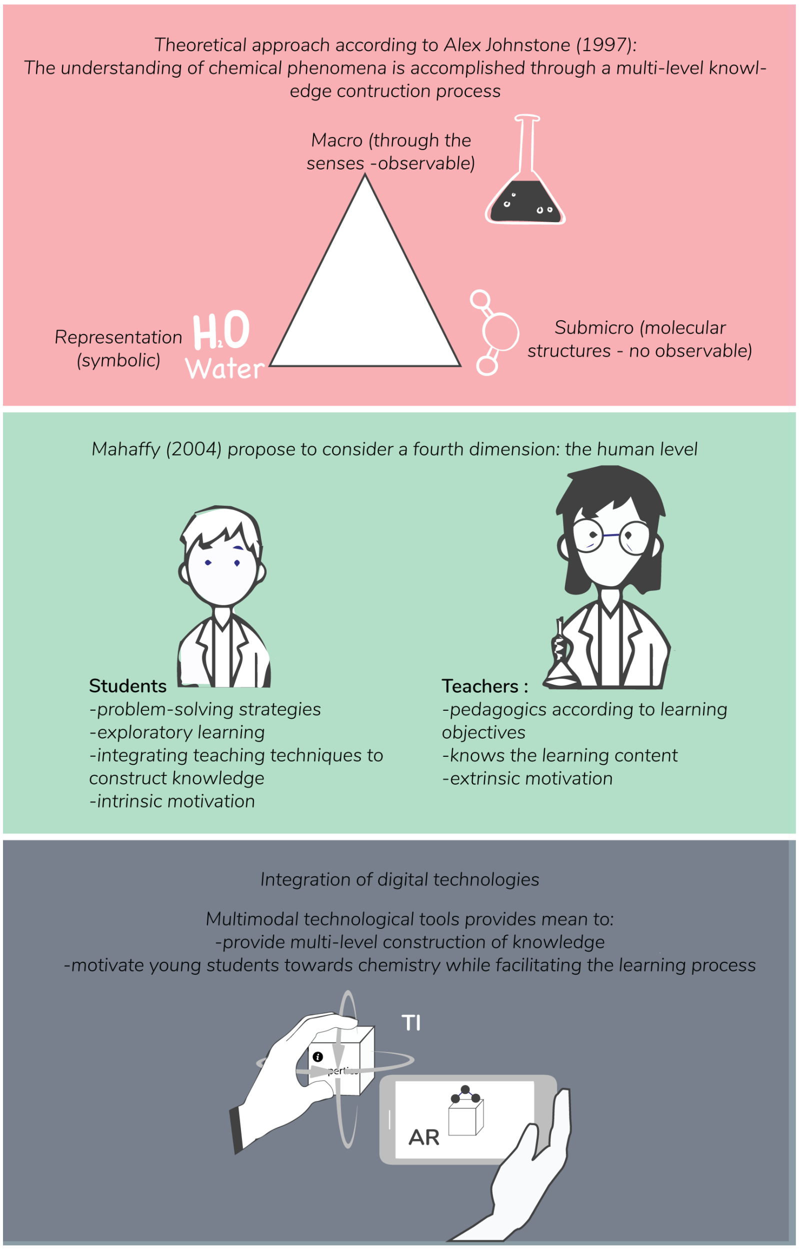

Figure 4.2: Design Factors when developing chemistry apps

4.1.2 PF Concept Design

PF benefited from an extensive participatory design approach. Unfortunately, taking place during the COVID-19 pandemic's conditions, some of the involvements were not as extensive as desired. Mostly the interaction with children was severely limited. The PF co-design approach initially involved experts (Teachers, chemistry researchers, HCI and game designers)- subsequently involving children in formal and informal learning contexts.

4.1.2.1 Co-Designing with school Teachers and postgraduate chemist specialist

The PF participatory design process included school teachers and postgraduate chemistry researchers in the game's initial concepts and design process. Their expertise was needed because of their high degree of knowledge through their pedagogical practice and educational psychology to help select, verify, and validate the content, approach to the subject, and how the scientific content was presented to the preteens. While we kept a steady collaboration with a fixed team of educational stakeholders at the beginning of the project, feedback from other teachers was gathered thorough out the design, development, and evaluation of the prototypes; however, these were punctual interventions. The Periodic Table was used as the topic of exploration to start an iterative participatory design session involving a team of three chemistry and science teachers and a Ph.D. student in chemical biology. The teacher's collaboration was secured after the leading researcher presented the project to the Regional Secretary of Education, Schools at Madeira and the Science Center in Lisbon, Portugal. The first interactions with the collaborators introduced the objectives and context of the Project. Subsequent interactions, some in person and some by online platforms (because of pandemic restrictions and time restraints), focus on identifying the target users, the learning objectives, the methods to accomplish the learning process, and evaluating the scientific content. At a later stage, teachers also provided feedback on the design solutions and developed tools created to engage children with the scientific content.

The researchers and teachers identify the target group as a first step to creating adequate content knowledge and pedagogical approach according to the characteristics of the users. The users were identified as students between the ages of 9- to 13-year-old who would encounter the topic of the Periodic Table for the first time. According to the chemistry Portuguese school curriculum, introducing this topic happens in the middle of the eighth grade when students are around thirteen. Furthermore, chemistry becomes a compulsory school subject for students once they reach 10th grade (14 to 15 old), meaning that we need to promote their interest to continue in this area before this age group. Also, according to several authors [128, 156], especially for Middle School students (10 to 15-year-old) [45], motivation has been indicated as one of the most reliable predictors of student success and perseverance in chemistry. This selection also considered the children's cognitive development stage, which can grasp abstract content at this age when provided with appropriate visual aids and activities [308, 340, 4]. Also, according to Piaget [250], and Stephanie O'Dell [234], some of these students are transitioning from a concrete (capable of inductive reasoning, i.e., take a specific experience and relate it to a more significant, more general principle) to a formal operation (take a general principle and relate it to a specific experience). Teachers also identify this group as avid game players who use mobile devices to play digital games during their breaks between classes.

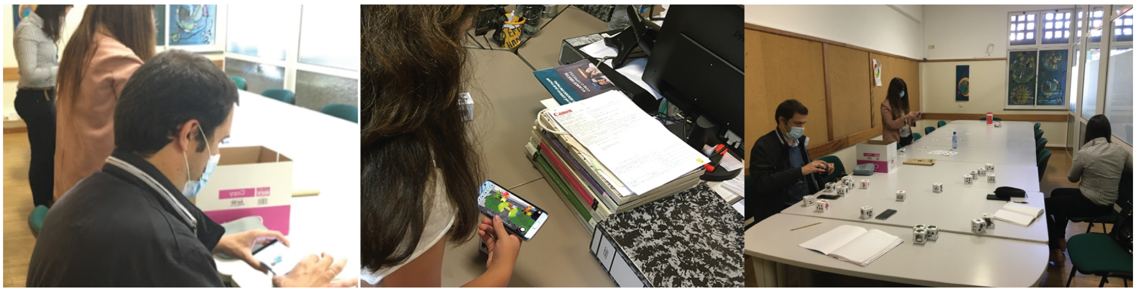

Figure 4.3: Participatory design interaction with educational stakeholders

4.1.2.2 Game design and design choices

With a small team of two designers and one developer supporting the game production, the decision was to start with five chemical elements: oxygen, hydrogen, carbon, nitrogen, and chlorine. These elements were considered important because their covalent bond combinations are responsible for most biological molecules on Earth and their possible compelling reactions. The teachers highlighted the importance of making children curious about the elements and encouraging them to speculate about possible combinations.

Later, another five elements considered critical or in danger of being depleted were added: helium, arsenic, zinc, platinum, and silver. The researcher added these characters as a medium to create awareness and chemistry literacy about the sustainability of the chemical elements. The urgency to tackle this problem and contribute to a sustainable future lead to introduction of the topic to educate and create public awareness among a younger audience.

The learning goals were identified as providing basic content knowledge about the chemical elements' properties, like their representation at a symbolic level (the name, atomic number, chemical abbreviation, and relative atomic mass). Acclimate children to the representation of chemical reactions or compounds (chemical equation). Give the students the notion of the position of the chemical elements within the Periodic Table (column and row) to familiarize students with the order of the elements according to groups or families of elements (same number of valence electrons - outermost shells) and periods (how many of its energy levels house electrons). Demonstrated to children that joining chemical elements (atoms) can lead to a chemical compound. Covalent bonding (two or more atoms share electrons to form the molecule) was selected because of its simple molecular structure, which bonding mechanism gives rise to the existence of various compounds, including water (H2O), ammonia (CH3), diamond (C), carbon dioxide (CO2) and Ozone (O3). We also showcase the compound Ammonium chloride (NH4CL), which, even though it has a covalent bonding with its composition, itis an ionic compound having chlorine represented separated in the molecular structure. These combinations permit the visualization of the results of joining the elements on a macro level. Furthermore, these combinations allow children to relate the information to the real world. Further descriptions of the learning affordances of the design choices are provided in Chapters 5,6 and 7.

4.1.2.3 Co-designing with experts - HCI and Game Designers input

Working at a research institution Interactive Technology Institute (ITI)-LARSys) provided us with the opportunity to interact with other HCI and game researchers, granting them expertise in this area. The five-interaction design researcher selected among HCI and game experts were involved in the preliminary design concept evaluation conducted at the institution's premises.

A gameplay flow chart showcasing the events and actions during the game, like interaction with the game's characters, objects, and surroundings, was used to create a paper prototype (see Figure 4.4). The paper prototype can be described as a rough mockup of a video game created on paper or cardboard before its digital development. This tool tests gameplay mechanics, the user interface, and understanding of the game's rules before spending time and resources in the programming and development of assets. This inexpensive method provides quick iterations and experimentation, with valuable feedback that can be incorporated into the digital game design. The validation regarded the gameplay and mechanics as well as the interactions and usability (intuitive, easy, fun) was gathered through interviews and a heuristic evaluation using Nielsen-Molich's work [230] (see Appendix D).

The HCI and game researchers were also consulted on the appropriate aesthetics for the target users' age, the game's playability, technology, gameplay engagements, and its level of usability. These collaborations led to different game iterations resulting in the initial game concept being split into two parts. Exploring a 3D map using a tangible cube to gather information was featured as too complex for the child to grasp. Besides, AR technology used by the mobile phone's camera will only provide the projection of the map in real space or the scanning of the markers in the cubes, but not both.

4.2 Interaction Design - PF Aesthetics and Technology

This section describes the initial steps for designing and developing the three games, starting with Aesthetics and Technology. In Chapters 5, 6, and 7, we continue to describe other design elements, showcasing the iterative design process consisting in the pilot

Figure 4.4: Game designers' interaction with a paper prototype

studies and several evaluations that were conducted, evolving the prototype from Low to High-fidelity, until the final artifacts.

According to Jon Kolko, interaction design is "the creation of a dialogue between a person and a product, service or system"[175]. Interaction design for children involves creating experiences that, besides being engaging, are intuitive and straightforward, relevant, and age-appropriate (content, graphics, mechanics). In the case of Serious Games, it is essential to balance the educational content with entertainment by incorporating interactive elements that provide content knowledge while being enjoyable and fun.

PF interaction design process, followed the Framework displayed at the end of the Theoretical work (see Figure **??**). In general terms, it can be categorized as Content (Chemistry - According to Johnstone), Approach (AR Serious Games), and Purpose (Learning following Bloom's Taxonomy).

After selecting the content and purpose described in the previous chapter, the PF development process aimed at creating a user-centered experience that was efficient and effective at providing educational content while being enjoyable. This process involved balancing game elements with the content and pedagogic for PF Discovery, PF an Augmented Journey, and PF in the Wild. While all the games had their unique pedagogic approach integrated within the game mechanics, the aesthetics and technology were common to all the games.

4.2.1 Aesthetics

Before engaging directly with the gameplay, players may come across images, animations, or gameplay videos from various media sources. Once immersed in the game, a crucial early objective for players is to familiarize themselves with the diverse onscreen elements, discerning their purpose and behavior, thus establishing a foundation for comprehension

[358].

Research indicates that "Children engage with apps on emotional, sensorimotor and verbal levels"[125].

Kaiqing Chen claims that the users will naturally endow a digital experience based on the interface design and their strong emotional connection with the visuals, in the case of children: anticipation, joy, and trust [63]. This author also claims that the style and purpose of the visuals can be powerful tools for enhancing learning experiences, particularly for children.

PF Games leverages a diverse array of visual elements, including vibrant colors, appealing characters, and interactive animations, to captivate young players' attention. As per Steve Swink [322], the theory of "look"and "feel"within a game is critical for user engagement. PF graphical style, or "look,"provides a sense of continuity and representation of the project (see Figure 4.5). All the games share the same icons for continuity, using simple forms, and shapes like a plant for fertilizer, a drop for water, a diamond for jewelry, a house for habitat, a book for stories, and others. The "feel"component of the aesthetics builds in the character design, environment, and icons developed to be attractive and engaging for preteens.

Periodic Fable **character design and animations** are utilized to mimic the properties of the chemical elements. Previous research provides evidence of the usefulness of analogies in teaching science to support the understanding of complex concepts [193, 288]. This method facilitates the connection with the cognitive objectives of teaching and appeals to students from an affective perspective [288]. The analogies are provided in the shape of the characters (round bodies with long arms) inspired by the ball and stick physical molecular models (see Figure 4.6). The colors assigned to each character reflect the Corey, Pauline, Koltun (CPK) coloring standard convention color [1], used to distinguish the atoms of chemical elements in physical molecular models.

Each specific element's properties are reflected in each character's personality and animation. Some additional accessories (glasses, feet, hands, and other human features) were designed to highlight the anthropomorphic personification of the characters (see Figure 4.7 - 4.8). The aim is for children to associate the creatures with the element's properties and empathize and engage with them.

The aesthetics of the PF result from several ideation rounds aimed at creating a fun environment and stimulating children's empathy with elements as characters. As said previously, a vibrant color palette to develop the stories and games assets (characters, scenarios, Graphics, User Interface) was deemed effective in reaching and capturing our young audience. Scenarios that better stimulated the user's curiosity and emotions were preferred, like an aqua park, a forest with colorful fruits and exotic plants, and a bright chemistry lab.

All the 3D assets from characters, trees, pictures, chairs, lab equipment, and world

[1] https://sciencenotes.org/molecule-atom-colors-cpk-colors/

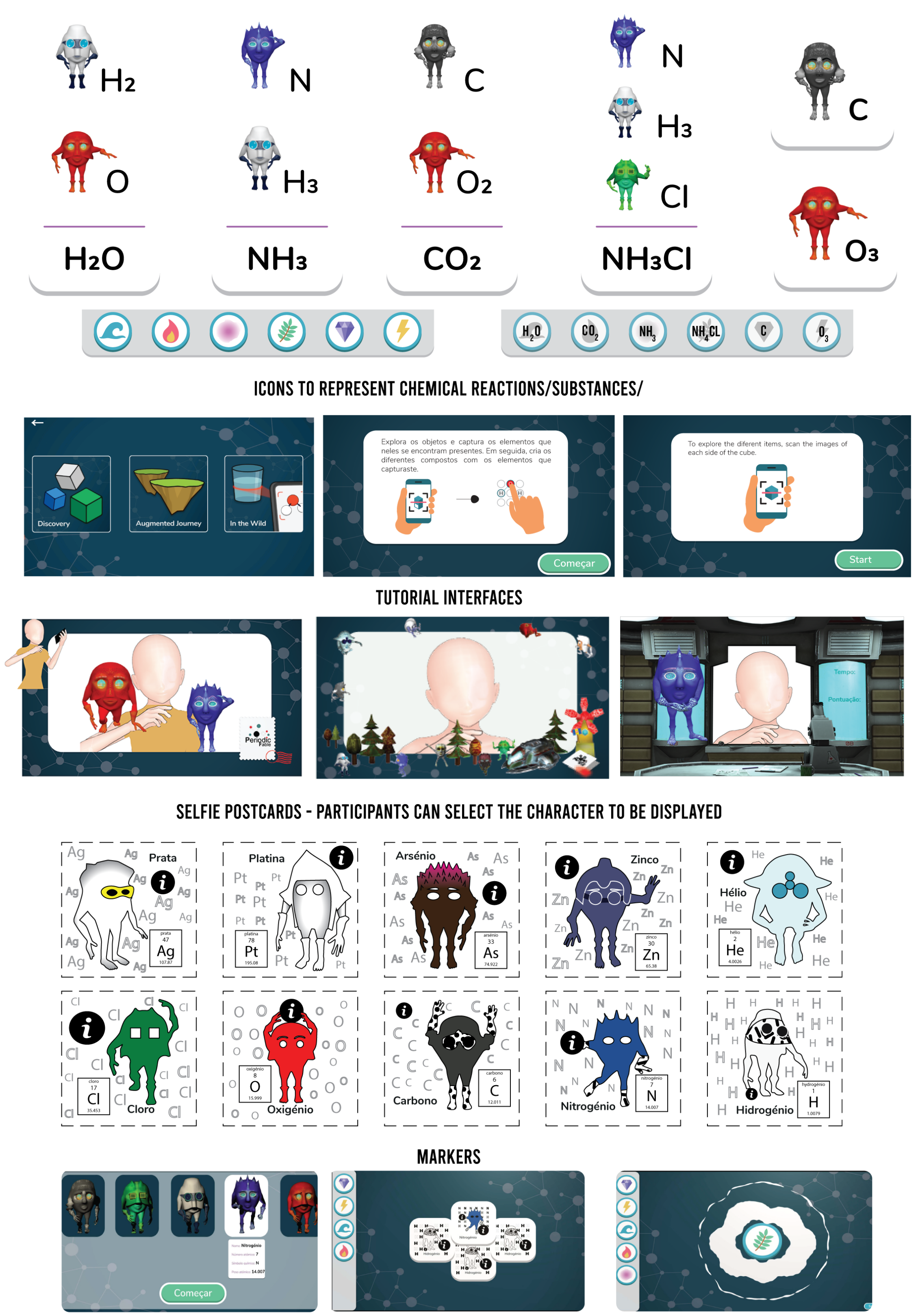

Figure 4.5: Examples of Common Visual Elements Used in PF Games.

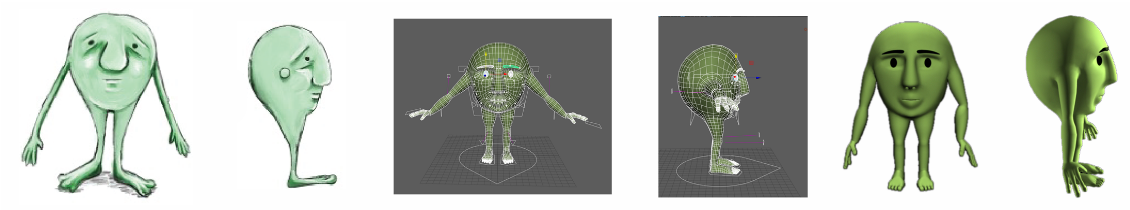

Figure 4.6: Character sketch, basic mesh, and 3D render

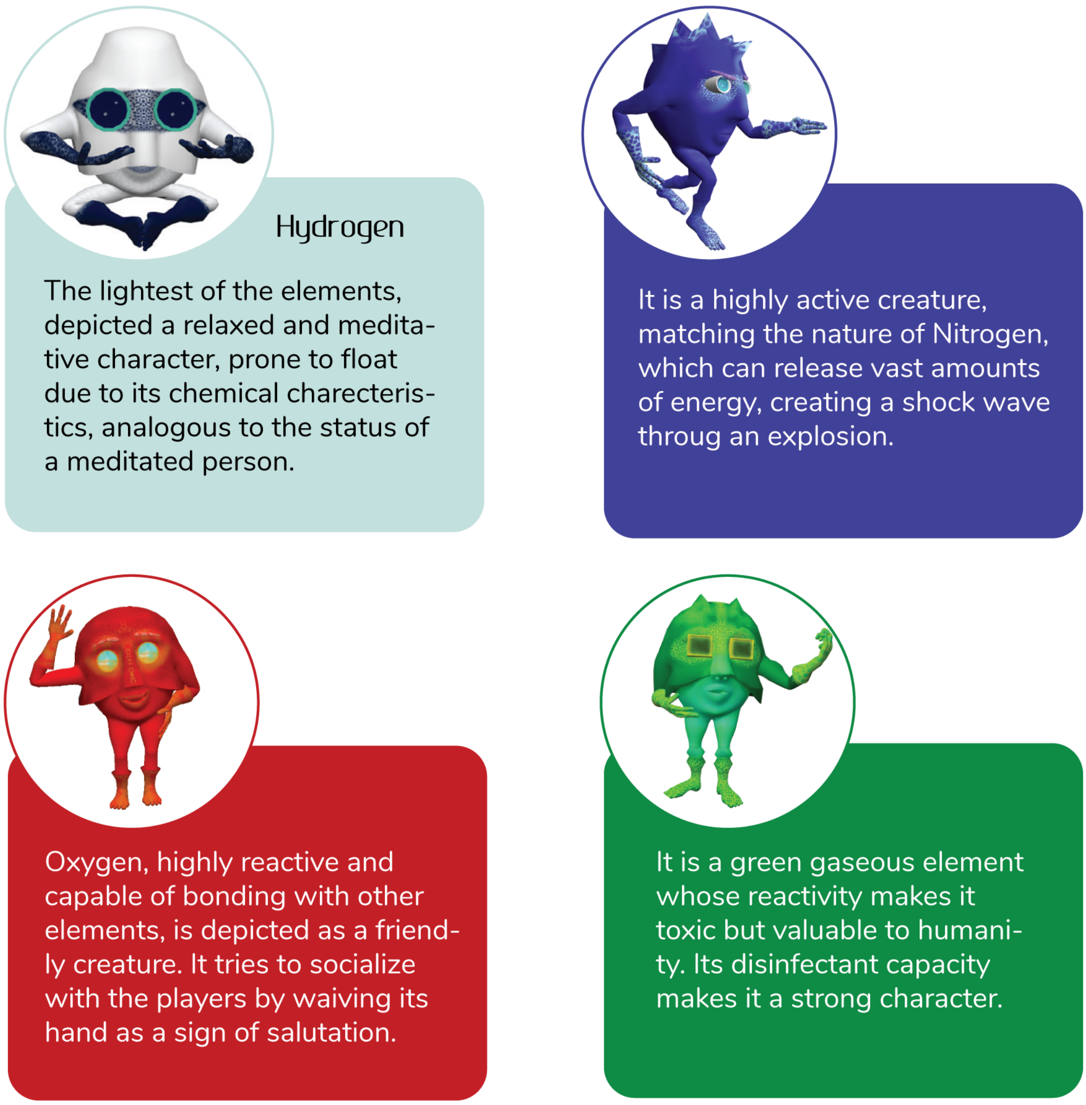

Figure 4.7: Characters - Hydrogen, Nitrogen, Oxygen, and Chlorine

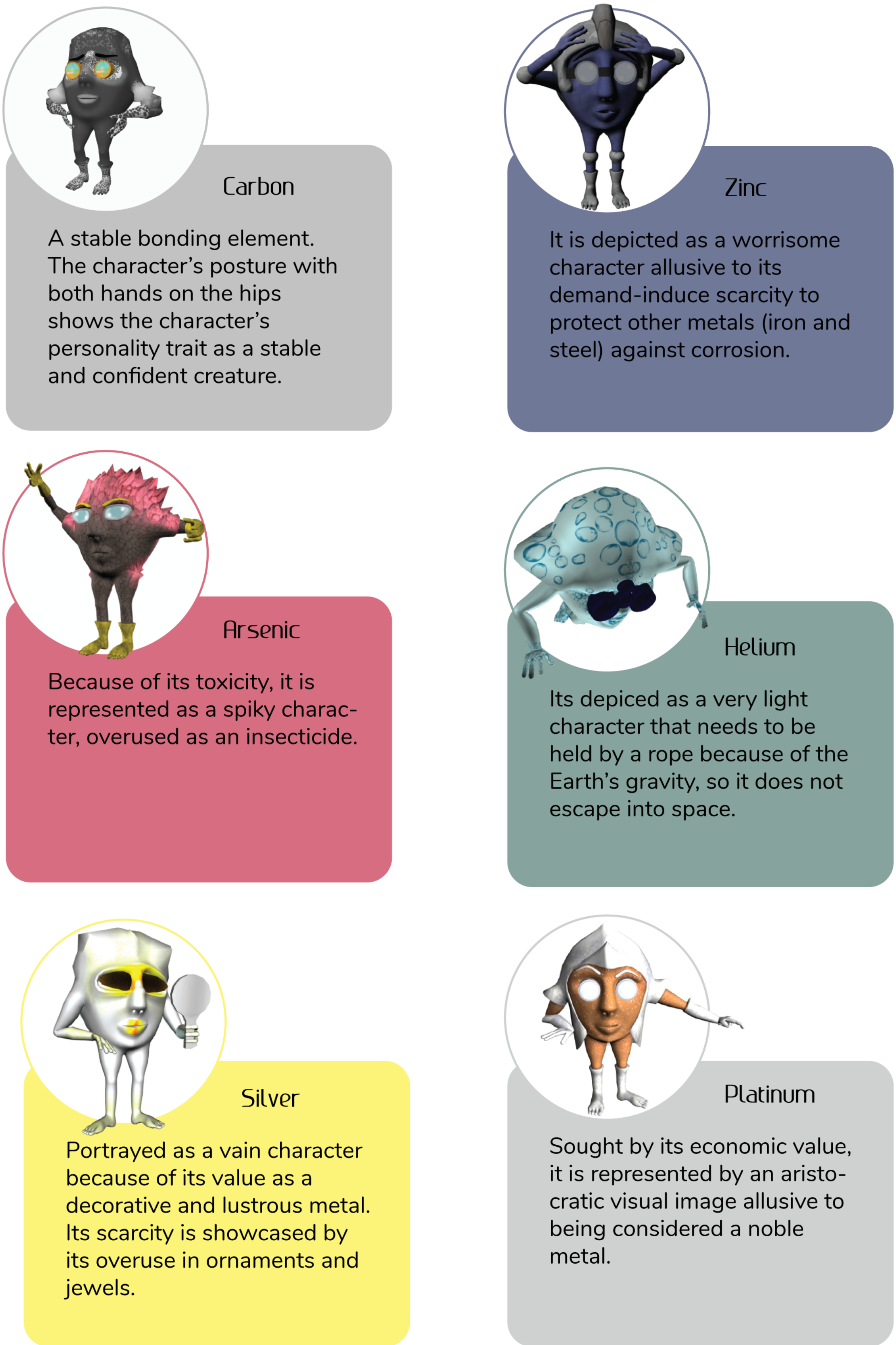

Figure 4.8: Characters - Carbon, Zinc, Arsenic, Helium, Silver, and Platinum

environments had unique textures created and applied to maintain the same artistic style and follow the overall aesthetics of the games. The assets were developed using Autodesk Maya, Mudbox, Adobe Photoshop, and Illustrator. We rely on simple graphic representations in the tutorial to convey actions that players must take, avoiding an overload of textual content (see Appendix B).

4.2.2 Technology

Secondary research in Chapter 3 (State of the Art) guides us toward using AR to provide multi-level information on STEM domains. Besides allowing the display of tridimensional information, AR technology supports other formats and multi-modal approaches (2D, animations, text, audio), allowing designers and developers to be creative when adapting the content knowledge according to the adequate pedagogical approach.

This adaptability allowed the team to use analogies, storytelling, and activities to acquire the content while playing and positive reinforcement employing rewards. It also allowed using other senses in learning by incorporating tangible interactions and audio. Furthermore, it allows the exploration of the content according to multi modes of representation, obtained using 3D AR molecular structures, animations of the created substances/reactions, display of the symbolic information of the properties of the elements and chemical equations, and simultaneous reactions.

The games were developed using Unity Engine [2] version 2019.3.0a11 with ARcore v1.10.0 and Fungus SDK to handle the narrative flow. Because of the gameplay mechanics, we used AR Marker base technology in two of the systems PF Discovery (see Figure 4.9) and PF in the Wild (see Figure 4.10) and marker-less technology in PF an Augmented Journey (see Figure 4.11). Marker base technology uses visual cues like images or patterns as a point to overlay digital information within the real world. The camera or scanner recognizes the marker to trigger the AR system to display on the screen of the mobile device the digital content on top of the marker in real time.

PF An Augmented Journey employs marker-less technology, also known as location-based AR, which uses light estimation and motion tracking technology of the mobile phone's camera to identify interesting points, within the environment called features and track how those points move over time, enabling the system to detect any flat surfaces, like a table or a floor, and allowing for the placement of virtual objects and any other type of digital data. AR markerless uses several sensors such as GPS, accelerometers, and gyroscopes to detect the user's location and orientation, allowing the virtual information to be placed in the correct position and perspective in relation to the real world. This technology allowed the navigation of a 3D virtual world (by moving within the actual space), a part of the gameplay of PF an Augmented Journey, providing a more natural and seamless experience and learning through a more immersive and engaging activity.

[2]https://unity.com/releases/editor/archive

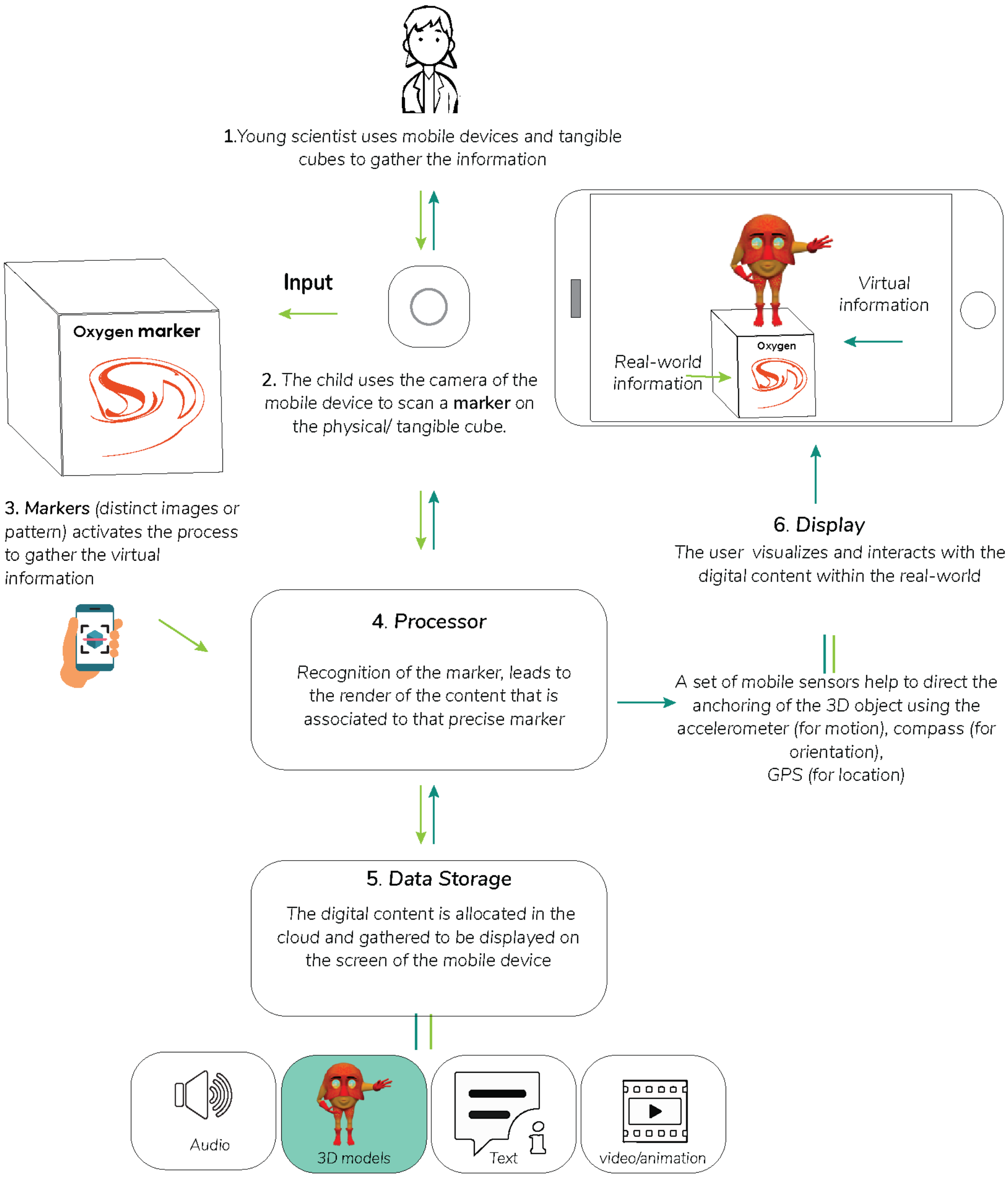

Figure 4.9: PF Discovery System Overview

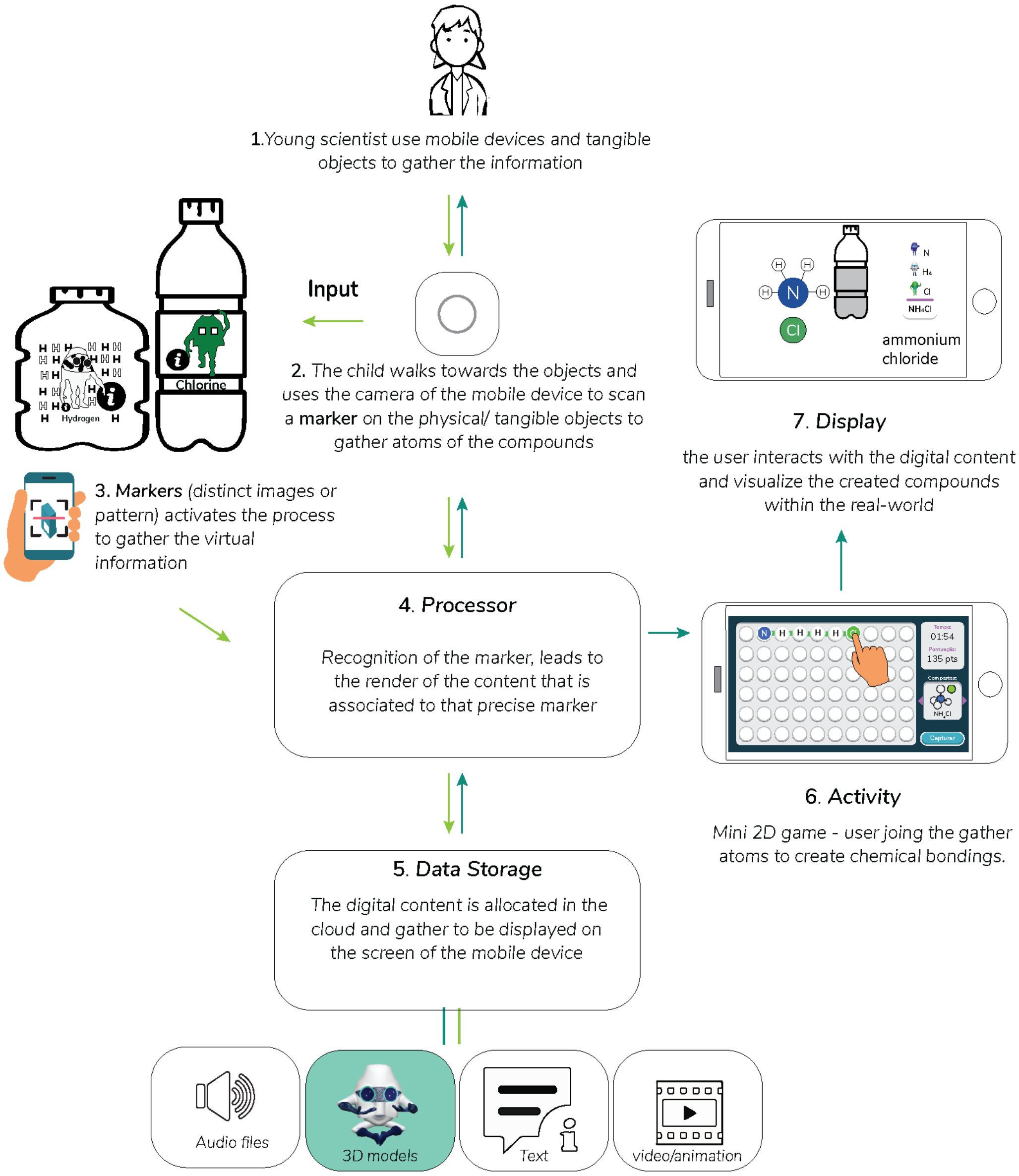

Figure 4.10: PF in the Wild System Overview

In Portugal, mobile devices are widely utilized by preteens in their daily lives. Compared to other AR-enabled equipment, such as head-mounted displays, mobile devices offer greater cost efficiency and accessibility, particularly within the school environment. Consequently, mobile devices were chosen as the preferred device for implementation.

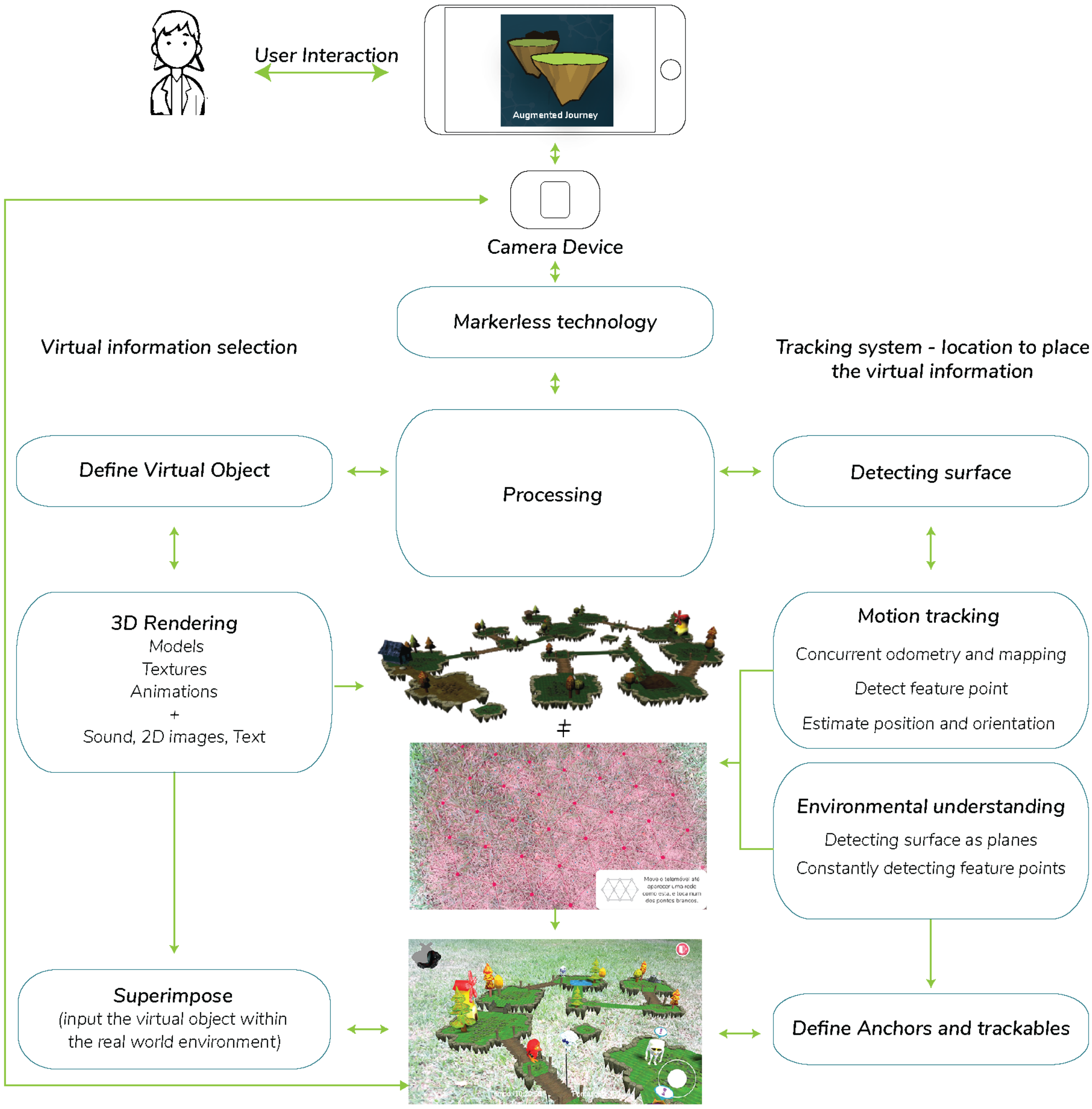

Figure 4.11: PF an Augmented Journey System Overview

While these elements (Aesthetics, Content, and Technology) were shared, the mechanics of the games and storytelling were specific to each game. Using different pedagogical approaches, and strategies to display the content knowledge incorporated within the gameplay or game mechanics, allow us to identify the benefits and limitations of AR in each method. In the next chapter, we describe the mechanics and gameplay decision's rationale to evaluate the effectiveness of each game on the student's affects and learning outcome.

4.3 Digital Prototype Development

Once the learning objectives were defined and the game interactions validated, a team of one programmer, and two 2D/3D artists (see Figure 4.12), started the development process. This process included the creation of all the 3D assets (characters and different environmental settings), user interface (UI), story plots, and programming.

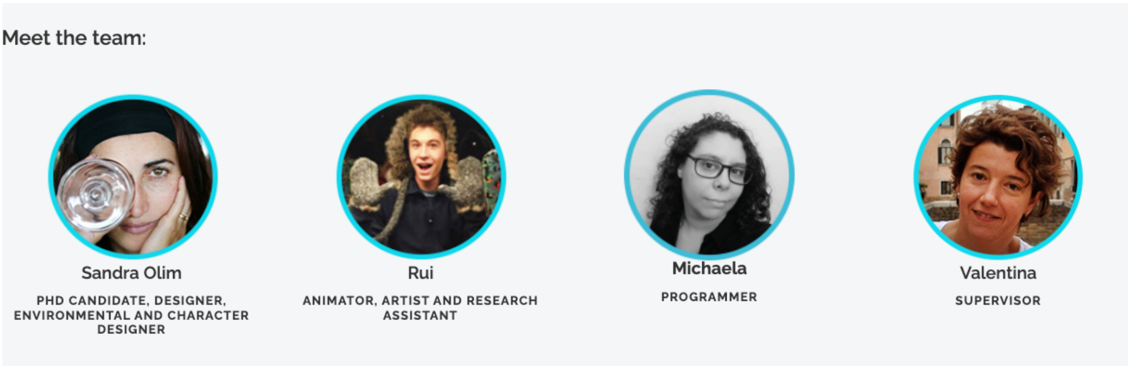

Figure 4.12: PF Games development team

Three AR Serious Games were designed and developed to introduce and engage children (9 to 13 years old) with concepts about the Periodic Table. Each game is developed with different pedagogical approaches embedded within the game mechanics.

PF Discovery presents children with scientific content supported by physical cubes manipulable through Tangible Interaction (TI) and AR. The user can create their own tangible interaction system by downloading a 2D printable plan of the cubes through our website and assembling it. The system provides content knowledge by rotating and scanning markers (images or patterns used to deploy the information) on each cube facet. There are five cubes, each dedicated to one chemical element: oxygen, hydrogen, chlorine, carbon, and nitrogen. Each facet of the cube displays different information in the Periodic Table (see Figure 4.13.)

PF An Augmented Journey is an adventure game where the learning content is deployed in favor of the narrative. The learning content is part of a story that develops around exploring a AR 3D world. Players must find and collect parts of a spaceship in the 3D world by moving within the real environment to help the protagonists fix their vehicle and continue their journey. The use of 3D AR technology affords participants' immersions simultaneously in both the real world and virtual information. The gameplay allows communicating with characters through textual input and output to gather the information that helps them to complete the task while learning about the sustainability of the elements (see Figure 4.14).

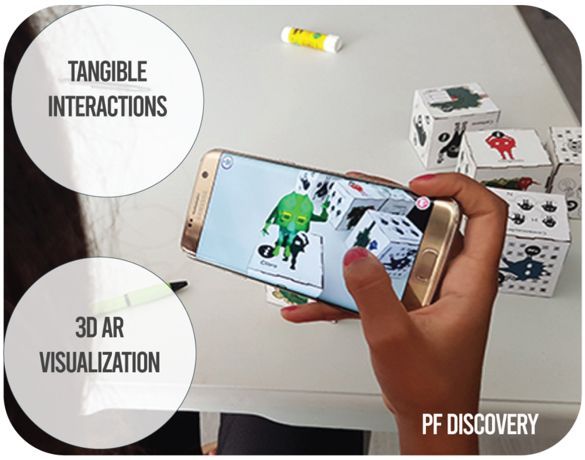

Figure 4.13: Periodic Fable Discovery

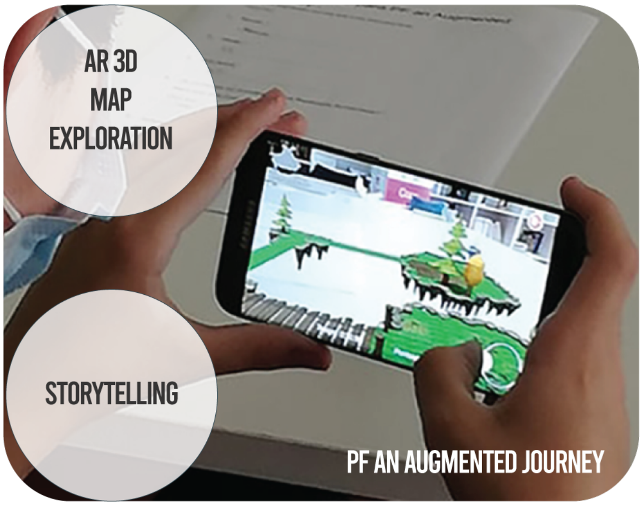

Figure 4.14: Periodic Fable An Augmented Journey

PF in the Wild uses a situated learning pedagogical approach by integrating everyday routine products (e.g.water bottles, bleach, batteries, balloons) as part of the gameplay mechanics. The game starts with a tutorial that guides the user toward gathering chemical elements/atoms by scanning codes (markers) allocated to the products displayed on shelves (see Figure 4.15).

The learning process is scaffolded through the display of the information of the chemical elements' properties (2D) (symbolic understanding), with the respective AR tridimensional model of the covalent bonding (microscopic understanding), and finally, the use of the real component (macroscopic understanding). The learning content is also reinforced in a mini-game (like word puzzle [3] mechanics) where the user has to create or re-create chemical compounds or substances.

[3]https://thewordsearch.com/

Figure 4.15: Periodic Fable In The Wild

Figure 4.16: Link to video showcasing Periodic Fable games

Chapter 5

PF Discovery

This chapter describes the PF Discovery game interaction design and development process according to its gameplay mechanics, storytelling attributes, and pedagogical methods.

Periodic Fable Discovery was the first of the three games to be developed and aimed to facilitate the learning of five selected elements (oxygen, hydrogen, carbon, nitrogen, and chlorine) at various levels of comprehension. Drawing inspiration from Johnstone's viewpoint [161], our game seeks to optimize learning outcomes by enabling students to engage with information at macroscopic, microscopic, and representational levels. We incorporated Augmented Reality (AR), 2D displays, and 3D animations to achieve this. The display of the reactions/substances through AR 3D animations (macro), while simultaneously showcasing the symbolic representative information of the chemical equation involved (2D display), helps to create a mental connection between both. The visualization and interaction with a 3D AR molecular structure at a micro-level allow for displaying the spatial relationship between the chemical elements (see Figure 5.1).

The game relies on a constructivist pedagogical approach, where preteens can explore and interact freely with the tangible artifact, thus acquiring knowledge about chemical elements through AR visualizations and tactile information. The user can also create their tangible interaction system by downloading a paper file with the 2D plan of a cube dedicated to each one of the chemical elements (total of five) through our website (see Appendix F) and assembling it (see Figure 5.2). As per Billinghurst, we explored the combination of tangible, physical interfaces with tridimensional virtual imagery allowing children to engage and have fun as they learn, facilitating the cognitive load [37] in a natural and genuine way [52].

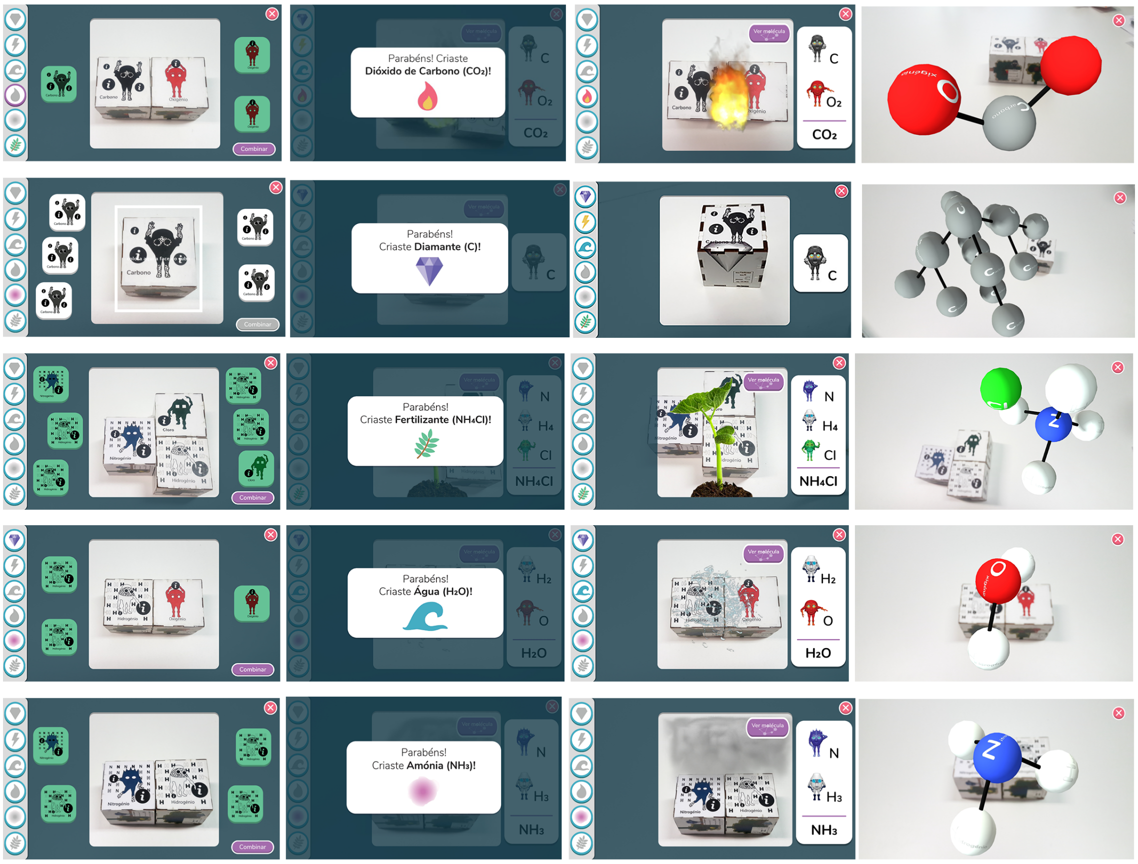

Figure 5.1: Understanding of different levels of chemical bonding.

Figure 5.2: Assembling of the cube

5.1 Storytelling

Previous work demonstrated that character embodiment and storytelling could promote exploration and discovery in Science learning [293]. PF Discovery followed this approach by creating stories relatable to the users and integrating information about reactions and covalent bonding Storytelling is a known device in digital games to engage and maintain the players' focus [40]. Storytelling is explored in two of our games (PF Discovery and PF an Augmented Journey) in different ways, adapted according to the pedagogical aims of the game.

We explored storytelling as an informative and memorable medium to create a connection between the element's behavior and the character. Short and simple plots were created according to the elements involved in chemical reactions/compounds like water (oxygen and hydrogen), carbon dioxide (carbon and oxygen), laughing gas (nitrogen and oxygen), the photosynthesis process, and finally, the chlorine antibacterial properties. The stories were scripted and storyboarded (see Figure 5.3), and assets and animations were created by the development team at the ITI institute (see Figure 4.12).

PF Discovery makes use of character design and plotting devices (see Figures 5.4 to 5.8) grounded on the properties of the elements and their most common chemical reactions. Each element has a dedicated short visual story (the longest being 44 seconds) built on a tightly structured beginning, development, and end. The aim was to create fun, short and engaging stories using situations and settings children could empathize with.

A vignette-like short story was created for each one of the elements portrayed within the cube: Oxygen (see Figure 5.4), Hydrogen (see Figure 5.5), Nitrogen (see Figure 5.6), Chlorine (see Figure 5.7), and finally Carbon (see Figure 5.8).

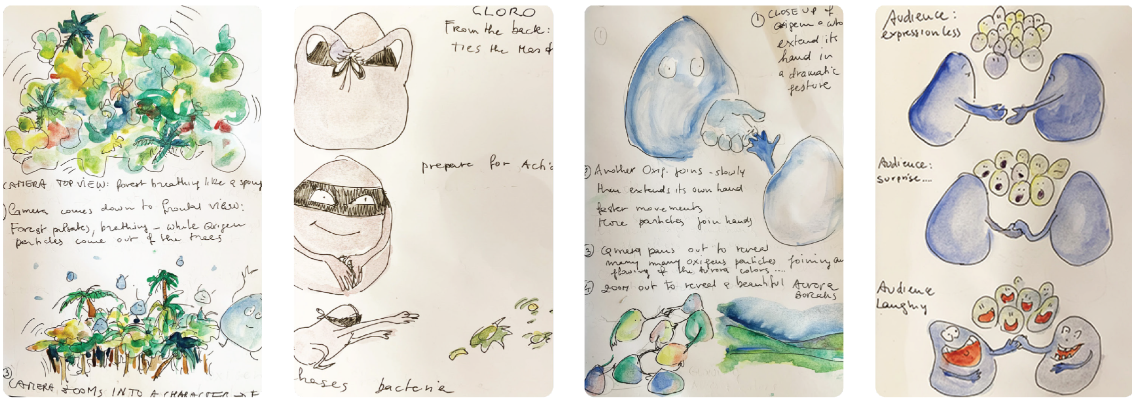

Figure 5.3: Storyboard

5.2 Game Mechanics

The game mechanics of each game are designed to incorporate the pedagogical methods dedicated to that game. As said before, PF Discovery provides the learning content by

Figure 5.4: Oxygen and Carbon (carbon dioxide) showcase how the chemical elements are part of the photosynthesis process, whereas the plants absorb carbon dioxide, and then oxygen is liberated.

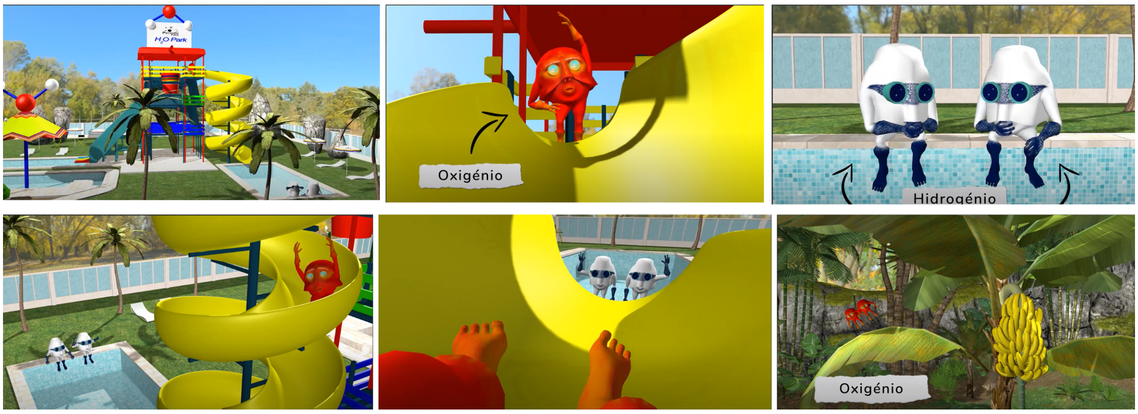

Figure 5.5: Hydrogen and Oxygen (water) The story revolves around oxygen losing control while coming down on a toboggan and smashing into hydrogen, thus creating water.

Figure 5.6: Nitrogen and Oxygen – the story takes place on a stand-up comedy show, showcasing Nitrous Oxide, commonly known as laughing gas.

Figure 5.7: Chlorine is portrayed as a superhero because of its disinfecting properties.

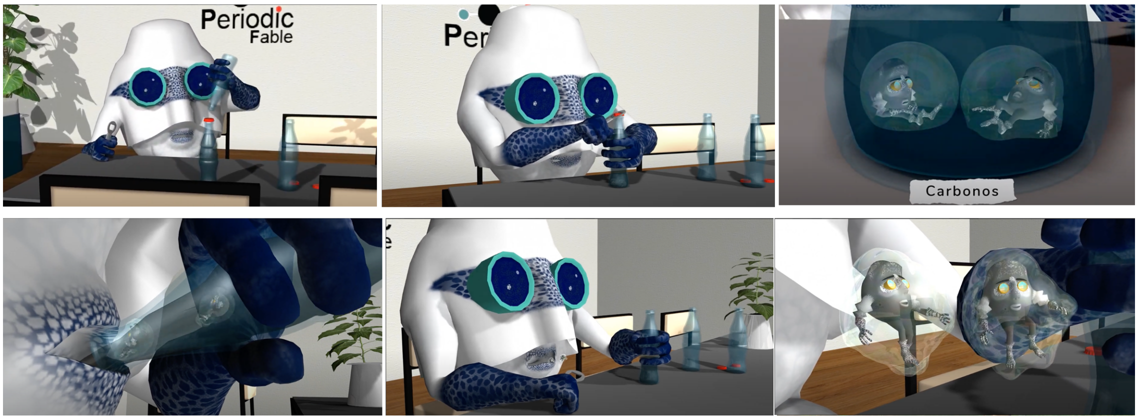

Figure 5.8: Carbon story showcased these elements as part of the gasified soft drinks with a funny twist, showcasing the main character burping.

rendering and uploading the virtual information according to each face of the game. The criteria for this approach is the delivery of content in manageable portions, preventing children from feeling overwhelmed and facilitating the understanding and assimilation of the information, following Bruner's Cognitive Load Theory [47, 155].

The game starts with a short tutorial that guides the children in understanding the game's mechanics: how to explore the faces of a tangible cube, gather the elements/characters, and use them to create reactions. The participant selects one of the cubes (this selection can be random) and scans one of the markers/images on each facet, generating/uploading the information linked to that particular pattern.

- Facet 1: Triggers an animation of a 3D character representing a chemical element. It also provides information about the chemical symbol, including atomic mass, chemical name, and atomic number (see Figure 5.9, number 1).

- Facet 2 (Habitat): Uploads an image of an apartment building divided according to the blocks of the Periodic Table (atomic weight and arranged in horizontal

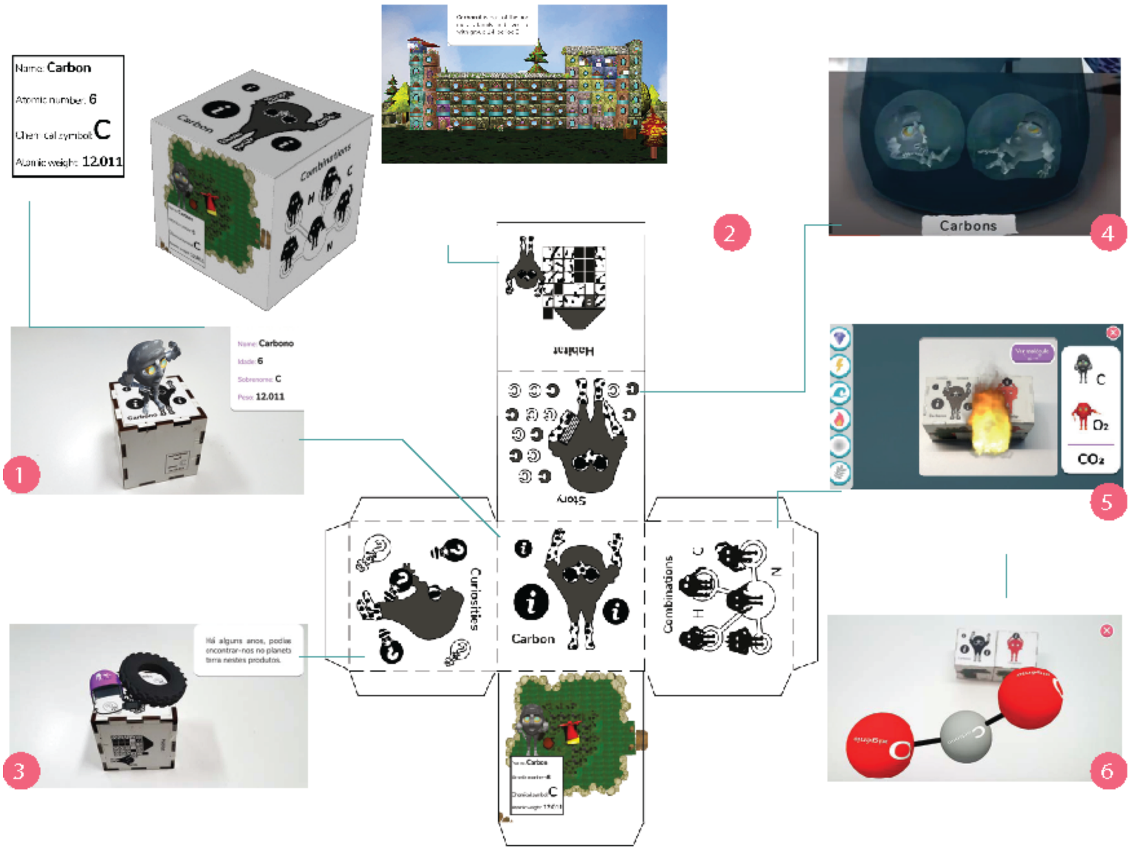

Figure 5.9: PF Discovery Interaction Design

rows/periods and vertical columns /groups). We decided to showcase the different characters in this block/apartment location, creating an analogy (apartment building vs. location of the element in the periodic table), so children will assimilate the lodging of the element in the Periodic Table (see Figure 5.9, number 2).

- Facet 3 (Curiosities): In this facet, corresponding AR scenes and 3D models of products that have that element within their composition are visualized. For example, we depict oxygen as being a compound that can be found on a Pepsi drink, a cleaning product like Vanish (see Figure 5.9, number 3). Our design took a situated learning approach, whereby children can connect with the products in their surroundings and chemical elements.

- Facet 4 (Stories): Capturing facet triggers a short clip (less than one minute) dedicated to that particular element's reaction with other elements (see Figure 5.9, number 4).

- Facet 5 (Combinations): Capturing facet 5 allows the children to select and explore the reactions of different elements. We placed icons on the left side of the screen for the user to select and then explore several reactions (water, fertilizer, ammonia, fire, ozone, or to create a diamond) (see Figure 5.9, number 5). Once the user clicks on the button, the application will indicate what type of creatures/elements are needed, and the user will be prompted to scan the corresponding cube with the mobile device's camera.

- If this activity is performed correctly, the interface notifies the child with a message congratulating him or her for the reaction just created and showing the elements that were part of the reaction. Then an animation of the reaction just created plays out (see Figure 5.9 - number 5). This action also unlocks the possibility of observing and interacting with the molecular structure just created (see Figure 5.9, number 6).

  The game also provides a final reward once the player has explored all the cubes and assembled a map using a dedicated facet. This gives access to a selfie with the player's favorite chemical element/character (see Figure 5.10).

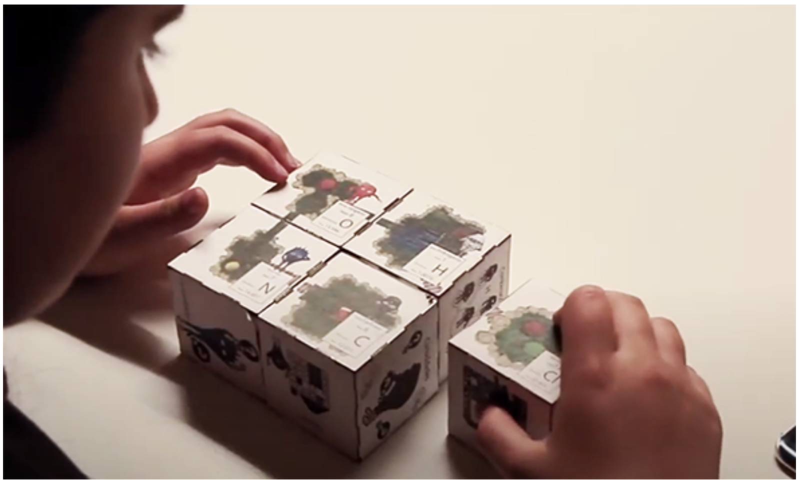

Figure 5.10: Map assembling

Each element experience ends when the user has explored all the cube facets dedicated to that element and captured its reactions. The experience can be repeated for the other cubes until all cubes have been explored. Since no content dependencies have been designed, each child can explore one, two, three, or all the cubes, consistently achieving full closure with each experience. A more detailed illustration of the gameplay interaction is provided in appendix C.

5.3 Game Playtest and Iterations

Like most forms of design, game design is an iterative process. This implies that several approaches are tested and refined in a cycle process (prototype, playtest, evaluation, and design iteration) before a final product.

The initial testing of a digital interactive system is especially critical in developing serious games for children. It allows for gathering feedback about the game's concept, identifying potential issues (usability or not achieving the learning goals), and identifying weaknesses to improve the final product. When designing and developing apps for children, usability is analyzed according to how quickly and effortlessly children accomplish tasks and how many mistakes they make along the way [87]. Due to children's growing use of technology in education, it is important to assess the usefulness and efficiency of these tools. The usability assessment allows the understanding and readability of the material, the ability to retain information by its users, and the application function [227]. It also helps to make the information relevant to the user in a specific situation, allowing for iteration and adaptability.

Designing for children requires distinct usability approaches, including targeting content narrowly for children of different ages. Because of this, it is essential that usability testing is performed by a representative sample of the target users [86]. When designing and developing apps for children, usability is analyzed according to how quickly and effortlessly children accomplish tasks and how many mistakes they make along the way [179].

Various usability evaluation techniques have been used to predict usability issues early in software design to reduce their severity and avoid redoing the design [208, 355]. Usability in learning environments utilized more general metrics like learnability, efficiency, memorability, user happiness, effectiveness, simplicity, performance, and understanding [269]. In the following, we describe the methods and results from preliminary studies and pilot tests with children 9 to 14 years old as informants towards refinements of the final prototype.

In the forthcoming section, we present the methods and outcomes of preliminary studies and pilot tests conducted with children aged 9 to 14. These studies aimed to gather feedback and insights from the participants, which subsequently informed the refinements made to the final prototype of each game. This detailed account of the studies and test results contain within the dedicated chapter of each one of the games.

5.3.1 PF Discovery Pilot Test

PF Discovery's initial iteration and findings were designed to evaluate the children's acceptance and satisfaction of the PF Discovery, engagement, and overall feedback from our target audience. Although the overall assessment showed positive results in AR's entertainment value and usability, a preliminary pilot test (N=8) using a mix-method approach identified the need for minor gameplay interventions.

Procedure

The eight participants, four females and four females aged 8 to 13, were recruited through opportunistic sampling. Children were asked about their interest in participating, and their parents/guardians were contacted and informed of the study. Then the children and their parents were informed of the protocol and purpose of the research. Three participants attended private schools, and the other five public schools. The study took place at ITI - Interactive Technology Institute installations, and it took about 40 minutes for each child to evaluate the game (30 minutes of interaction with the game and 10 minutes to fill out surveys and answer questions). While one of the participants was younger than the identified target group (8-year-old), we included him in the study to gather information about the system's usability. The study began with a short explanation of the purpose of the preliminary study, which involved a demographic survey with questions regarding age, gender, and grade level. We also included questions about previous knowledge of the Periodic Table and AR technology; 2. Participants had to interact with the game PF Discovery (using the equipment we provided); 3. While the players interacted with the game, the lead researcher observed and took notes about the participant's comments, expressions, and struggles with the technology or equipment; 4. Finally, we applied post-test questionnaires and interviewed the participants. The Post-test questionnaires included a usability and satisfaction assessment using the Likert scale with smileyometer (see Figure 5.11) [259] of five levels - "1"for totally disagree and "5"for totally agree (see Table 1). The interview questionnaire also evaluated participant satisfaction and allowed us to gather suggestions from our target users. Questions like: *What did you like the most? What didn't you like? If you had to change anything, what would it be? Did you find the game useful? Why? What did you learn? Any suggestions to include in the game?*

Figure 5.11: Smileyometer

Evaluation, Results and Reflections

Regarding the technology, half had previous knowledge or had used augmented reality applications before by playing other games. Three participants, the oldest (13 years old) of our sample group, had previous knowledge of the Periodic Table content.

While experiencing PF Discovery, our users had high positive scores in Q1, Q4, Q3, and Q7, with reported high means of engagement and usability (see Table 2).

During the interview, the participants reported that the game's most enjoyable part was viewing the character's animations. Some of the participant's comments were: *"Hydrogen is so funny and calm"; "This is so cool! I can see Oxygen is waving at me!"; "The characters are so cute!"*. The comments also show amusement when viewing the product's chemical composition: *"My helmet has carbon!"; "My mom uses chlorine to clean."* When we asked the participants how to improve the game, most of the recommendations were

Table 5.1: Usability and satisfaction assessment results from PF Discovery

Q#	Question	Mean	SD
Q1	I would like to play PF Discovery again	5.00	0.000
Q2	I would recommend the game to friends and family	4.71	0.488
Q3	I thought that PF Discovery was easy to use	4.86	0.378
Q4	I think that the game is fun to play	5.00	0.000
Q5	I found that the various functions in the game were well integrated	4.00	0.816
Q6	I found the game useful	4.57	0.757
Q7	I would imagine that most people would learn to use this game very quickly	4.86	0.488
Q8	I felt very confident using PF Discovery	4.57	0.756

undivided and about the color of the character:*"Oxygen should be white because it is on the air"; "Oxygen should be blue because of the sky"; "Hydrogen should be blue because it is in the water."* The participants also suggested developing more stories:*"I like the story of oxygen, but what about the other elements?"; "I enjoy the story, but why is it only about Oxygen?"; "My cube says Chlorine, but the story is about Oxygen."* The players considered the game fun and useful (Q4 and Q6): *"I think that this game can be useful for my future classes "; "I like learning like this, it is fun"*. Moreover, the children recalled specific scientific information: *"I created water by putting together Oxygen and Hydrogen "; "The only symbol of the elements that is not like the names of the characters is Azoto (Nitrogen) "; "Diamonds are made of Carbon."* The participants were also asked about allocating the chemical elements since the participants provided no feedback. What is your opinion about this part (location of the chemical elements within the Periodic Table)? *"The building is cute!"; "I think that the characters are getting a sun tan"; "I think it is funny that the elements are neighbors of a hotel."* It was eminent that the learning goal was not obtained or understood. From the observation notes, it emerged that several participants struggled to find specific areas of information in the cube. The use of abstract markers did not provide enough guidance to the participants about the areas of information. The participant manipulated the cubes back and forth (overlooking the written information), gathering the same information several times. Their comments demonstrated their frustration: *"I want to see Nitrogen, but I cannot find it"; "Where is the part with the objects?""I want to see all the parts about the curiosities, but it takes time."*

Conclusion

In sum, this preliminary test confirms the potential of PF Discovery to gather the interest of a younger population in the topic of the Periodic Table while pointing at some flaws that needed refinements, for example, the design of Markers that can quickly allow the users to identify the areas of exploration, and a new design solution to transfer the content about the allocation of the chemical elements.

5.3.2 Design Iterations

After conducting our Pilot Study and consulting with two teachers, PF Discovery was iterated to tackle some of the identified flaws. According to Allan Harrison et al., analogies need to support the mental images and the construction of ideas needed to facilitate the understanding of a concept [17]. The initial concept was to demonstrate the placement of the chemical elements through a 3D building (see Figure 5.9, number 2). In contrast, the characters were allocated in apartments indicative of the row and columns used in the Periodic Table. Even though the aim was to provide learning information and entertain the students, this analogy was arbitrary and superficial. Teachers suggested using an analogy that was specific to the standard content used in the context of the classroom and chemist books (see Figure 5.12, right).

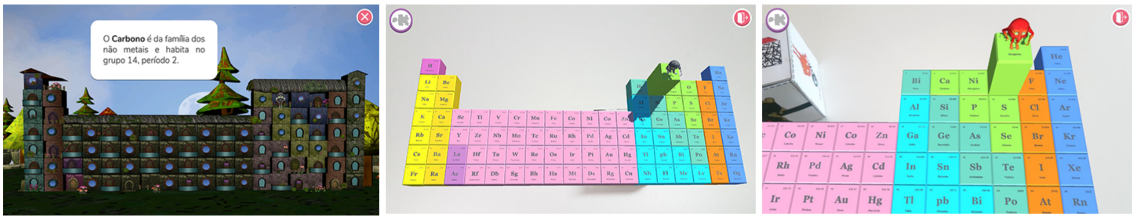

Figure 5.12: Iteration of analogy used of the position of the chemical elements within the Periodic Table.

The Marker's initial concept aimed only to provide enough detail to the system and upload the information dedicated to that pattern. To guide the user in gathering the pretended information and facilitate the mechanism of the game, for each one of the facets of the tangible interface, it was designed icons and graphic elements representing the area of exploration (see Figure 5.13).

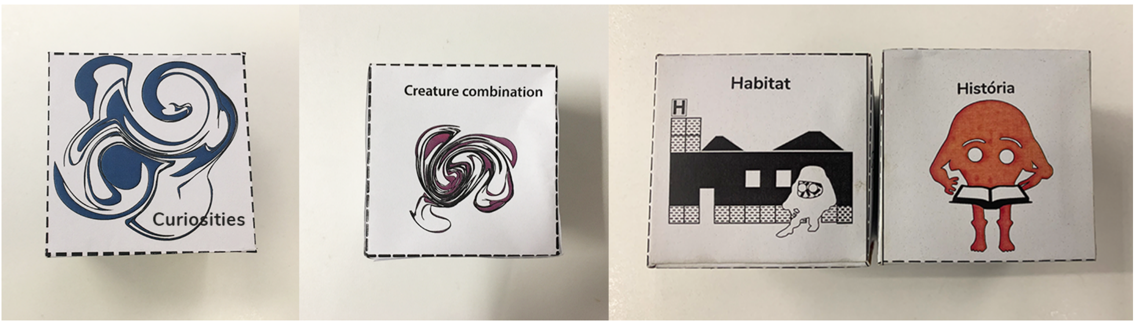

Figure 5.13: Tangible Interface changed from abstract images (left) to an icon that reflected the area of exploration and the element to be explored.

5.4 PF Discovery Game Evaluation

PF Discovery has been assessed at different moments in formal and informal learning contexts. We described several conducted studies, results, and insights in the following.

The aim was to ensure that the resulting theory would have application in practice by "simultaneously and iteratively addressing the scientific processes of discovery, exploration, confirmation, and dissemination."

5.4.1 Study I - Periodic Fable: an Augmented Reality Serious Game to Introduce and Motivate Young Children Towards Chemistry

In this study, we use the PF Discovery high-fidelity prototype for testing theoretical interventions in the active context of informal educational environments. The research questions (RQs) and methods were grounded in the relevant literature and practical experience with Periodic Fable Discovery.

PFDaRQ1: Can mobile Augmented Reality serious games significantly affect students' learning outcomes and motivation compared to traditional teaching methods while exploring concepts about the Periodic Table?

PFDbRQ2: How can Augmented Reality serious games design elements (technology, aesthetics, story, and mechanics) contribute to facilitating the learning process of scientific concepts?

While previous studies with children were conducted comparing a more traditional method of teaching with digital games in the learning context, we believe that it was important to address this study in the context of preteens (9-13 years old) in Madeira Island, where textbooks continue to be the primary tools used to convey the information.

Procedure

After the pilot study previously described, we were able to identify resources, technological and time constraints needed for the main study. This information guided us through the different steps and helped us refine our final protocol. Even though the pilot study worked well, we anticipated the need to have more than one researcher in our main study. We could also estimate the study time for each condition (approximately 40 minutes). We recruited 30 participants (15 females and 15 males) from three different institutions and clubs: Doutorecos (summer camp), Associação Olhar (occupational social association for children), and CAB Junior Basketball (sports club). The study was carried out on the premises of the children's institutions and followed the same process at the different locations: 1) initial contact and scheduling with the institutions; 2) signed consent forms from the guardians of each participant; 3) and data gathering.

Data Gathering- Pre-test

Both groups had to complete a pre-test questionnaire to collect demographics, technology usage, and topic knowledge. The learning outcome was gathered using a test

Figure 5.14: Left: Experimental condition - right: Control condition

consisting of 5 multiple-choice questions, each worth 5 points. The participants had to answer: *1. What is the symbol for oxygen? 2. What type of compound results when you mix hydrogen and oxygen? 3. What is the chemical formula for ozone? 4. What product contains chlorine? 5. Which element is responsible for diamonds?*

The same questionnaire (questions randomly ordered) was applied after the intervention in a post-test to assess the effectiveness of the interventions. We also conducted a final post-test, using the same questionnaire to evaluate the student's retention and recall of the information (sometimes referred to as the week-after test or evaluation of knowledge of the topic-retrieval/recall test). However, since the study took place at a summer holiday club, attendance was not required, and as a result, many study participants did not return on the week that we conducted the week-after test. As a result, our sample group was too small, and we decided not to analyze or report the week-after test results.

Intervention

The participants were randomly separated into two groups (one for each condition); one group used AR (experimental condition) and the other a textbook (control condition)(see Figure 5.14).

The participants using the AR applications sat at a table where the tangible cubes were displayed (five cubes for each participant). The researchers handed each participant a smartphone (Samsung Edge S7) with a previously installed application. They were instructed to click on the app, follow the tutorial and freely explore the content. The participants were also informed to raise their hands in case of any doubt or upon finishing the game. Once the game was finalized, the researcher used the same smartphone to conduct the post-test questionnaire, created using Google Forms. A similar process was followed for the experimental condition, with the difference in the resource used, which was a textbook. The textbook provided the same information as the game, like the narrative of each story in written format using some images (clips gathered from animations in the app), displaying the actions about the covalent bonding of water, ozone, diamonds, ammonia, and carbon dioxide. Furthermore, it also showed images (once again gathered

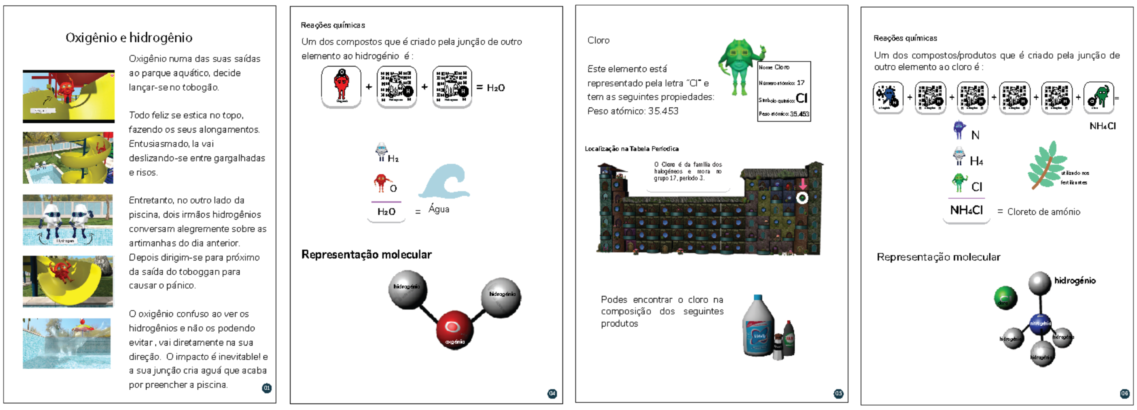

Figure 5.15: Example of some of the information provided in the textbook

from the app) of the molecular structures of the combined elements, products, and substances that contain such chemical elements, replicating the same information as in the cubes (see Figure 5.15).

Data Gathering - Post-test

In education, motivation can be defined as the desire that the individual has to engage in a learning process [74]. To identify the weaknesses and strengths of our design in motivating the children to learn, we conducted an *Instructional Materials Motivation Survey (IMMS)* [196], which is based on the Attention, Relevance, Confidence, and Satisfaction (ARCS) motivation model [170]. This particular instrument has been validated by several research studies using technology as a motivational factor in learning [131, 206, 24]. Since our users were not English speakers, we adapted a translated version [290]. Besides the post-test questionnaires, two researchers were involved in the study; one observed and took notes during the intervention, and the other supported and helped the participants in case of technical difficulties. In the end, the researchers interviewed 9 participants from the AR activity.

Finally, a comparative analysis was undertaken to determine the participants' learning outcomes between those who used the AR app and those who used the textbook (between-subjects analysis). We also examined and compared pre and post-tests to assess the learning differences between groups (within-subject analysis).

Results

According to the demographic results, our users were mostly fifth-grade level students (53.3 %); others were in the sixth grade (26.7 %), seven (10 %), and eighth (10 %) grades. The majority of the participants (13) were ten years old (43.3 %); six were 9 (20 %); six were 11 (20 %); three were 12 (10 %); two were 13 (6.7 %). All the users had access to or owned a mobile device. Most participants were unfamiliar with Augmented Reality (56.7 %), and only 11 participants had used it previously (36.7 %). We also asked the

Table 5.2: Learning outcome (Between-subjects)

Method	AR	Textbook	Sig. (2-tailed)	Effect size
Results	(M=11.67, SD=6.98)	(M=6.67, SD=5.56)	0.03	r=.39

students about their familiarity with the content: *"Do you know or have you heard about the Periodic Table of Elements?"* Ten students (33.3 %) responded *"yes."*

Learning Outcome: A Shapiro-Wilk's test (p >0.05) and a visual inspection of histograms, normal Q-Q plots, and box plots showed that the difference of post-pretest results was normally distributed for both methods, Textbook and AR approaches, with skewness of 0.412 (SE=0,580) and kurtosis of 0.010 (SE=1.121) for textbook method and skewness of 0.034 (SE=0.580) and kurtosis of 0.047 (SE=1.121) for AR method. Since normality is assumed, we identify the parametric test as the tool for our analysis. To evaluate the differences in the efficiency of learning outcomes, we used the post-test's total score (0 - 25) minus the pre-test score (0 -25).

We evaluated the difference in these results using an independent T-test to compare the learning effect of the participant using the AR method compared to the participants using the textbook method. The experimental group that used the AR app as their method of learning had higher learning outcomes (M=11.67, SD=6.98) than the group that used a Textbook as their method of learning (M=6.67, SD=5.56), resulting in a mean increase (M=5.00, SD=2.306). The difference between means was significant, t (28) = 2.16, (p=0.03) $p < 0.05$, two-tailed. The effect size is r=.39 representing a medium effect (see Table tabA).

We also conducted a repeated measures test (since participants had contact with the learning content before the experience and during the experience) to evaluate the effect of the activity in both groups, using Paired sample statistical analysis. The total score of the pre-test (0 - 25) and the post-test (0-25) was again used. The mean number of post-test (M=13.67, SD=6.68) was higher than the mean for the pre-test (M=4.50, SD=4.01), resulting in a mean increase (M=9.167, SD=6.706). This increase was statistically significant, t (29) = 7.48, $p < 0.001$, two-tailed. The effect size r=0,45 represents a fairly substantial effect. In the specific case of Periodic Fable, constructivism /experiential and situated learning proved to be valid and valuable approaches (PFDbRQ2). The Usability questionnaire was applied only to the participants that used the system, n=15. Usability standards are supported by Cronbach's alpha coefficient report of $\alpha > 0.88$.

The Usability and learnability dimension of the system is very positive (see Table 6). Since some questions were inherently negative (Q2, Q4, Q6, Q8, and Q10), before analyzing the results, we reversed them. Learnability factors (involving questions Q4 and Q10) mean (M=8.66, SD=1.91) imply that the participant's interaction with Periodic Fable

Table 5.3: Usability Results

Q#	Question	Mean	SD
Q1	I think that I would like to use Periodic Fable frequently	5.00	0.000
Q2	I found the system unnecessarily complex	4.40	1.242
Q3	I thought that Periodic Fable was easy to use	4.67	1.047
Q4	I would need the support of a technical person to be able to use this app.	4.27	0.884
Q5	I found the various functions in this app. were well integrated	4.00	1.254
Q6	I thought there was too much inconsistency in this application	4.60	0.828
Q7	I would imagine that most people would learn to use this app. very quickly	4.40	0.910
Q8	I found the system very cumbersome to use	4.53	0.915
Q9	I felt very confident using Periodic Fable	4.60	0.507
Q10	I needed to learn a lot of things before I could get going with using the app.	4.40	1.242

Table 5.4: IMMS measurement data results

		Textbook		AR		
IMMS measurement	n	M	SD	M	SD	t
Attention	15	47.13	3.889	52.53	6.357	$0.063 \geq 0.05$
Relevance	15	35.73	2.987	39.80	4.828	$0.029 \leq 0.05$
Confidence	15	37.13	3.461	41.73	3.751	$0.023 \leq 0.05$
Satisfaction	15	22.67	3.716	27.87	2.503	$0.003 \leq 0.05$

was easy. The Usability factor (Q1, Q2, Q3, Q5, Q6, Q7, Q8, and Q9) means (M=36.20, SD=5.36) showed high acceptance of the system. The average System Usability Scale (SUS) score for our system is 87.1 > 68), which is very positive and considered over average (see Table 5.3).

Again-and-Again table results to the question: Would you like to repeat this activity again? Showed a higher enjoyment among the participants using AR as their method to learn (MD=1.20, SD= 0.41) than the ones using Textbook (M=1.07 SD=0.59)

The overall reliability of the scales on standardized Cronbach alpha was 0.95 (n=30 on 36 items), and the internal consistency for all IMMS scales was 0.75, which suggested good reliability of the IMMS result. The Cronbach's alpha values of the four dimensions were 0.843, relevance 0.857, confidence 0.857, and satisfaction 0.853, respectively.

Results from IMMS displayed higher motivation to learn from the experimental group (that used Periodic Fable) (M=161,93, SD=15,243) in comparison to those that used the traditional method (the textbook) (M=142,666, SD =11,505). Analysis of the four motivation factors underlying user motivation showed that AR-based learning activities fostered higher levels of attention, relevance, confidence, and satisfaction than traditional teaching activities. All the factors (relevance, confidence, and satisfaction), except for attention, showed significant effects when compared to the traditional method (see Table 5.4). We believe that this positive outcome from the Periodic Fable experience results from the capability of the AR system to visualize the learning content in real-world contexts.

Table 5.5: AR correlations data results

		Learning outcome	Engagement	Motivation
Learning outcome	Pearson correlation	1	.634**	.732**
	Sig. (2 -tailed)		.011	.002
	N	15	15	15
Engagement	Pearson correlation	.634 **	1	.767**
	Sig. (2 -tailed)	.011		.001
	N	15	15	15
Motivation	Parson correlation	.732**	.767**	1
	Sig. (2 -tailed)	.002	.001	
	N	15		

Following a constructivism approach, the participants interpret the information through observation and are proactive in the learning experience by performing practical tasks to access the learning content. According to Thomas Malone, these results could also be associated with factors that trigger intrinsic motivation (internal motivation to do something) like a challenge, curiosity, control, and fantasy [204]. Periodic Fable mechanics challenge the participants to find and combine the appropriate elements to create a reaction, use fantasy in the characters with analogies to the elements; users have unrestricted control of the information and decide which elements and areas to visualize, and finally, the use of stories and AR technology can inspire the children curiosity. Unblocking the last facet of the cube to assemble a map and then reach the end of the game could also contribute to extrinsic motivation (a means to reach a goal); however, further research must be conducted to corroborate these statements. We also conducted a correlation test to perceive if there was a relationship between the variables motivation, engagement, and the participant learning outcome performance. Based on the results obtained, there is a significant correlation between the variables in both conditions.

In the group that used the AR application, there was a statistically significant between motivation and learning outcome (r= .732, n=15, p=0.002 <0.05), engagement and learning outcome (r= .634, n=15, p= 0.011 < 0.05) and also the motivation and engagement (r= .767, n=15, p=0.001 < 0.05). In the group that used the textbook, we also found statistically significant between motivation and learning outcome (r= .712, n=15, p=0.003 < 0.05), engagement, and learning outcome (r= .620, n=14, p= 0.014 < 0.05). However, there was no statistical significance between motivation and engagement. In other words, changes in motivation do not reliably predict changes in engagement or vice versa within the sample or population under study, (r= .390, n=15, p= 0,151 > 0.05) (see Table 5.5 and Table 5.6).

Regarding the acceptance of the system – motivation and enjoyment –the qualitative

Table 5.6: Textbook correlations data results

		Learning outcome	Engagement	Motivation
Learning outcome	Pearson correlation	1	.620**	.712**
	Sig. (2 -tailed)		.014	.003
	N	15	15	15
Engagement	Pearson correlation	.620 **	1	.300
	Sig. (2 -tailed)	.014		.003
	N	15	15	15
Motivation	Parson correlation	.712**	.390	1
	Sig. (2 -tailed)	.003	.151	
	N	15	15	15

results from the informal interviews are aligned with the results from the questionnaires in proving that the Periodic Fable is a highly appreciated and engaging system to learn about chemistry domains. The children were excited about almost all the system features. When asked what they liked the most, around 80% answered *"Everything!"*. More articulated participant's answers stressed different aspects of the system: *"The creatures are so cute!"; "To see that when I scanned the image something happened!"; "I like to watch the videos and learn about the elements"; "I like when the creature moves and does stuff"; "I like to put together things and make reactions"; "To view the curiosities and videos."* When asked *"What didn't you like?"*, the majority answered *"Nothing!"*. One participant replied: *"The app keeps closing,"* and another said: *"Sometimes I lost what I was looking at."* We also asked if they thought the app would help them in school and would like to keep using AR in their learning activities. 100% replied *"Yes."* Our last question was, If they could change anything, what would it be? None wanted changes, except for a student who said afterward: *"Perhaps the color of the characters because oxygen is air and so it should be blue."* During the observation, we also gathered comments like *"I just created water, whoa!"; "I want to see oxygen now"; "This is cool!"; "The creature disappeared, oh!"; "I want to touch nitrogen!"*. Their facial expression was also of excitement and satisfaction. While watching the story clips and characters' animations, more than half of the participants were eager to keep visualizing the story of each one of the elements. They rotate the cubes to look for the markers with icons dedicated to that area of exploration and scan them. After viewing the animation clips, the children would look around for their colleagues and smile. We also observed that two participants showed frustration because the rendering of the information took longer (oxygen info). We attribute this to the system not recognizing the markers because of light conditions and the image on the oxygen cube not containing as much detail as others. However, as reported in previous studies [202], technical problems and usability issues can reduce engagement, especially for younger users. In this particular case, the gameplay flow was interrupted, leading to the participants' reactions. One participant also complained that the mobile device was very hot, and sometimes the program application crashed.

Limitations and Future Work

Some limitations of this research were related to the technology, especially the malfunctioning of some markers affected by the light conditions, making it sometimes difficult for the participants to upload the information and creating frustration. This is a significant issue because of the young age of the participants, where frustrations and negative experiences can bias their attitudes towards the subject or the technology in the future. Luckily in our study, only two users among 30 were affected by this issue; nevertheless, consideration should be taken towards this potential problem in the future. Moreover, one user in our study reported the overheating of mobile devices when using AR, and in this instance, it caused the system to crash. This episode highlights how special care and constant supervision of the equipment must be in place during these events. Furthermore, if the system crashes because of the device's overheating, a substitute device should be provided to the user so as not to ruin his/her experience. We believe this work will benefit from future studies with a larger sample group and expand our age gap.

Conclusion

Based on the results presented in this study, it appears that the AR-based edutainment application Periodic Fable might be more effective than the traditional textbook method of teaching chemistry to young first-time learners of the subject. However, further investigation and additional research are needed to confirm and strengthen this claim. Period Fable Discovery promoted students' knowledge of the basic principles of the Periodic Table and fostered motivation toward the instructional material. The results also suggest that AR edutainment can be effective in non-formal learning contexts. We believe that the playful approach to teaching chemistry to young children will help demystify the perception of that subject as difficult and facilitate their learning experience.

We also propose that to establish a positive role of immersive technologies in education and improve their effectiveness, we need to design the scientific content with reasonable pedagogical goals according to the cognitive development and cultural reality of the students, understand the balance between the game elements, and finally evaluate and verify the effectiveness of the tools according to learning goals. Finally, we advocate for further studies investigating AR potential in young children's scientific learning environments, long-term retention, and the novelty effect of the technology. The study highlighted the need for strategies for attendance on non-formal context studies that required more than one session (for example, a week post-test questionnaire). Our research will benefit from testing long-term retention.

This study is part of a publication in the Multimedia Tools and Applications Journal

2023:
Camara Olim, S. M., Nisi,V., & Romão, T. (2023). Periodic Fable Discovery: An Augmented Reality Serious Game to Introduce and Motivate Young Children Towards Chemistry. Multimedia tools and applications, 2023. Included in Appendix C

5.4.2 Study II - Augmented Reality Towards Facilitating Abstract Concept Learning

This study evaluated PF Discovery learning effectiveness according to the AR experience being conducted by participants individually or in pairs.

Research shows that students' performance is affected by different variables of the learning process while engaging in an activity individually or in a collaborative process [196]. Some effects are related to intrinsic motivation (performing an action or behavior because of (enjoying the activity itself), self-efficacy (expectation or belief in the capacity to solve a task), and self-determination (decision to do something). These results have been shown in many AR experiences where the activity is performed individually. Studies also showed a tendency for an active exchange of knowledge while students performed an AR activity [144]. However, limited research is known about the learning efficacy when comparing both methods [207]. The study aimed to assess whether using the AR Serious Game facilitates learning concepts related to the Periodic Table. We also wanted to analyze whether interventions in pairs had higher gains than individual interventions. The result helped to obtain insights with a research focus on AR Serious Games design principles towards facilitating the learning process.

Procedure

We based our study on a Computer Science Club at a public school in Madeira, Escola Básica de Santa Cruz (see Figure 5.16). We engaged 36 participants, 20 females and 16 males aged 8 to 11 years old. The study was designed as in between study, where 18 participants experienced the Periodic Fable in pairs (50%) - Experimental Condition/Group 2, while 18 individually (50%) - Control Condition/Group 1. The study was designed to explore whether the AR game would support learning abstract concepts, such as chemistry basic, in children with no previous exposure to the subject and to explore which interaction conditions (single or pairs) would yield the best learning outcome.

Figure 5.16: Participants' interaction with PF Discovery

The intervention took place on one day, November 27, 2019. On the intervention day, after a short introduction to the activity, the participants were asked to answer a pre-test questionnaire, which included questions like *What happens when you combine one oxygen and two hydrogens? What is the symbol for nitrogen? What formed the ozone? What products have chlorine in them? What are the elements found in diamonds?* After answering the questionnaire, the participants were assigned randomly to one of the two groups, using a digital generator code to avoid bias.

While in the control condition, individual students were seated at their desks and given a set of 5 cubes and a mobile phone to explore the cubes by themselves; in the experimental condition, students sat in pairs and shared the five cubes and the mobile phone. Both groups of participants had to answer individually a post-intervention questionnaire with the same questions as in the pre-intervention questionnaire but posed differently to assess the learning more accurately. Three researchers monitored the participants during the interactions. Observation notes were taken regarding struggles with the application, the points students seemed to enjoy most, confusion with any of the tasks, and emotional reactions. The whole experience, including pre-and post-questionnaires, took 30 minutes. The experiment material consisted of an Android smartphone and five tangible cubes.

Results

Most of the students (32; 88.9%) had access to a mobile device prior to the study, but four (11.1%) did not. 15 participants (41.7 %) had access to a mobile device less than a year ago. 11 participants (30.6 %) had had access to a mobile device for more than a year, 7 (19.4%) had had access to a mobile device for over two years, and only four (8.3%) had no access to a mobile device. Twelve participants (33.3%) knew or had heard about AR technologies, while five (13.9%) had already used AR. Only four students (11.1%) had previous knowledge of the Periodic Table.

The normality of the sample in terms of results was evaluated. Since the values of Skewness and Kurtosis (p= 0.002) showed that the normality assumption was violated, we used a non-parametric test. We used the Wilcoxon signed rank test for analysis within each group, with the game played individually (Control Condition or Group 1) and in pairs (Experimental Condition or Group 2). The results show that the post-intervention learning outcome is significantly higher for participants in the Control condition (Mdn = 2), T= 78, p=0.001, r=0,54 (large effect) as well as in the Experimental Condition (Mdn=1), T=36, p=0.010, r=0.43 (large effect). In sum, the application had a strong, positive effect on learning concepts about the Periodic Table in both groups (see Table 5.7).

We also conducted a between-group analysis – using the Mann-Whitney test – with the same conditions as above. When measuring the children's knowledge before playing the game (Mdn=.00) U= 110.00, p= 0.10, r=-0.31(medium effect), the results show that the difference in learning outcomes between groups was not significant. However, in

Table 5.7: Within Subjects Learning Outcome Results

		Individual intervention	Pair intervention
Within Groups Learning Outcome	Total N	18	18
	Test Statistic	78.000	36.000
	Standard Error	12.124	6.955
	Standardized Test Statistic	3.217	2.588
	Asymptotic Sig. (2-sided test)	.001	.010

the post-intervention test, the children that played individually had significantly higher results than those that did the intervention in pairs (Mdn= 1), U= 98.50, p=0.04, r=-2.09 (medium effect). Contrary to the findings of Martín-SanJosé [207], the individual intervention had higher learning gains than in a collaborative setting. We attribute these results to the fact that the participants that did not share the mobile device had more freedom to explore the tangible cube, controlling the areas that they wanted to visualize, the time dedicated to each area, and could repeat the tasks ad libitum (see Table 5.8).

Table 5.8: Between Subjects Learning Outcome

		Pre test	Pos test
Between Groups Learning Outcome	Total N	36	36
	Man - Whitney U	110.000	98.500
	Wilcoxcon W	281.00	269.500
	Test Statistic	110.000	98.500
	Standard Error	27.842	30.415
	Standardized Test Statistic	-1.881	-2.088c
	Asymptotic Sig. (2-sided test)	.060	.037
	Exact Sig. (2 -sided test)	.104	0.44

We also performed a Whitney U analysis to evaluate if there were any gender differences in the learning outcomes. From the data, we can conclude that gender differences were not statistically significant (U=139, p=.519) (see Table 5.9).

The second measurement, related to enjoyment, was gathered through questions about the participants' intentions to repeat the experience. This measure is based on the knowledge that people like to do fun things again (J. C. Read, 2008). We also analyzed which part of the experience was most enjoyable for the participants by answering *"Yes"*, *"No"*, and *"Maybe"* - 2 questions related to each side of the tangible cube (see Table 5.10).

The users were satisfied with factors about the game's usability, usefulness, ease of use, and learnability (see Table 5.11). Question 6 (Q6) had the lowest score (Mean=4,25). Few children had difficulties when scanning the cube's images/ markers. Kruskal-Walli's test results do not demonstrate any difference in the usability and satisfaction of the activity

Table 5.9: Results of gender difference in the learning outcome

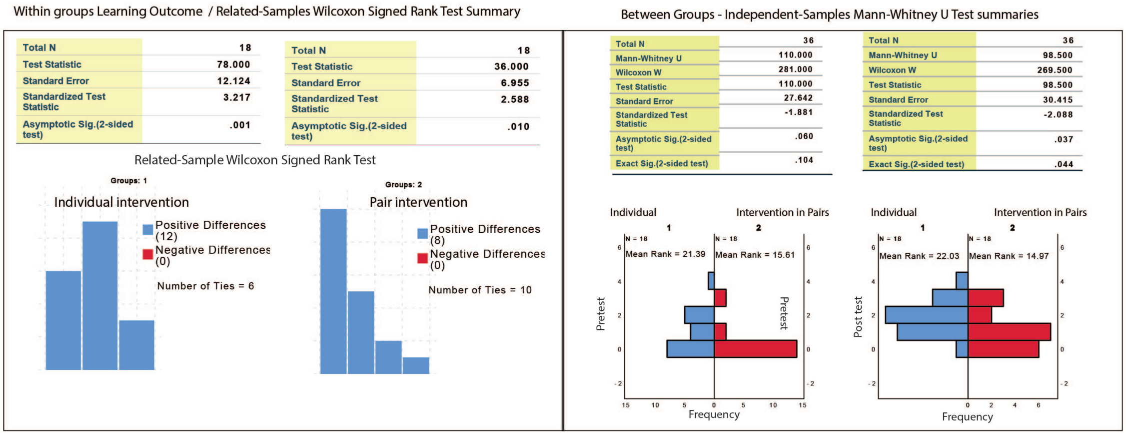

Table 5.10: Again and Again / Engagement scale

Q#	Question	Percentage	Mean / SD
Q1	Do you want to see the animations of the elements/creatures again?	94.4%	1.06/0.232
Q2	Would you like to watch the stories again?	72.2%	1.25/0.500
Q3	Would you like to make more combinations of elements?	86.1%	0.66/ 0.398
Q4	Would you like to see the habitat of the elements again?	86.1.1%	1.08/0.439
Q5	Would you like to see more information about the elements?	80.6%	1.19/0.401
Q6	Did you learn any information from this experience?	88.9 %	1.11/ 0.319

between the group's conditions, $\chi^2(1) = 0.22$, p = 0.15.

Table 5.11: Usability and engagement data results

Q#	Question	Percentage	Mean / SD
Q1	I enjoy using Periodic Fable	88.9%	4,89/0.319
Q2	It was easy to use the application	55.6%	4,39/0.803
Q3	I knew what to do during the game	75%	4,72/ 0.513
Q4	The instructions were easy to follow	61.1%	4,53/0.696
Q5	I always knew what to do during the game	52.8%	4,11/1.214
Q6	The capture of the information with the markers always worked	44.4 %	4,25/ 0.770
Q7	The camera never lost the information of the marker	55.6%	4,29/0.926
Q8	The application always read the correct marker	77.8 %	4,67/0.717
Q9	It was a great experience to play the game	88.9%	4,83/0.561
Q10	I was always performing the same action during the game	58.3%	4,36/0.961
Q11	The amount of information was enough	69.4%	4,58/0.692
Q12	The 3D objects always appeared on my mobile screen	66.7%	4,56/0.695
Q13	There was a tutorial	75%	4,67/ 0.676

Conclusion

In this paper, we have reported on the design and preliminary study of a Periodic Fable AR serious game designed to support children's understanding of abstract concepts such as those found in chemistry. Our study demonstrated that the AR game facilitated the understanding of chemistry and learning abstract concepts in non-formal settings. Further research is needed to categorize its benefits and limitations more clearly and develop guidelines and appropriate tools to address these challenges.

This study was part of a published paper:

Olim, S. C.,& Nisi, V. (2020). Augmented reality towards facilitating abstract concepts learning. In Entertainment Computing, ICEC 2020: 19th IFIP TC 14 International Conference, ICEC 2020, Xi'an, China, November 10–13, 2020, Proceedings 19 (pp. 188-204). Springer International Publishing. Included in Appendix C.

5.4.3 Study III - Periodic Fable Using Tangible Interactions and Augmented Reality to Promote STEM

This study was designed to understand if the multi-level knowledge construction of the game can contribute to facilitating the learning of scientific concepts. The aim was to assess PF Discovery technology, aesthetics, and game mechanics as tools that could change the participant's affects on chemistry.

Procedure

Twenty participants (aged 11 to 13 years old) were recruited through a local public school, Escola Básica do 2º e 3º Ciclo do Caniço (see Figure 5.17). The teachers collected the signed forms (sent two weeks before the study) and communicated the number of participants to the researchers, who prepared all the resources for the study. Demographic data and previous knowledge of the topic and the technology were collected.

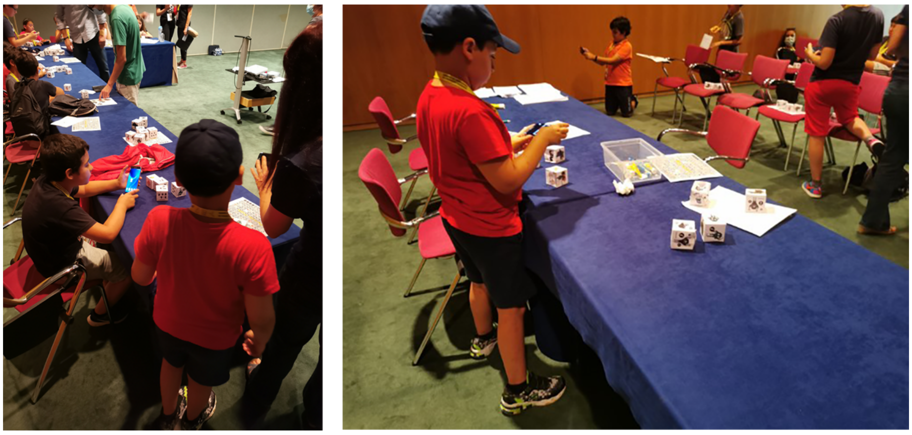

Figure 5.17: Participants' interaction with PF Discovery

The content knowledge test developed by the principal researcher and validated by the teachers attributed a value of "1"for each correct answer and "0"for incorrect - for a total of 10 points. The same questions were used (in a different order to avoid bias) in a post-test conducted after the participants interacted with the game. We used a PANAS scale and added two open questions to measure the participant's affects:

1. Do you think that chemistry could be your favorite school domain? 2. In the future, would you like to study or have a profession in chemistry?

We also conducted an informal interview with each child, with open questions like *"Did you like the game? ", "why?", "What would you change?", "What is your opinion about the game? "*, and took observational notes during the intervention. After verifying the consent forms as per the guardian's authorization to film, we recorded the interaction of the participants with the game. This provides insights we may have missed while taking the observation notes.

Results

The female participants had more experience with AR technology and knowledge about the content (see Figure 5.18).

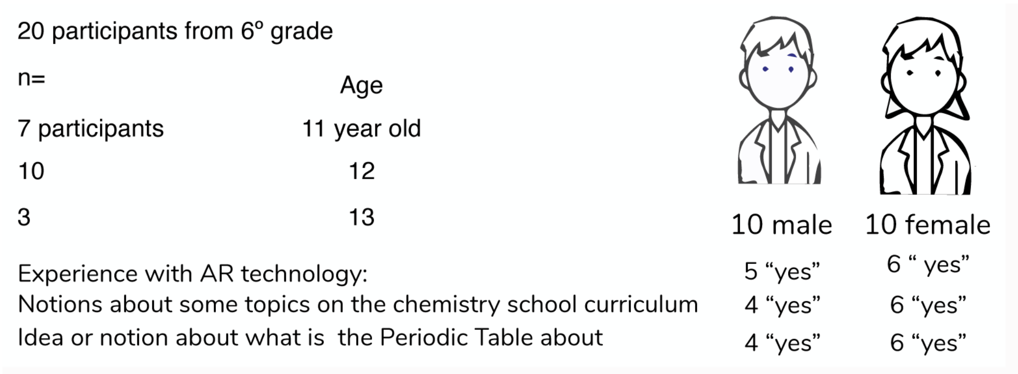

Figure 5.18: Demographics Results

We assessed the normality of the distribution of the learning scores of the participants to find what type of analysis to perform. Our result Sig. p =.593 of the Shapiro-Wilks suggested no violation of the assumption of normality. We used a between-subject parametric independent paired T-test using the post-test and the pre-test results. The learning outcome results after using the PF Discovery game are higher (M=5.80, SD=2.46) than before using the game (M=4.65, SD=2.73). This difference was positive, t(19)=2.42, p=.026, and represents a large effect, r= .48 (see Figure 5.19).

The result of the perception of chemistry after interacting with the game showed a decrease in the negative affects pre-results (M=1.50, SD=0.82) vs post-results (M=0.70, SD=0.73) and an increase in the positive affects pre-results (M =1.10, SD=1.02) vs post-results (M=2.20, SD=1.05) (see Figure 5.20). However, in the answers to the question *"Do*

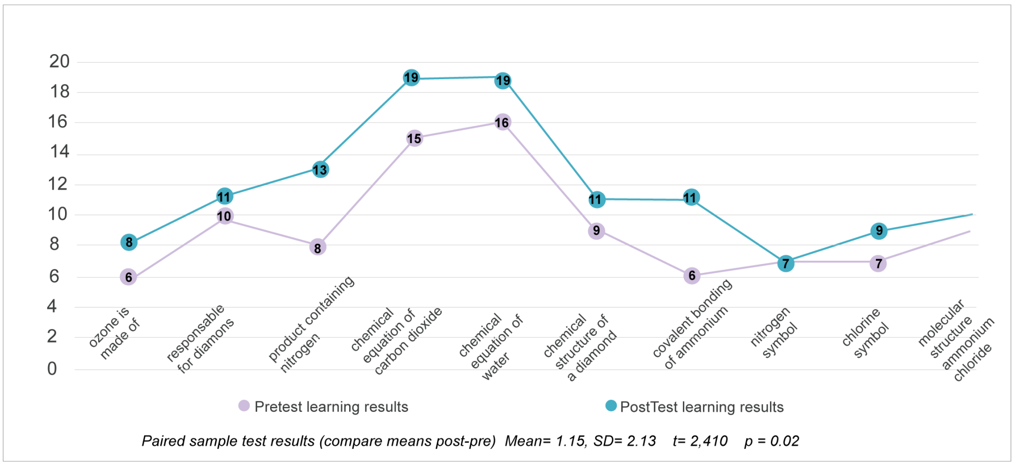

Figure 5.19: Learning Outcome Results

you think that chemistry could be your favorite domain? only six said *"yes"*, two said *"no"*, and 12 said *"maybe"*. Also, their answer to the possibility of having chemistry as a future profession, only five participants said *"yes"*, four said *"no"* and 11 *"maybe"*.

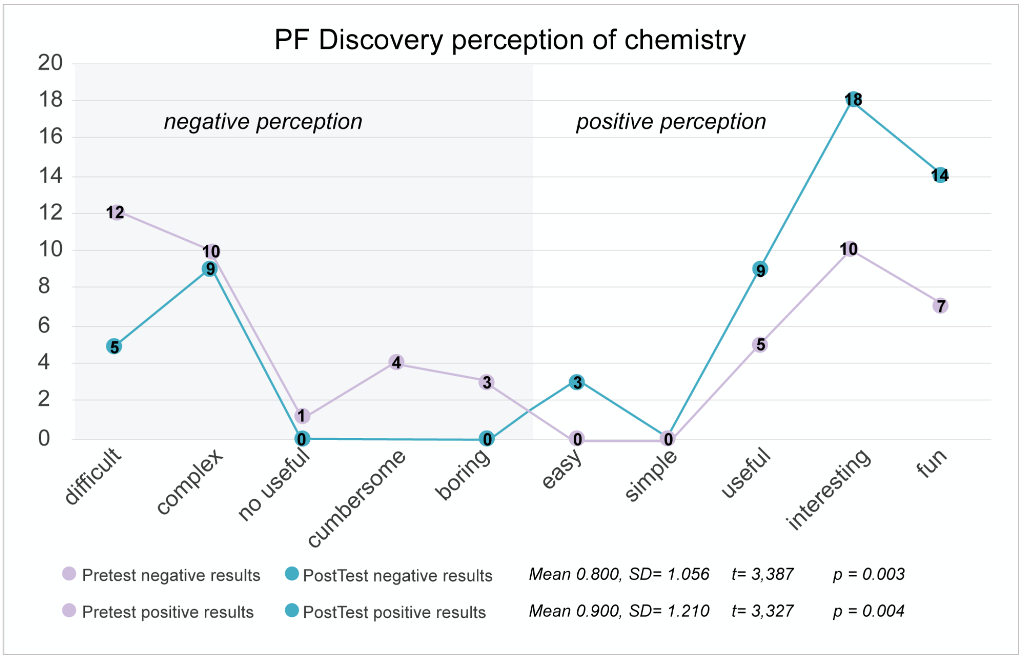

Figure 5.20: Negative and Positive Affects Results

At the beginning of the game, two participants were sitting, but as the game went along, they started to stand up to move around to get closer (by moving the mobile phone) to the characters. The game incentives a cooperative environment. Participants smiled and communicated with other colleagues, giving tips on how they gathered some chemical reactions: *"I bet that Oxygen is going to create air"*, *"Have you seen this?"*. The game shows potential to promote chemistry literacy and symbolic representation by the participant's comments when viewing the information: *"whoa! I just saw Hydrogen waiving at me", "I am only missing Chlorine story," "I just made water!", "Now I have to put together Nitrogen, the "N"and Oxygen, the "O""What am I going to get now?"*. The aesthetics and the animations were appealing to the participants: *"Hydrogen just burped...laugh", "The characters are so cute!"*.

The overall feedback was positive. The satisfaction was apparent *"I liked everything", "I like it, can I download it?"*. The children realized that playing the game could enhance their future chemistry classes: *"I like looking at the molecules... this will prepare me for my future classes", "I think this game is going to be useful for my classes"*. The stories and characters played an important role in engaging the children: *"I enjoy viewing the stories,""I will put shoes on the characters,"and "Oxygen is cool,""I think that the characters and animations were amazing!"*. One participant reported a technical issue during the game: *"I did not like when I scanned oxygen, and the information was not showing up."*

Conclusion

Periodic Fable Discovery's objective is to entertain children while engaging them with the basic of chemistry and the Periodic Table. Using an interdisciplinary approach allowed the unfolding of our design choices from content aesthetics, game mechanics, interaction design, and technology, providing adequate methods for our users. The overall balance between all the game elements to create an entertaining experience while engaging children with STEM subjects worked well. Periodic Fable Discovery aesthetics appeal to our audience by using fun characters and mimicking each element's properties. The display of the characters within the AR tridimensional Periodic Table (columns and rows demonstrating the group and period to which the elements belong) is an innovative framework for allocating the chemical elements within the Periodic Table. The exhibit of compounds containing the game elements created curiosity in our users and instigated them to look for more information. The AR technology allows game elements to foster children's engagement with the scientific subject. The creative process was not limited by AR technology. AR supports different digital formats providing flexibility when adapting content knowledge to children, e.g., using 2D video clips to display short stories about the bonding of the elements, 3D animations to showcase the properties of the elements and 3D AR display of molecular structures.

The manipulation of the cube to gather the information is accessible and stimulating, which incentives the user to engage with the learning process. The quality of the graphic, organization of the information, and language used in the app proved to be adequate for the target group, facilitating the understanding of the information. An active exploration of the cube facets invites a more exploratory approach and becomes easier to learn as it reduces cognitive load.

Finally, the user study's quantitative and qualitative results showcase an opportunity for using similar guideposts to develop apps to engage children with STEM domains and facilitate learning content.

Limitation and Future work

While a tentative was made to include children in the initial design process (10 students), their feedback was mainly directed at the character's color, with no concise opinion. Another feedback was to add more stories to the app, which can create frustration for the children. Also, AR technology can lead to equipment overheating and battery draining.

Despite the enthusiastic results obtained, we want to replicate the study with a larger number of participants to validate our results. We also believe that a longitudinal study to identify the use of these tools in the students' perseverance in science education and its effects on spatial skills development will benefit the research and educational community.

This study is part of a published paper at:
Camara Olim, S. M., Nisi, V., & Rubegni, E. (2023, February). "Periodic Fable Discovery"Using Tangible Interactions and Augmented Reality to Promote STEM Subjects. In Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (pp. 1-15) - (see appendix C).

5.5 PF Discovery Studies Discussion

In the following, we reflect on the results from the studies with PF Discovery, some with similar findings and significant positive effects.

5.5.1 Discussion - Study I

The specific research questions of this study aimed to understand whether Augmented Reality serious games while exploring concepts about the Periodic Table affect learning outcomes and student motivation compared to traditional teaching methods (PFDaRQ1). We also sought to investigate how AR serious games design elements (technology, aesthetics, story, and mechanics) contribute to facilitating the learning process of scientific concepts (PFDbRQ2).

Quantitative and qualitative positive results confirmed that children could benefit from the affordance of Augmented Reality games to explore content in the chemistry domain for the first time. The visualization of 3D information, instead of using the printed information of the textbook, resulted in a more effective method for understanding the content administrated, similar to the findings of P.Maier and Klinker [203]. While the participants that used the textbook had to rely on the mental images and the reading of the material to understand the information, the experimental group transfer of information was facilitated by the visualization of the content using the AR technology, as per Dunleavy et al. findings [90].

Using a participatory design approach towards the use of proper analogies and aesthetics, selecting and validating the information considering the different educational stakeholders were crucial in the effectiveness of the Periodic Fable. Children's learning motivation towards the Periodic Table also showed significant statistical results advocating that AR game-based applications are more likely to motivate the learning activity than a more traditional method. These results are consistent with the results of other studies claiming that AR-based applications promote higher levels of motivation than traditional teaching methods.

We also believe that the higher learning outcome results from the game balance of the elements corroborating Jessy Schell [292] claims, whereby each game element is part of a whole system and supports each other to help the user experience. The game mechanics with a constructivism approach provided freedom and control over the time and type of information the user wanted to explore, allowing a proactive and dynamic learning process.

When scanning the markers and "revealing"the information, the children's comments and attitudes demonstrated that PFD engages, creates interest, and develops children's curiosity toward the content. The use of analogies, fun stories, and links to the children's environment (routine products) also contributed to their continued desire to explore the different areas. The use of simple icons and images to illustrate how to interact with the areas of exploration avoided the employment of extended written instructions, making the user focus on the content and facilitating the gameplay mechanics. The characters' aesthetics and animations were appealing, hankering the children's interest in viewing the elements' representation by rotating the cubes to gather the corresponding marker. The observation confirms their enthusiasm once the stories and other digital information are visualized. There seems to be a compelling reason to argue that an ideal entertainment and learning experience results from the combination of pedagogic (using the collaboration of educational stakeholders) delivered with the support and adequacy of game balance elements (technology, mechanic, aesthetics, and storytelling).

5.5.2 Discussion-Study II

The results of study II reinforce the positive effects of gaming techniques and AR technologies in the engagement and motivation of the students [37].

According to the answers from the questionnaire, the AR visualization of the animated characters/elements introducing themselves to the players was the most enjoyable part of the experience. Hence we can infer that the creatures/elements' captivating characterizations as funny-looking, intriguingly futuristic characters were a successful factor in engaging the children. The participants' reactions show they enjoy combining the elements through the cube facets that triggered the AR scenes. One of the students commented aloud, "I just made water!"and another responded, "I just created a diamond!"According to the data, the 2D animated short stories about the elements were the least captivating part of the experience. Overall, the participants acknowledged learning something new about the Periodic Table. The data also show that the application increased the children's curiosity regarding other chemical elements.

The preliminary study results reported that our game has positive learning outcomes regarding basic Periodic Table concepts in non-formal settings. Our results also show that there is potential in combining smartphones and Augmented Reality in non-formal spaces to facilitate learning content that is not available through the school curriculum. This helps to create intrinsic motivation toward future STEM subjects. Young students who came in contact with chemistry through the Periodic Fable game for the first time could learn while engaging in the activity. However, we need to study further if the engagement and motivation of the users also result from the novelty of the technology. Our student participants were excited about technology because they were part of a Computer Science Club. We need to conduct studies with students from other areas to avoid bias.

Exploring the tangible cube's faces to gather/visualize information was an intuitive and rewarding process. Nevertheless, some technical challenges were identified regarding the ease of use of the Augmented Reality application. Technical problems such as tracking loss made the interaction difficult for some. Since our application depended on image-based tracking, the experience stopped when moving away from the marker. This was frustrating to some children who wanted to view the animations without being interrupted. Other technical limitations when using AR marker-based technology are

- dependency on light quality to read the images/markers;
- delays in the rendering of data;
- over-heating of the equipment;
- battery consumption;
- the need for robust equipment with the required sensors (gyroscope, accelerometer, and compass).

The results of the study enabled us to distill insights that could be beneficial when designing an AR serious game for a young audience:

1. Find the appropriate pedagogical framework for the content to be delivered, AR benefits situated, and constructive methods.
2. Pay attention to the adequacy of aesthetics to the age range.
3. Design analogies and metaphors carefully, ensuring that they support the mental images and the construction of ideas needed to facilitate the understanding of the concept.
4. Balance the amount of information delivered with the usability load to avoid cognitive overload.

5.5.3 Discussion Study III

This study reflects on the design and development of an AR and TI educational game to support children's understanding of abstract concepts in science. This study focused on introducing the content: the properties of the chemical elements, bonding and chemical reactions, molecular structure, and location of the element found in the Periodic Table, using tangible interactions.

As in previous studies, the design choices were guided by a participatory design process including teachers, chemistry specialists, and game experts and evaluated by children. The quantitative results showed significant results in the learning outcome of the participants, increased their positive affects, and decreased their negative affects. These results are supported by the qualitative data, which showcased the children's enthusiasm and engagement with the content.

Overall, we found that the AR technology supports different digital formats providing flexibility when adapting content knowledge to children, allowing the interaction with chemistry content on a symbolic, macro, and micro level, and facilitating chemistry understanding. The display of the reactions/substance using AR animations (macro) while simultaneously showcasing representational information of the chemical equation involved in such reactions (symbolic) helps to create a mental connection between both. At a micro-level, the visualization and interaction with a molecular structure allow for displaying spatial relationships between the elements. Children can view all the elements and their covalent bonding, helping to create a more accurate mental process of this phenomenon compared with a more traditional method of learning, as per previous claims by Üce, Musa, and İlknur Ceyhan [333].

The mechanics of the PF AR system (scanning the markers to get the information) created a feeling of anticipation, promoting the children's curiosity and leading them to gather the information. We believe this is also linked to the aesthetics and animations used to provide the content. The characters/elements and the stories were designed to be appealing and funny to the children while providing learning information through the analogies and narrative plot. According to Jessy Schell, balancing these game elements (aesthetics, story, mechanics, and technology) can enhance the user experience [292]. The mechanics also incites the participants to explore the content and view information related to their real-world (products that contain such elements), promoting a constructivist learning approach. The physical cubes, besides being intuitive and easy to use (grabbing and rotating), provide the children with a stronger sense of direct stimuli and a realistic feeling of the experience by directly interacting with the virtual world.

As previously stated, stakeholders from different areas of knowledge and expertise contribute in different ways. Teachers can help filter the adequate scientific information to showcase according to students' characteristics helping to adapt mechanics, aesthetics, and assets towards the learning goals, convey the proper analogies, and provide methods to reinforce the learning content. Game designers can support usability issues, playability, and balance of game elements. Finally, children's usability evaluation allows us to see their natural interaction with the game's features validating or not our design decisions.

We believe that the symbiosis between learning content, human factors (teachers, designers, and students), and technologies (AR and TI) can affect the rapid development of individual interests in chemistry. AR function appears to be a promising avenue for promoting students' long-term engagement in science. It can also provide a novel interface parallel to the use of tangible physical interaction that stimulates the senses with benefits to the cognitive process of children while engaging and motivating towards more abstract domains.

5.5.4 Summary of Lesson Learned

The results from quantitative and qualitative data gathered through our conducted studies provide essential insights about PF Discovery efficiency according to its usability, learning outcome, affects towards the domain, engagement with the app, benefits, and limitations of the technology.

When comparing AR serious games with a more traditional teaching method, we can conclude that PF Discovery can complement chemistry lessons by providing different levels of understanding. Teachers can use this technology for the visualization of reactions/phenomena at a Micro level (e.g., displaying a 3D AR model of the bonding of atoms and molecular structure, not visible to the naked eye, thus making it harder to understand), simultaneously providing the visualization of the same reactions/phenomena in a symbolic level (providing 2D representation of the formulated chemical equations) and finally consolidating the learning process, by showcasing videos/animations of the created substance/reaction (leading to its understanding at a Macro level). This approach also offers students who are encountering this content for the first time the understanding that there exists a correlation between these understandings instead of fragmented information. It was possible to expand the information into these different levels, since AR can integrate different mediums, such as 2D information, 3D models, animations, and videos, into a single system. This allows designers and developers to be more creative and adapt the content according to specific learning goals without significant constraints. This feature benefits chemistry and other STEM domains that employ diverse approaches to grasp abstract concepts.

Finally, we believe that the visualization and interaction with the AR 3D information also mitigate the occurrence of student misconceptions, which may be harder to detect by teachers through conventional evaluation methods (which often rewards the memorization of information), which is supported by previous research [326, 333]. AR dynamic visualization facilitates the transferring of information into mental models, which through a book (2D diagrams and text), is more complex since it lacks essential data for chemistry like depth.

While PF Discovery provided better results than the traditional method of teaching/learning, the use of a participatory design process with feedback from teachers and chemist specialists was critical towards the use of proper analogies, aesthetics, selecting and validating the information, and exploring pedagogic methods to facilitate the learning process.

PF Discovery manipulation of the Tangible Interfaces to uncover the information gave participants a sense of control and freedom, whereby they could select, view, and in some cases, review the content. The action of rotating the 4 x 4 object, while natural, provides the opportunity for the exploration and "discovery"of the virtual information leading to excitement, fun, and anticipation, boosting preteens' curiosity. Furthermore, according to Zimmerman, this type of activity also can provide the opportunity to develop spatial skills [369].

Simple mechanics avoided the employment of extended written instructions, making the user focus on the content and not on the system per se. We can conclude that PF Discovery gameplay mechanics promote a constructivism learning approach allowing a proactive and dynamic learning process. Study II showed that the participants that engaged individually with the app had better learning outcomes than those that interacted with the app in pairs. In the interaction in pairs, while collaboration was essential, the participants had less time and control to manipulate the cubes and obtain the information, meaning that the constructivism process was less effective. In this note, using the participant's context (routine products) to convey the information facilitates understanding the concepts and makes it more memorable and relevant. Participants can remember the information and perceive that chemistry is not only a subject within the school curriculum but is part of their lives.

To conclude, the motivation and engagement of the participants, according to the results from the qualitative and qualitative studies, were eminent. Study I corroborates this by the significant positive results of correlated data between the Learning outcome, Engagement, and Motivation. Participants showcased engagement with the app in all the studies, resulting in significant positive results in the learning outcome, engagement, and affects on chemistry. We attribute these results to the use of the balance of game elements, pedagogic, and iterations according to the game dynamics (see Periodic Fable Game Design Framework Approach 2.7). The characters/elements and the stories were perceived as appealing and funny to the children while providing learning information through the analogies and narrative plot. The participants' reactions show they enjoyed combining the elements through the cube facets that triggered the AR scenes. Besides helping to guide the users through the game and providing feedback, the gamification elements promoted the user's sense of self-efficacy, competence, and satisfaction when finishing each task.

As per the reported results of study III, we believe that the symbiosis between learning content, human factors (teachers, designers, and students), and technologies (AR and TI) can affect the rapid development of individual interest and long-term engagement with chemistry. It provides a novel interface parallel to the use of tangible physical interaction that stimulates the senses with benefits to the cognitive process of children while engaging and motivating towards more abstract domains.

Chapter 6

PF an Augmented Journey

In this chapter, we describe PF An Augmented Journey interaction design and development process according to its gameplay mechanics, storytelling attributes, and pedagogical methods.

The second game, originally intended as a continuation of PF Discovery, can be played as a standalone experience. Periodic Fable An Augmented Journey is an adventure game with an expository and consolidating approach (closer to a traditional pedagogical method). In the game, the educational content is introduced at the start, followed by a narrative-driven progression that leads the player to use this knowledge (consolidation) on tasks (aligned with specific learning objectives) to complete the game successfully.

Like previous work by Ferraz et al. (2021), we intended to use storytelling as a pedagogical method to foster students' interest in chemistry [109]. Prior research demonstrated that children could immerse in a narrative, leading to raise interest and change in attitudes towards the learning of sciences [197]. Furthermore, if the child is emotionally engaged with a fictional world and character, their interaction with the content is more memorable and easier to remember [195]. Following this assumption, PF an Augmented Journey exploits a fictional world (a tri-dimensional map) (see Figure 6.1) and character design (see Figure 4.7-4.8), promoting the full involvement of the child in the activities, and providing the sense of being part of the narrative (immersion). Exploring the 3D AR world, besides promoting the interaction between the real world and digital information, simultaneously provides a physical activity linked to conceptual understanding of the educational content, helping with its visuospatial comprehension [297]. Furthermore, the use of 3D AR technology affords participants' immersions simultaneously in both the real world and virtual information.

Storytelling reminds an important teaching and learning tool when adapted meaningfully to a school topic, leading to reflection, critical thinking, and a deeper understanding.

Figure 6.1: Players can navigate the entire three-dimensional map by successfully overcoming obstacles, unlocking the subsequent module of the map, and the next task.

By incorporating motives or incentives within the narrative structure, children are more likely to engage actively and willingly in learning. PF storyline uses an altruistic approach, where the children are presented with the opportunity to help solve a problem (fix the spacecraft to help the characters go back to their planet) while acquiring content knowledge (see Figure 6.2).

The gameplay is also designed for the players to communicate with characters through textual input and output to gather the information that helps them to complete the task. The communication with the characters permits an emotional connection with the players as they learn about the sustainability of the elements. This is supported by Sherry Ruan's insights, where character bonding was associated with engagement and interest in the learning domain [276] (see Figure 6.3).

The gameplay was designed to promote the children's problem-solving skills by applying information about the bonding of the elements to overcome some challenges (obstacles). For example, if an empty lake stops the game character, the player must select water as the correct compound to overcome the obstacle. Once selected, the player can see oxygen and hydrogen atoms joining and transforming into water. The chemical equation of the water is also showcased while the combination of the atoms is happening. This approach follows Johnston's theory of multi-level knowledge construction process [160]. As such, the game provides the visualization of the molecular structures used in the reactions selected to overcome the obstacle (micro), shows its symbolic representation, and finally, provides an animation of the created compound/reaction (macro) (see

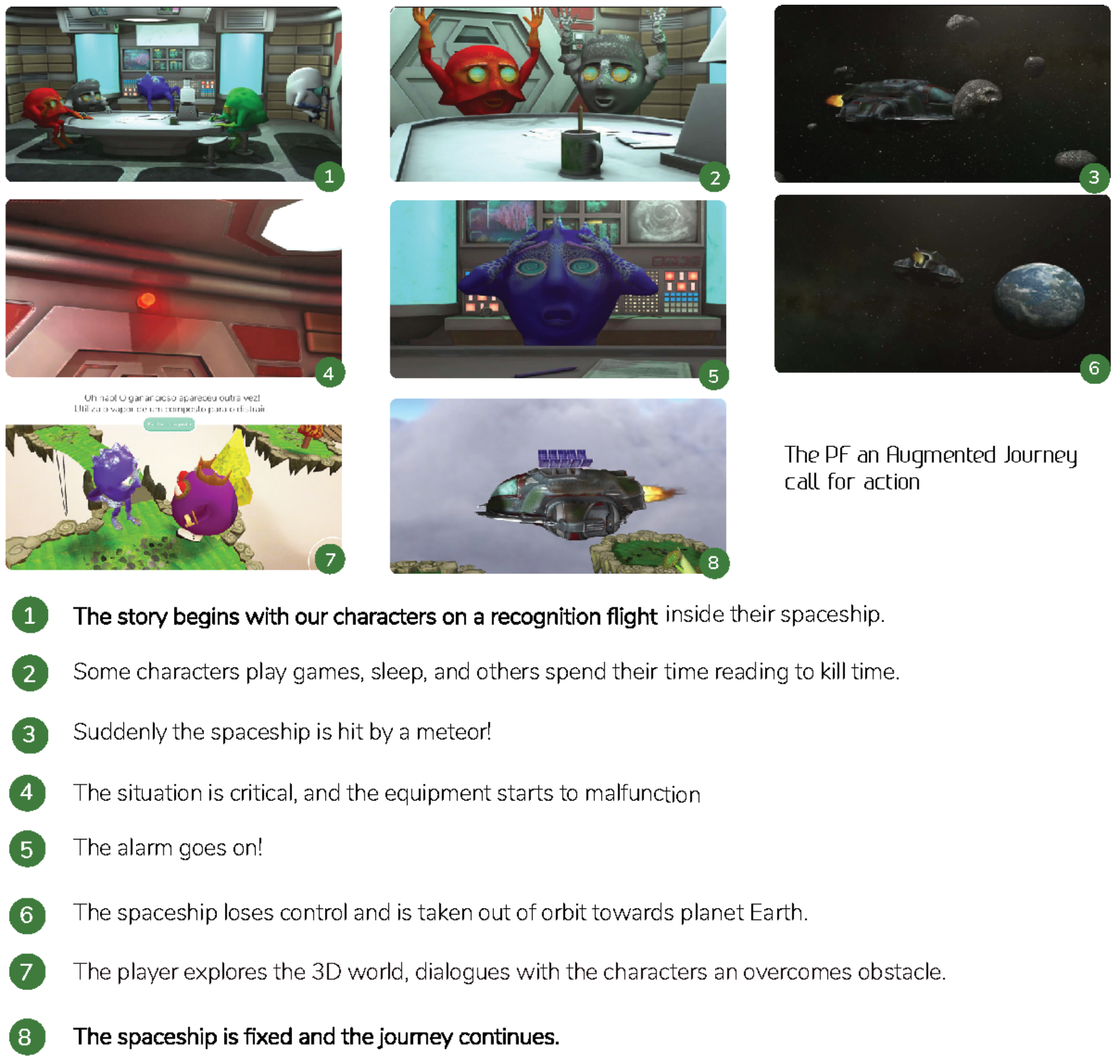

Figure 6.2: Narrative Development of PF an Augmented Journey

Figure 6.3: Player dialogue with characters learning why these elements are in danger of depletion

Figure 6.4). As in traditional teaching methods, the repetition of this activity promotes the consolidation of the acquired knowledge.

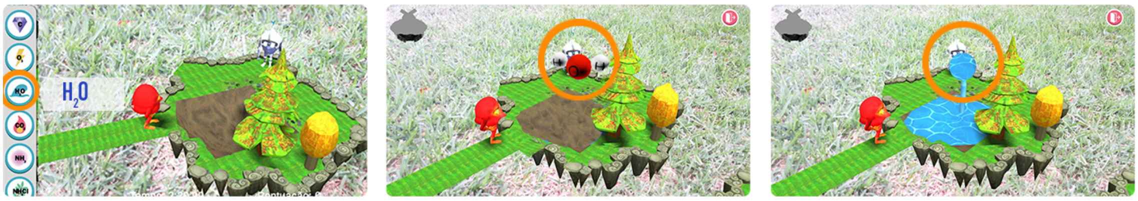

Figure 6.4: Multi-Level Understanding from left to right: Symbolic, Micro and Macro

6.1 PF An Augmented Journey Game Mechanics

As said before, PF and Augmented Journey is deployed in favor of the narrative as a medium to provide the content knowledge. The game starts with displaying the story plot through an animation showing the characters/elements (Oxygen, Hydrogen, Chlorine, Nitrogen, or Carbon) together on a space trip.

- After being hit by a comet, their spacecraft is taken out of orbit and crashes into our world (see Figure 6.5, number 1).
- The player can select their main character (see Figure 6.5, number 2)
- A short animation shows the composition of some compounds/reactions needed later in the game to overcome some barriers (see Figure 6.5, number 3).
- The tutorial then asks the player to use the device camera to scan and recognize a pattern in the surrounding real world to anchor the tri-dimensional AR world 6.5, number 4).
- The player is asked for action - helping to find the aircraft pieces (see Figure 6.5, number 5).
- Using a digital joystick, the player navigates the AR world, reaching some barriers that must be overcome by selecting the appropriate chemical compound or reaction (see Figure 6.5, number 6).
- If the player selects the appropriate compound/reaction, an animation is displayed. Also, a 3D AR model of the molecular structure is revealed (see Figure 6.5, numbers 7 and 8), and the obstacle is vanquished. A message, *"please try again!"* and sound feedback indicates the answer is wrong.
- Throughout the game, the player also meets other elements (Helium, Zinc, Arsenic, Platinum, and Silver) and receives information on why they are almost depleted or in critical danger (see Figure 6.5, number 9).

- As the player overcomes obstacles and interacts with other characters, he/she gathers content knowledge and a reward (parts of the spacecraft) (see Figure 6.5, number 10).

- The game ends once the player has explored the entire 3D world and gathered enough pieces to fix the spaceship. A congratulatory message is then displayed, and the player can obtain a final reward-Selfie with the characters (see Figure 6.5, number 11). We also provide a detailed description of the gameplay in appendix C, IDC publication page 3.

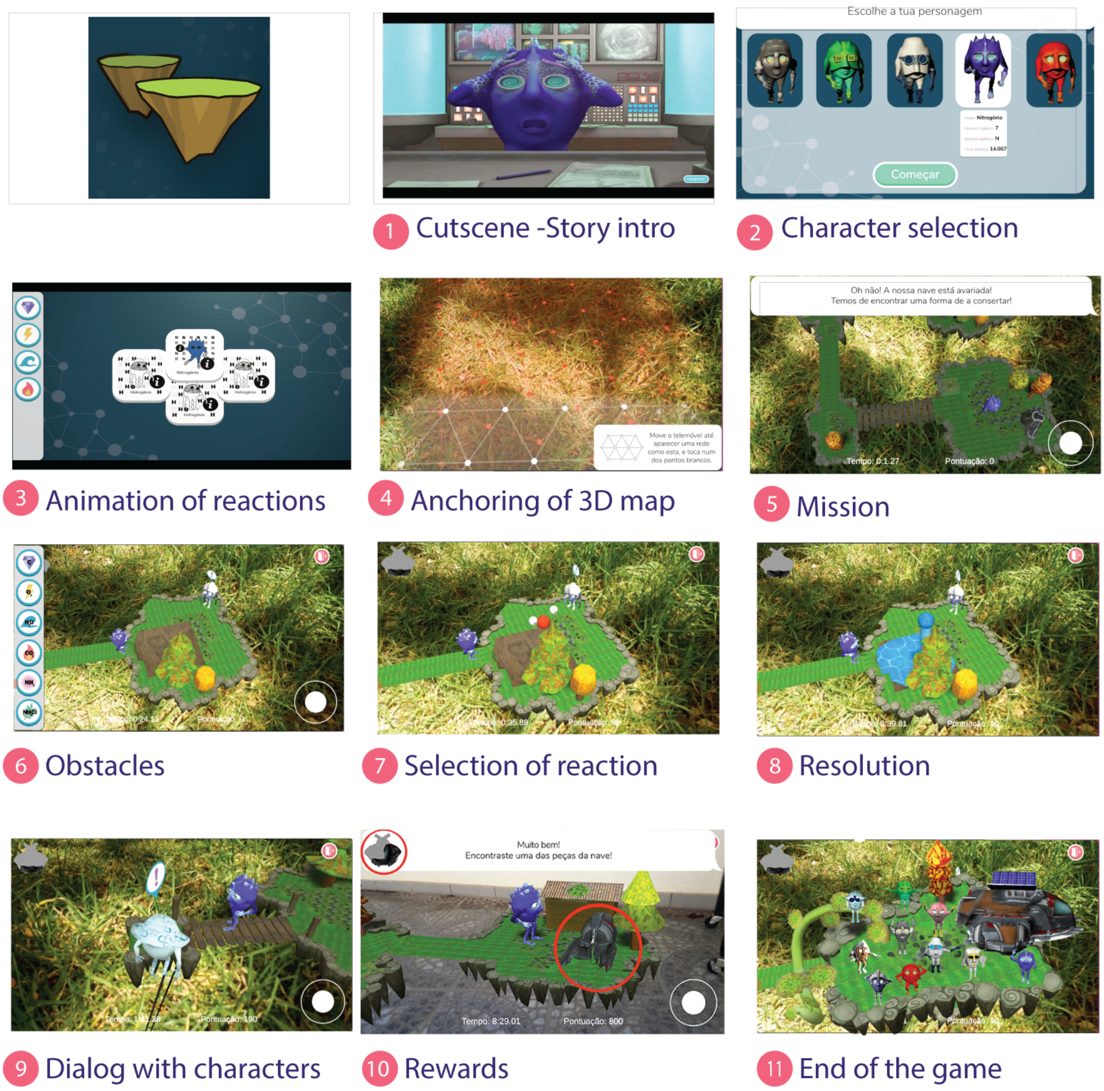

Figure 6.5: The PF an Augmented Journey Game Mechanics

6.2 PF an Augmented Journey Game Playtest and Iterations

This section described the first exploration assessment of PF An Augmented Journey and posterior iterations according to the feedback and results.

6.2.1 PF an Augmented Journey Pilot Test

Using the same sample group, we conducted a pilot study for PF and Augmented Journey and PF in the Wild. In the following, we present initial findings regarding the children's acceptance and satisfaction of PF An Augmented Journey usability, engagement, and overall feedback from our target audience. Although the overall assessment showed positive results in AR's entertainment value and usability, a preliminary pilot test (N=7) using a mix-method approach identified the need for minor gameplay interventions.

Procedure

Our seven participants, three females and four males aged 11 to 13, were recruited through opportunistic sampling (see Figure 6.6). Children were asked about their interest in participating, and their parents/guardians were contacted and informed of the study. Then the children and their parents were informed of the protocol and purpose of the research.

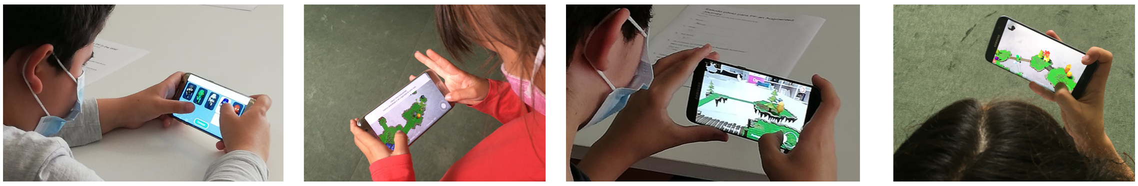

Figure 6.6: Participants PF an Augmented Journey game interaction

The participants attended different public schools, and only three students had some previous knowledge of the content. The study took place at ITI - Interactive Technology Institute installations, and it took about one hour for each child to evaluate both games. The study began with a short explanation of the purpose and followed the same protocol for both games: 1. A demographic survey with questions regarding age, gender, and grade level. We also included questions about previous knowledge of the Periodic Table and AR technology; 2. Each participant received a mobile device (Samsung S7 edge smartphone) with installed games; 3. The first game was Periodic Fable and Augmented Journey. While the participants played, two researchers observed and took notes regarding struggles, doubts, expressions, and comments; 4. Finally, we applied post-test questionnaires and interviewed the participants.

We used a PANAS C test [350], a shortened version of the PANAS (Positive and Negative Affects Scale) adapted for children (20 items), to evaluate the entertainment value and the affects of the Apps on the participants. According to Watson et al., Positive

Table 6.1: Usability and satisfaction assessment results from PF an Augmented Journey

Q#	Question	Mean	SD
Q1	I would like to play PF an Augmented Journey again	5.00	0.000
Q2	I would recommend the game to friends and family	4.86	0.378
Q3	I thought that PF an Augmented Journey was easy to use	4.86	0.488
Q4	I think that the game is fun to play	5.00	0.000
Q5	I found that the various functions in the game were well integrated	3.71	0.756
Q6	I found the game useful	5.00	0.00
Q7	I would imagine that most people would learn to use this game very quickly	4.57	0.757
Q8	I felt very confident using PF an Augmented Journey	4.29	0.756

Affects (PA) represent the extent to which an individual experiences pleasurable engagement with the environment. A high PA score indicates emotion, such as enthusiasm and alertness. In contrast, a low PA score characterizes emotions such as lethargy or sadness.

The Post-test questionnaires included a usability and satisfaction assessment using a Likert scale with a smileyometer [259] of five levels - "1"for totally disagree and "5"for totally agree (see Table 1). The interview questionnaire also evaluated participant satisfaction and allowed us to gather suggestions from our target users. Questions like: *What did you like the most? What didn't you like? If you had to change anything, what would it be? Did you find the game useful? Why? What did you learn?* This information was also crucial for our games' continuing evaluation and iteration.

Evaluation, Results, and Reflections

Regarding the technology, five of the seven users had previous knowledge or had used augmented reality applications before. Three participants, the oldest of our sample group, had knowledge of the Periodic Table content.

While experiencing PF an Augmented Journey, our users had higher Positive affect scores with Mean Scores (M=18,57; SD= 3.04) than Negative affect Mean Scores (M=6.28; SD= 0.95). These results show that the participants were engaged with the game. The results obtained in Q1, Q2, and Q4 (see Table 6.1), where the players reported high means of engagement, also confirm this.

In addition, the participants reported during the interview that the most enjoyable part of the game was exploring the 3D world environment through the knowledge acquired about using chemical reactions/compounds to overcome obstacles. Children lamented the lack of interaction with some characters representing the "almost depleted chemical elements."Participants said *"I want to interact more with these characters"*, and *"I did not feel they were doing anything in the game"*. When we asked our participants how to improve the game, their answers reflected previous statements: *"make the endangered* *elements/characters more interactive and more expressive"*. Upon these comments, the researchers noticed that their facial expressions and movements were almost unnoticeable since the characters were displayed on top of the large virtual world. While this reveals a design flaw that can be corrected, on the other hand, these comments highlight the engagement and empathy of the children with the characters and their struggles, pointing at the potential of characters' persuasion and narrative immersion in delivering important messages through such games. While this has been investigated in media and communication studies [222], further investigations could target the specifics of serious games and AR games.

The players considered the game easy to play and useful (Q3 and Q6), and it allowed them to learn about chemical reactions/compounds: *"I think this is good for learning, and I need to use the right compound to keep going"; "I like learning like this, it is not boring"*. Moreover, the children recalled specific scientific information *"I learned that ammonia at room temperature is a gas"; "Water is created with oxygen and hydrogen"; "Carbon is on a diamond"; "I learned the symbols of the chemical elements"*. Although we need to undertake additional studies to test the learning effectiveness of the app, these answers confirm the potential of the technology for learning. From the observation notes, it emerged that several participants struggled to start the game. It was noted that the digital graphic joystick implemented to move characters through the 3D environment was not intuitive or easy to use. Improvements in terms of simplification of usability and instructions are needed.

In sum, this pilot evaluation confirms the value of PF in the learning of Chemistry and fostering of spatial reasoning while pointing at some flaws and improvements. All users engaged and enjoyed both games, with PF An Augmented Journey being more exciting than PF in the Wild (evaluated simultaneously with results provided in Chapter 8). We can infer that refinements on fixing the graphic Joystick of PF Augmented journey can improve its usability. The use of AR in dialogues with the character can be overlooked, losing its impact. Close up of the character while expressing emotions is needed to create empathy.

6.2.2 PF An Augmented Journey Design Iterations

While AR can enhance the child's experience by allowing the visualization of real objects within the real world, it may not be the most effective tool for generating empathy in a scenario with dialogues. The players reported the need to have a close-up view of the character's expressions and other detail, and being distracted by the background (real-world) made it hard to follow the dialogue and feel an emotional connection (see Figure6.7).

The joystick design was improved by augmenting the size and providing visual feedback at the beginning of the game on how to move (left, right, up, and down). Some bugs were also fixed, and the game was optimized.

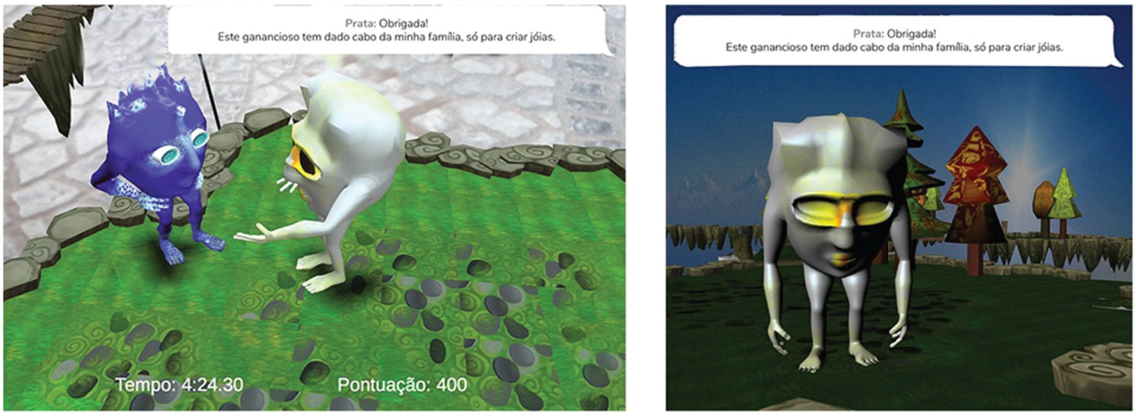

Figure 6.7: The use of AR (right) was substituted by uploading video animations (left) after reaching the characters to create an emotional connection with them and the topic that was being presented, the sustainability of the chemical elements.

6.3 PF An Augmented Journey Game Evaluation

After the exploratory study and game iterations, we used the high-fidelity game prototype to continue our research.

6.3.1 Periodic Fable Augmenting Chemistry with Technology, Character, and Storytelling

In this study, we address the use of game elements within AR Serious Games, focusing on character design and storytelling to promote interest in Chemistry. We assessed the role of storytelling through levels of narrative transportation as a mechanism that can improve preteen perception and learning outcomes of chemistry.

Procedure

On the day of the study, the leading researcher presented a small debrief about the activity and study process. The 21 young participants, five females and 16 males, were divided into two groups (10 and 11 participants) for ease of logistics. Half of the students stayed in the classroom with their school teacher. In contrast, the other half moved to the school library, where the other two researchers had previously prepared the game's mobile devices and the study's equipment (recording cameras). A mobile phone (Samsung S7 Edge) with the game installed was provided to each participant, who was asked to follow the game instructions. The participants were given 15 minutes to interact with the game (the time necessary to beat the game) while all the researchers took observation notes. The session was also recorded. After all the participants finished the game, they were guided to the classroom and asked to complete several questionnaires. The remaining participants were asked to move to the library and follow the same procedure. These questionnaires gather data again about the participants' perception of chemistry as a subject and content knowledge about the Periodic Table.

The children were also asked to compile a narrative transportation scale measurement, to investigate the potential and effects of storytelling in this context. While previous research has been conducted using the narrative transportation scale by Green and Brock, 2000 [132] to analyze the effect of stories as a medium to influence attitudes, beliefs, and behavior [9], it is mainly applied to films or in the written context of a book; however, it is a novel approach when applied to a serious game narrative. We believe it is crucial to quantify the participants' immersion and cognitive and emotional empathy with the characters as a part of the game elements that contribute to the overall engagement of the users. For this reason, we conducted qualitative and exploratory research to identify the dimensions of narrative transportation (loss of the notion of reality and time, projection in the narrative universe, or development of mental imagery and identification with the character).

We created the following research question to guide our research:

PFJaRQ1: Can AR serious games change students' perception of Chemistry?

PFJbRQ2: How to design AR serious games balancing mechanics, technology, story, and aesthetics to provide content knowledge to children about the Periodic Table effectively?

PFJcRQ3: Can character and storytelling engage students with Chemistry while facilitating the learning process?

Results

Participants were familiar with Chemistry as a domain. Quantitative and open questions answers reflected that even though Chemistry is a subject only introduced in the 7th grade, students already have an overall perception of this area (see Figure 6.8). However, regarding the Periodic Table topic, only 12 of the participants had some knowledge about it. Some of the participant's answers were: *"I learn about chemical equations,""We do lab experiences,""We learn how to mix two or more elements,""Learn about substances, energy, and other things,""We learn about the Periodic Table"*.

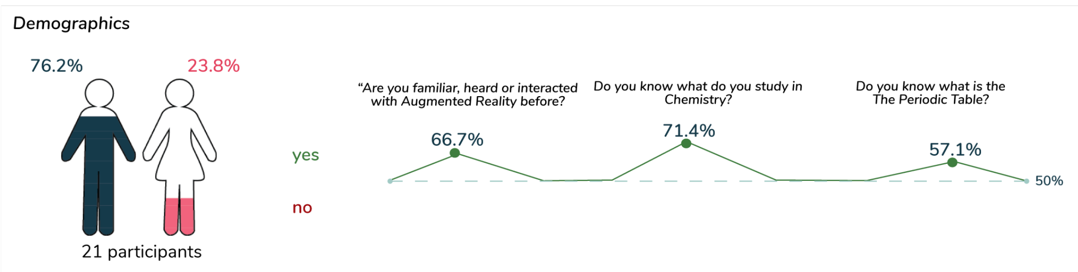

Figure 6.8: Demographics Result

Multiple choice pre-intervention (before using PF an Augmented Journey) and post-intervention (after using PF an Augmented Journey) questionnaire with a negative and positive perception of chemistry. Compared results from Pre-intervention and Post-intervention about the participants' perception of Chemistry exposed a decrease in the negative perception and an increase in the positive perceptions of the participants (see Figure 6.9).

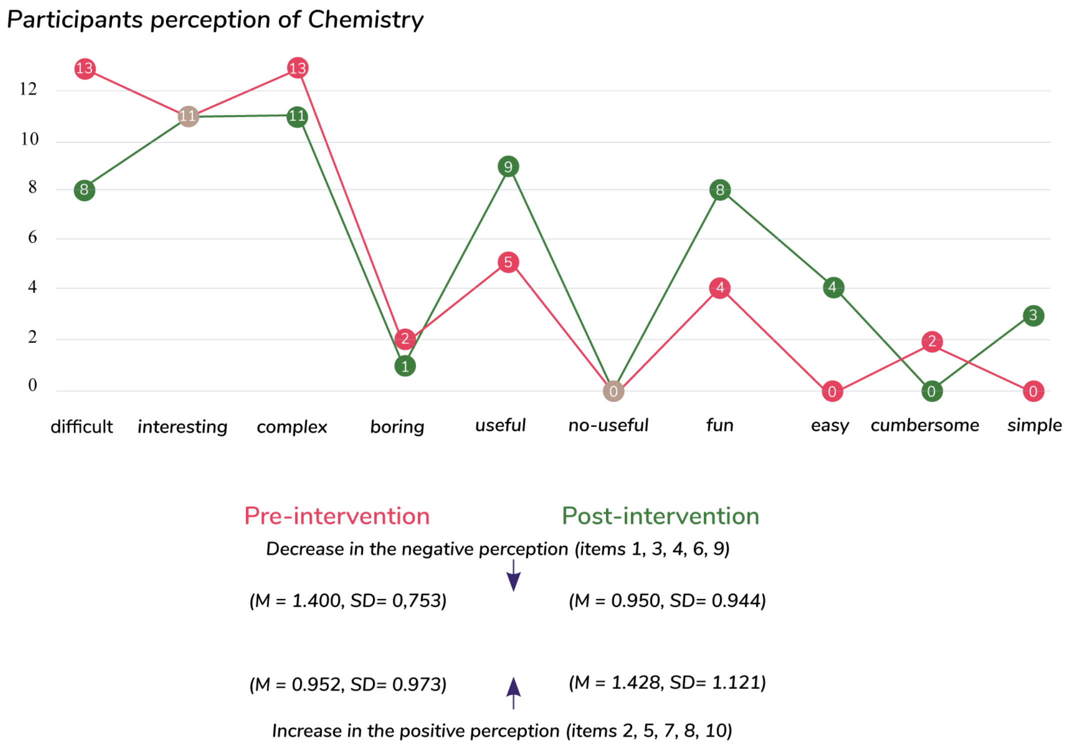

Figure 6.9: Participants Perception of Chemistry Results

The assessment of the normality of the distribution from learning outcomes, Shapiro-Wilk test Sig. p <.093 suggested a non-violation of the assumption of normality. A Paired-samples t-test revealed a statistically significant difference between the Post-intervention and Pre-intervention scores, with mean scores of 1.04 and 95% confidence interval ranging from .045 to 2.04. The eta squared (η2p) statistic (.19) indicated a large effect size. These optimistic results showcased the game's potential to facilitate the learning process in the context of chemistry (see Figure 6.10).

The Narrative Transportation Scale had good internal consistency, with a Cronbach alpha coefficient reported of η =0.93. According to Elodie Jarrier et al.[18] , the transportation scale identifies various factors. The first factor reflects the participant's experience of becoming the character and having an emotional empathic reaction (first six questions). The second factor (question 7) is the emotional involvement in the story. Finally, the third factor is the imaginative facet which covers the imagination produced by the story (4 last

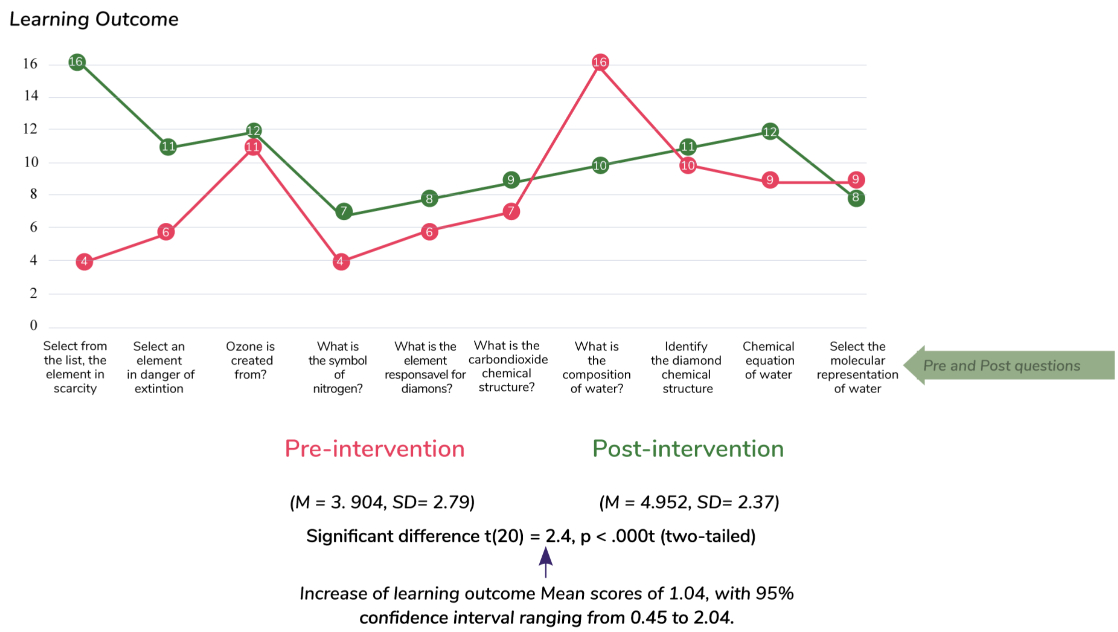

Figure 6.10: Participants Learning Outcome Results

questions). In our results, the highest scores were obtained in the first factor (mdn= 4), then the mental imagery (mdn=3), and finally emotion with the lowest score (mdn=2) (see Figure 6.11).

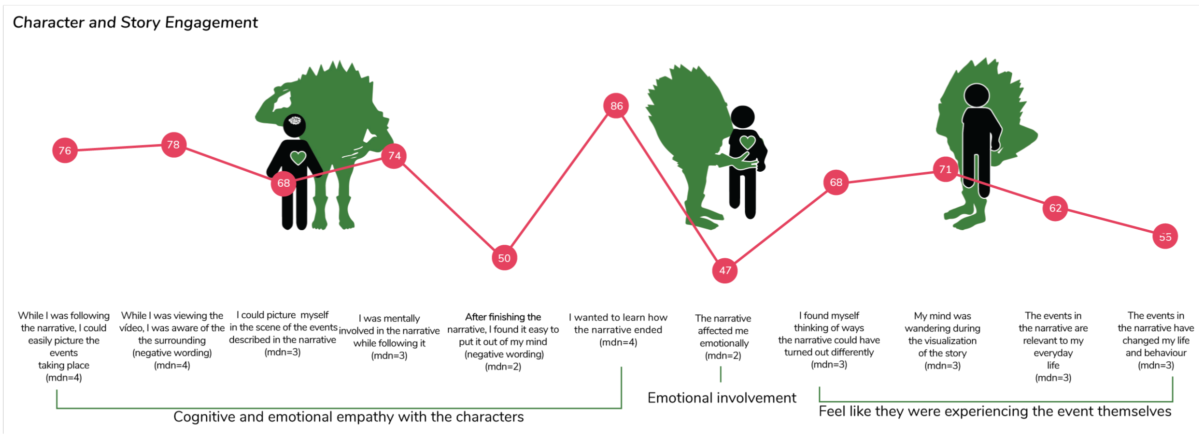

Figure 6.11: Narrative Transportation Scale (TS) Results

The evaluation of the system helps to understand how technology, game mechanics, aesthetics and story (character and narrative), and pedagogics can provide interactive ways to foster children's interest in chemistry and the potential for their career path. Our findings suggest that children's engagement with the system positively affected the learning process of the content knowledge; however, despite our positive results, our small sample group limited our study. This research will benefit from future studies with a larger number of participants to validate our findings in formal and non-formal settings. The design of educational serious games is a complex process that includes designers, game developers, and pedagogical experts that must be able to efficiently communicate to produce a product that is both educationally efficient and fun to play.

This study is part of a published paper:

Câmara Olim, S. M., Nisi, V., & Rubegni, E. (2022, June). Periodic Fable Augmenting Chemistry with Technology, Characters, and Storytelling. In IDC – Interaction Design and Children (pp. 123-136). Included in Appendix C

6.4 PF An Augmented Journey Study Discussion

The PF An Augmented Journey is designed to facilitate better learning acquisition through gaming and storytelling. The results of our study showcased the potential of PF as a tool that can engage and help understand concepts in the context of Chemistry. Regarding our PFJbRQ2, there were significant learning outcomes, indicating that the interaction with the game elements facilitated the acquisition of knowledge about the Periodic Table. We believe that these results positively reflected some of our design and development goals and design choices, which can be summarized in:

Designing the game mechanics to implement specific pedagogical approaches can optimize the learning experience. The gameplay mechanic must be designed according to the most suitable method for the learning goal. PF, by allowing virtual objects' superimposition on the real world, AR facilitates children's understanding of complex and abstract concepts through spatial reasoning by making them visible and allowing for multidimensional perspectives. The participants could visualize 3D AR atoms bonding in different perspectives by moving around the physical space, contributing to their notion of molecular structure. The use of AR also allowed for the movement of the participants in a real-world, making the space part of the gameplay, increasing the children's immersion support [85]. However, AR was not the best technology to showcase dialogue with endangers elements because of its scalability. The participants wanted a close-up of the character's expressions and movements while acquiring the information.

The cognitive and emotional empathy with characters incites problem-solving skills while acquiring scientific content knowledge. Experiencing emotions through characters engages the child and maintains his/her desire to reach the game's final goal. PF supports the players' identity transfer into the game world to form a bond with the virtual identity, promoting the desire to explore (3D environment and other characters) to discover a solution (gathering pieces of the spaceship) and reach the final goal (help the character reach their planet). This supports Schloss, I. et al. claims about the potential of character embodiment as a tool to promote exploration and discovery in science learning [293].

AR's playful experiences also positively affected the student's motivation and attitudes toward the sciences. After interacting with the game, the participants' positive perception of chemistry increased, while the negative decreased, showcasing that PF can help improve students' attitudes toward scientific domains (answer to PFJaRQ1). Designing visual storytelling, plot development, and characters is critical when developing an educational game. PF exploits visual storytelling and gaming balance elements to foster players' immersion (full involvement in the activity and the sense of being part of the narrative).

The Narrative Transportation scale can provide insights toward identifying the user's immersion in an interactive AR story. As per our results, Periodic Fable ignites both narrative-induced imaginative immersion, "character immersion,"and "narrative immersion"(PFJcRQ3). PF calls for a strong connection with the learning content by immersing the player in the character and the story. It is also possible that the fantasy world created by the narrative offered a more friendly learning environment and a mechanism for learner-character bonding, which aligns with prior work by Sherry Ruan et al. [276]. These results are also supported by Steen, F., & Owens, S., who stated that the more immersed children are in a game, the more they invest and the more educational potential the game can harness [318].

6.5 PF An Augmented Journey Summary of Lessons Learned

The evaluation and analysis of PF an Augmented Journey according to its usability, learning outcomes, engagement, affects on chemistry, and the effects of game elements, including pedagogic, help us to distill some insights about the effectiveness of using AR serious games towards facilitating the teaching/learning of concepts about the Periodic Table:

- Following previous claims about the use of storytelling to promote student interest in chemistry (received increasing attention)[109], PF narrative flow is a valuable pedagogical method. Using a storyline with an altruistic approach, where the children were presented with the opportunity to help solve a problem (fix the spacecraft to help the characters return to their planet) while acquiring content knowledge, seems effective. Participants attitudes and comments demonstrated a connection between the characters (character immersion) and narrative immersion with the AR experience. This connection led the participants to focus on the tasks, which evolved around the learning content, to finalize the game and bring closure to the story narrative.

- As Shelton and Hedley's research [297], PF an Augmented Journey promotes the interaction between the real world and digital information simultaneously (moving around the real space to explore the 3D AR map), providing a physical activity that is linked to conceptual understanding of the Periodic Table, helping with its visuospatial comprehension. Furthermore, the use of AR also allowed for the movement of the participants in a real-world, making the space part of the gameplay, increasing the children's immersion support [85]. The micro, macro, and symbolic representation is also provided in the dynamic visualizing of 3D AR atoms bonding (in different perspectives by moving around the physical space), making the connection between content and context and the acquisition of knowledge memorable.

- In the context of augmented reality (AR), character immersion can be achieved. However, designers must consider whether the interaction with characters requires a closer approach to convey emotions or obtain information through dialogues effectively. In our initial attempt, we failed to adequately address the characters' expressions and movements and maintain the participant's focus in this interaction. This resulted in a lack of empathy and overlooking the dialogue messages within the overall environment.

- The use of similar actions throughout the game (chemical reaction to overcome obstacles) also contributes to learning. The decreased complexity and need for skill acquisition of game mechanics help participants to focus on learning content.

- Finally, like in the case of PF Discovery, AR playful experiences also positively affected the student's motivation and attitudes towards chemistry. Using character and storytelling balance with AR technology and pedagogic (within the gameplay mechanics) incited students to continually engage with the educational content, thus full filling the learning goals thus gathering positive learning outcomes.

Chapter 7

PF in the Wild

This chapter describes PF in the Wild interaction design and development process according to its gameplay mechanics, storytelling attributes, and pedagogical methods.

PF in the Wild employs a Situated learning pedagogical approach by integrating commonly used products found in everyday routines (such as water bottles, bleach, batteries, and balloons) into its gameplay mechanics. By incorporating real physical products and AR technology, users engage in a multi-level learning experience where they acquire scientific knowledge about chemical properties and reactions. This pedagogical approach builds upon social and development theories, according to which the quality of learning depends on social interaction with the learning context [14].

In this line, Constructivism theory refers that children learn by interacting with the physical environment, connecting socially, and responding to external stimuli consciously [371]. Supporting this method is the work of Dunleavy et al., who demonstrated that even high-achieving students in formal educational settings can benefit from the connection of content and context since they also struggle to apply their knowledge in real-world context [90]. As such, PF in the Wild builds in the simulation of real-world problems within the context, allowing the user to practice and develop specific skills, make mistakes, and get positive feedback when the task is performed in a low-risk environment before transferring this knowledge to real-world situations.

The game uses the same approach as the previous games, allowing users to view information about chemical reactions at different levels of understanding (see Figure 7.1).

The game uses a method of exploration and discovery wherein the player is tasked with gathering atoms from products dispersed in real space. By navigating and interacting with the space freely to accomplish the tasks, the users must mentally manipulate and

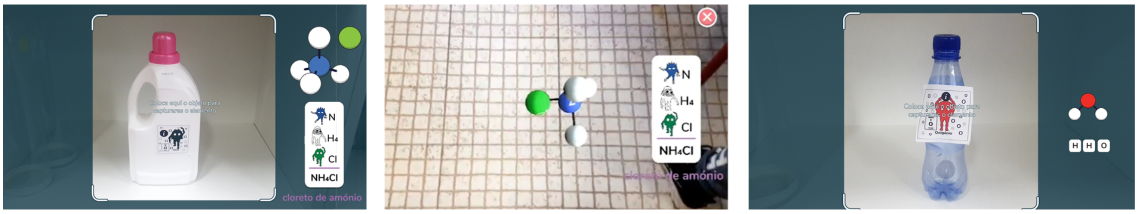

Figure 7.1: PF in the Wild Uses Real Products within the Game Mechanics

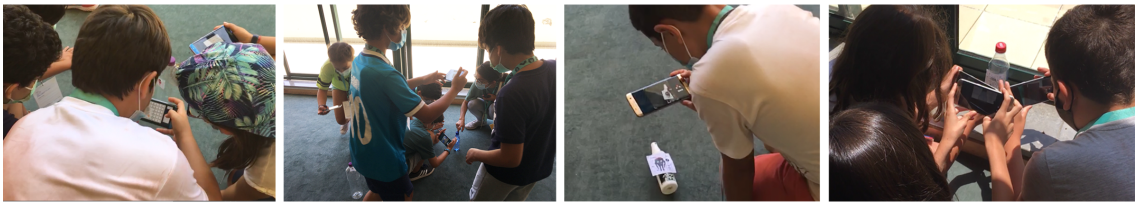

Figure 7.2: Preteens move around the real-space to accomplish the task

visualize spatial information, such as distances, directions, and relationships between objects. This active engagement with the spatial environment helps preteens to enhance their spatial reasoning skills, including spatial awareness, mental rotation, visualization, and spatial problem-solving abilities. Previous research with similar interventions proves that users significantly improved learners' spatial performances, which suggests that having learners exposed to spatial stimuli or explicitly instructing strategies for spatial thinking is an effective pedagogical intervention [95, 119].

In addition to enhancing spatial reasoning skills, this type of interaction fosters collaboration and dialogue among participants, thereby promoting teamwork to accomplish the tasks. The activity encourages participants to communicate, exchange ideas, and cooperate to overcome the game challenges (see Figure 7.2).

Another feature of PF in the Wild is a mini-puzzle 2D game dedicated to joining the collected atoms to replicate substances and chemical reactions, thus consolidating the learning content. The mini-game, with similar mechanics as a word puzzle, [1] asks the player to select from the previously gathered atoms the correct combination by pressing and holding the finger on top of the atoms that are needed to be joined together. Afterward, the player can see the created molecular structure and interact with it.

7.1 PF in The Wild Game Mechanics

The game starts with a tutorial that guides the user toward gathering chemical elements/atoms by scanning markers allocated to products displayed on shelves.

[1] https://thewordsearch.com/

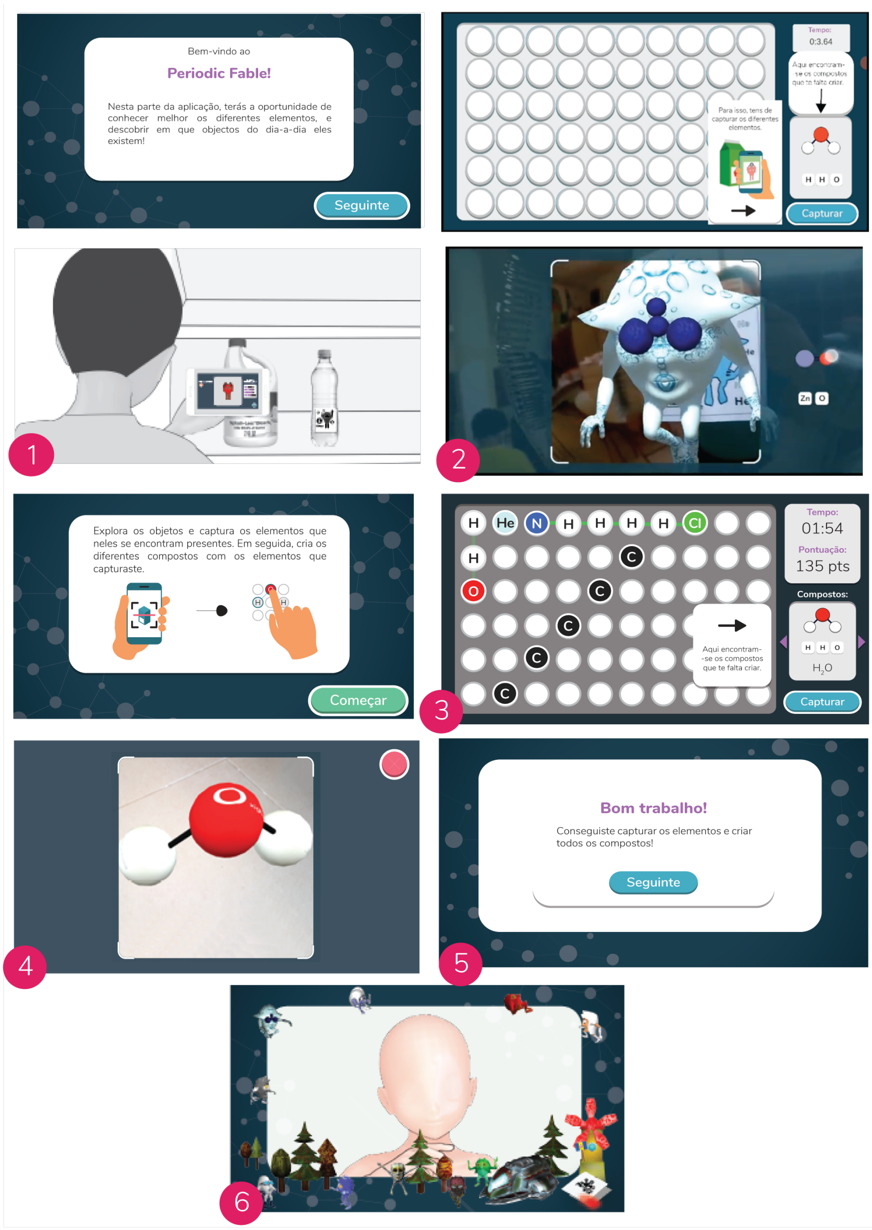

Figure 7.3: PF In the Wild Interaction Design

- 1. The user needs to move within a physical space to gather chemical atoms (allocated on the products) that are part of a certain compound (see Figure 7.3, number 1); Once the marker is scanned, besides gathering the elements, the user will be able to visualize animations of the character representing such elements with information about its properties.
- 2. While collecting the atoms, the user can also view the character's animations (see Figure 7.3, number 2);
- 3. All the collected elements are displayed afterwards on a 2D grid. The application indicates to the player when he/she has collected enough elements by blocking the capture button. The child is then asked to reconstruct the chemical composition of the selected product by combining the atoms (using a mini-word puzzle game) (see Figure 7.3, number 3);
- 4. Once the chemical bonding is achieved, the player can visualize and interact with the tri-dimensional AR compound/molecular structure he/she created (see Figure 7.3, number 4);
- 5. A congratulatory message is showcased (see Figure 7.3, number 5);
- 6. A selfie screen is displayed as a reward after the participant has completed all the compounds/ products. Like the other games, this selfie screen invites the player to take pictures with their favorite characters to share with family and friends (see Figure 7.3, number 6).

7.2 PF in the Wild Game Playtest and Iterations

As in the previous games, PF in the Wild exploratory assessment provided feedback incorporated within the high-fidelity prototype. Since this game was assessed at the same time as PF an Augmented Journey, we described the results of PF in the Wild and provided a joint conclusion of both games.

7.2.1 PF in the Wild Pilot Study

As in the previous games, PF in the Wild was assessed through a Pilot Study to gather information about the participants' acceptance and satisfaction of the games PF in the Wild usability, engagement, and overall feedback from our target audience. The overall assessment was positive, with encouraging results in AR's entertainment value and usability. However, using a mix-method approach, insights from the preliminary pilot test (N=7) identified the need for minor gameplay interventions.

Procedure

Table 7.1: Usability and satisfaction assessment results from PF in the Wild

Q#	Question	Mean	SD
Q1	I would like to play PF in the Wild again	4.14	0.900
Q2	I would recommend the game to friends and family	4.00	0.690
Q3	I thought that PF in the Wild was easy to use	4.71	0.488
Q4	I think that the game is fun to play	4.14	0.690
Q5	I found that the various functions in the game were well integrated	3.29	0.756
Q6	I found the game useful	4.71	0.488
Q7	I would imagine that most people would learn to use this game very quickly	4.29	0.756
Q8	I felt very confident using PF in the Wild	4.00	0.816

The procedure was the same as the pilot study of PF an Augmented Journey, in Chapter 7, where seven participants, aged 11 to 13, took a demographic survey, pre-test questionnaire, interacted with PF in The Wild, and finally, responded to a Post-questionnaires.

PF in the Wild Results

The participants reported higher Positive affect scores (M=18.00; SD= 2.12) than Negative (M= 6.00; SD= 0.70). The players enjoyed the exploration task of looking around the space and finding the products that displayed the game-specific markers. Scanning markers located on the product boxes and containers to collect the atoms of the chemical elements was also reported as a fun activity. Nevertheless, we also observed that once the players got familiar with the gameplay, they scanned the product markers to gather the proper atoms without reflecting on the product's composition. This was not intended to happen, and a second prototype iteration should ensure the design of a reflective activity after such a task. Children' found the animation of the characters representing the elements entertaining. They considered the game easy and useful since it allowed them to learn some products' composition and visualize the 3D molecular/compound structures (see Table 7.1).

They enjoyed this feature the most since they had to move around and collect atoms. However, they also highlighted some drawbacks of the game mechanics, identified mainly in repeating some tasks. The players observed: *"The mini-game of joining the atoms was repetitive"*; *"I thought it was too repetitive to put the atoms together"*; *"I would change the part of putting atoms together, and put something different every time."* Regardless, when asked if they would like to play both games again, all of them answered affirmatively.

Conclusion From Pilot Study of PF an Augmented Journey and PF in the Wild

Although we identified gameplay elements that need refinement, the overall players' assessment was very positive. The Positive and Negative Affects Scale for Children (PANASC) results with positive affect higher than negative means value affects indicate pleasure and engagement with the games. The fact that the participants regarded the game as easy and useful and expressed the desire to play it again, indicates that the players were thoroughly engaged. Due to the reduced number of participants in the study, however, the game prototypes could not be fully validated. Our next step is to act on the feedback and to conduct a broader study and usability testing of the AR serious games with larger sample groups in formal and non-formal settings.

Protocol refinements will also be implemented to recruit participants from schools, summer camps, and children's associations. Participants will be randomly divided into control (to play PF an Augmented Journey) and experimental (PF in the Wild) groups.

We intend to assess and compare both games' effectiveness in learning outcomes (pre- and post-questionnaires), motivation (Instructional Materials Motivation Survey), and engagement. We also aim to evaluate the games as to their benefits towards spatial skill development by conducting Pre and Postgame interaction tests using as an instrument the Mental Rotation Test (MRT) [248] and the Paper Folding Test (PFT) [298].

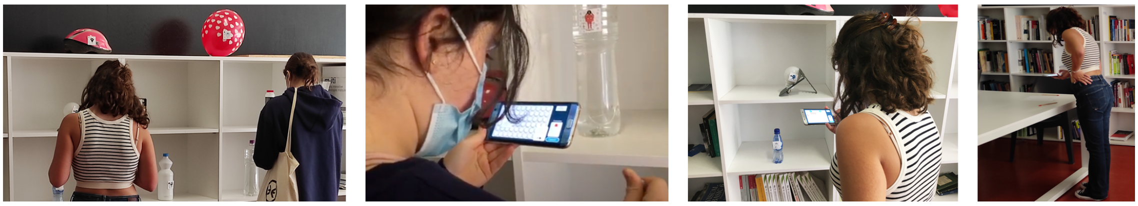

Figure 7.4: PF In the Wild Pilot Study

This study was part of a published paper:

Camara, S., Nisi, V., & Romão, T. (2021, October). Enhancing Children Spatial Skills with Augmented Reality Serious Games. In Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play (pp. 94-100). Included in appendix C.

7.2.2 Game Iterations

Feedback from the playtest with PF in the Wild indicated that the mini-puzzle game activity was too repetitive. As a result, the tasks were shortened, and animations and the visualization of the molecular structures were added. A punctuation system was used, whereas scanning the wrong atoms will reduce the score, promoting the need for the players to reflect the product's composition (see Figure 7.5).

7.3 Games Evaluation

The game "PF in the Wild"was the final game to be developed and was in its final stages of completion when the World Health Organization implemented Covid-19 pandemic restrictions. Consequently, the entire population was placed under lockdown, significantly limiting the opportunities to assess "PF in the Wild"compared to the other two games.

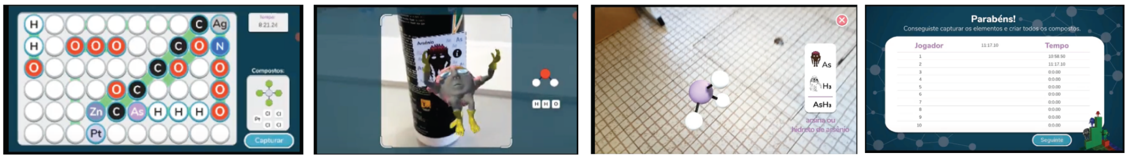

Figure 7.5: Iterations left to right - Decreased number of tasks from 15 to 10; added characters animations, 3D molecular structure, and a Leader board

Following a pilot study conducted exclusively on "PF in the Wild,"the subsequent and final evaluation encompassed all three games. The following section provides a detailed account of this last evaluation.

7.3.1 A Multi-level of Chemistry Understanding Using Augmented Reality Serious Games

In this study, we evaluate the design and implementation of PF AR games as learning experiences that can provide chemistry content at three levels: macroscopic, microscopic, and symbolic. We evaluated our experiences with 66 children (11-13 years old) (see Figure 7.6) with significant results: higher learning gains, an increase in the positive affect, and a decrease in the negative affect.

Figure 7.6: Participants' Interactions with the games

For this purpose, we created the following research questions:

- *PFWaRQ1 - How can we incorporate different pedagogical methods in AR serious games to facilitate the learning process of scientific concepts?*
- *PFWbRQ2 - Can AR serious games improve student' affects on chemistry?*
- And, finally, *PFWbRRQ3 - Can AR Serious Games engage and facilitate the learning of abstract content about the Periodic Table?*

We used the game prototypes to validate our research questions. The participants, a total of n=66, all students from 6th grade (ages ranging from 11 to 13), were recruited at Escola Básica dos 2º e 3º Ciclo do Caniço. According to the national school curriculum, the participants had no previous contact with the topic of the Periodic Table, which is only addressed in the 8th grade.

Procedure:

After the Ethical Committee at the Secretariat Regional of Education at Madeira approved the study, the public school teachers (n=3) and I recruited the participants. The children's guardians granted permission for their children to participate by signing a consent form. The document briefly explained the proposed research, the nature of the participation, and information about its confidentiality and image rights.

The study was conducted over three days by three researchers, me, and two assistants. The participants were randomly assigned to a game and followed the same study protocol. The aim of this process was to assess the pedagogical methods used in each AR serious game and their efficiency in facilitating the process involved in learning the scientific concepts. It followed the steps described below:

- The leading researcher briefly introduced the activity to the participants.
- Gathering of quantitative data -Pre-questionnaire to collect demographic data, previous experience with AR, awareness of chemistry and the Periodic Table, perception of chemistry, the preferred method of teaching/learning, content knowledge, Paper Folding Test (PFT), a Mental Rotation Test (MRT). -Subsequently, participants received a mobile phone with the previously installed games (the investigators' responsibility), and the researchers indicated which of the three games to interact with. - After the interaction, participants answered a post-questionnaire (the same questions about content knowledge and perception of chemistry, but in random order to avoid bias). We also added another question: *Would you play the game again?* to assess the participant's engagement with the game.
- Gathering of qualitative data - While the participants interacted with the games, the researchers took observational notes and recorded the session (to capture insights through expression, body movements, and comments). Once the participants finished interacting with the game, the researchers conducted a structured interview with open questions (ten participants from each game). The aim was to obtain information about usability and perception of the game's pedagogical value. The study took around 50 to 60 minutes, depending on the game.

The content knowledge data

Knowledge data was obtained through a questionnaire prepared by the researchers and validated by the teachers: *What is Ozone made of? Which element is responsible for diamonds? Which of these compounds contains nitrogen? What is the chemical equation of carbon dioxide? And water? Identify a diamond's chemical structure; What is ammonium's covalent bonding? What is the chemical symbol of nitrogen?* Each correct answer was given a "1"point, and wrong answers received a "0". Afterward, we compare the pre and post-questionnaire scores of each participant .

The perception of chemistry
This data was measured through an adapted Panas scale (Positive and Negative affect scale) [92]. A Panas scale contains several words describing different feelings and emotions. We used ten items; five questions reflected negative perceptions about chemistry, and five reflected positive perceptions. The participants could select more than one answer: I think chemistry is *difficult, interesting, boring, simple, not useful, complex, easy, cumbersome, useful, and fun*. Each selected answer was attributed a "1"point and grouped according to positive or negative perception. The results of the pre-and post-intervention questionnaires were then compared according to the group (e.g., pre-questionnaire positive perception compared to post-questionnaire positive perception).

Spatial skills
Since chemistry depends on comprehending, interpreting, and manipulating submicroscopic representations such as atoms and molecular structures, spatial skills are crucial in this field. Investigating spatial ability can offer valuable insights into how to enhance the learning process for preteens, particularly those with low spatial skills. Augmented reality (AR) can aid in visualizing information from multiple perspectives, facilitating the comprehension of phenomena in STEM domains. As part of the study, we conducted an exploratory study to gather data to reflect on the potential of PF Games in developing spatial skills. As such, we gather data from a Pre and Post-test using a Mental Rotation Test (MRT) and a Paper Folding Test (PFT), included in Appendix E.

The structured interview was guided by the following questions: *Did you like the game? Why? If you had the opportunity, what would you change? What is your overall opinion about the game?*

7.3.1.1 Results

The results were obtained by analyzing the data using Statistical Package for the Social Science (SPSS) 25, Chicago, Illinois) and using 2-tailed testing at α of 0.05. The assumption of Normality was tested by analyzing Kurtosis and Skewness (and their standard errors) and normality tests (Shapiro-Wilk). All the data was normally distributed and thus satisfied the assumptions required for parametric testing. We used a between-subject parametric independent paired T-test to compare the results of the content knowledge questionnaires (pre- and post-) and the chemistry affects. We used a cumulative frequency distribution analysis to calculate the means of the participants' preferred methods of teaching/learning.

Demographics
We distributed 66 participants (n=66) (41 males and 25 females) throughout the three

games. On the first day, 20 children played the game *PF Discovery* (10 females and ten males). On the second day, 25 participants interacted with *PF In the Wild* (10 females and 15 males). Finally, on the third day, 21 participants played *PF An Augmented Journey* (5 females and 16 males). Most of the participants had previous experience with AR (male 65% and female 40%). Also more than half of the participants (54%) were aware of the chemistry curriculum school programs, including the Periodic Table (57%) (see Table 7.2).

The majority of the participants (65%) preferred the constructivist approach, followed by an expository approach (50%), and finally, the use of storytelling (18%). Two teachers commented that using storytelling to provide content knowledge is not a standard method used within the classroom.

Table 7.2: Demographics, Previous experience with AR, Participants with the notion of the topics administered in chemistry, Participants with notions about the Periodic Table.

Games	N	Age	Gender	AR experience	Chemistry	Periodic Table
PF Discovery	7 10 3	11 year-old 12 13	10 females 10 males	60% (12 participants) (male=6, female=6)	55% (n=11) (male= 5, female=6)	50% (n=10) (male=4, female=6)
PF an Augmented Journey	11 7 3	11 year-old 12 13	5 females 16 males	66.7% (n=14) (male=12, female=2)	71.4% (n=15) (male=12, female=3)	57.1% (n=12) (male=10, female=2)
PF in the Wild	13 11 1	11 year-old 12 13	10 females 15 males	44% (n=11) (male=9, female=2)	40% (n=10) (male=7, female=3)	64% (n=16) (male=11, female=5)

Learning Outcome

The assessment of the AR Serious Games to facilitate the learning of concepts related to the Periodic Table was conducted by comparing the results of the post-questionnaires (after using the games) with the results from the pre-questionnaire (before interacting with the game). Results were positive for all the games, meaning the participants had higher learning gains after interacting with PF Discovery, PF An Augmented Journey, and PF in the Wild (see Table 7.3).

We also analyzed the overall results from all the participants for both genders. The results were also positive and significant for both genders: female (Mn= 2.040, Sd= 2.336), p=0.001, t=4.367 and male (Mn= 1.463, Sd= 1.451), p=0.001, t=6.459.

Participant's affects towards chemistry

The results of the participants' affects comparative analysis showed that, after playing with the games, their positive affects scores were higher than previously, and the difference was statistically significant for PF Discovery and PF in the Wild. PF An Augmented Journey, while gathering higher positive scores, the difference was not statistically significant (see Table 7.4). The negative affects also show significant positive results, meaning that the users' negative feelings about chemistry decreased after interacting with the

Table 7.3: Learning outcome results with higher learning outcome for PF in the Wild, PF Discovery, and finally PF an Augmented Journey.

Games	Mean	Std. Deviation	t	df	Significance
Discovery	1.650	2.033	3.629	19	p= 0.002
An Augmented Journey	1.280	1.369	3.337	20	p= 0.003
In the Wild	2.080	1.778	5.850	24	p= 0.001
Overall results (all games)	1.196	1.790	5.430	24	p= 0.001

games (see Table 7.5).

We also conducted a comparative analysis of all the participants and examined the results for both genders. Results from the positive affects of chemistry were also higher. The female participants results were (Mn= 1.160, Sd= 0.943) p=0.001, t=6.148 and male results were: (Mn= 0.878, Sd= 0.714), p=0.001, t=7.875. The negative affects also show a decrease: female (Mn= 1.040, Sd= 1.274), p=0.001, t=4.081 and male (Mn= 0.780, Sd= 01.037), p=0.001, t=4.819.

Table 7.4: Positive Affects Results

	Pre-test		Post-test				
Games	Mean	Std. Deviation	Mean	Std. Deviation	t	df	Significance
Discovery	1.10	1.021	2.00	0.858	3.327	19	p= 0.004
An Augmented Journey	1.14	0.910	1.430	1.121	1.000	20	0.005< 0.329
In the Wild	1.280	0.980	1.840	0.898	2.682	24	p= 0.013
Overall (all games)	1.169	0.961	1.769	0.980	4.088	65	p=0.001

Table 7.5: Negative Affects Results

	Pre-test		Post-test				
Games	Mean	Std. Deviation	Mean	Std. Deviation	t	df	Significance
Discovery	1.650	2.033	0.700	0.723	3.629	19	p= 0.003
An Augmented Journey	1.238	0.768	0.761	0.700	3.337	20	p= 0.004
In the Wild	2.080	1.778	0.560	0.820	5.850	24	p= 0.001
Overall (all games)	1.484	0.827	0.727	0.814	5.410	65	p= 0.001

In addition, we conducted a correlation analysis between learning outcomes and the participant's preferred method of learning/teaching; the Pearson Correlation Coefficient did not show any correlation.

Most of the participants (79%) agreed with the possibility of playing the games again, which indicates that they enjoyed them.

Spatial Skills Results

The comparative analysis of the MRT, while providing better results in the post-test (Mn= 2.651, Sd= 2.53) than in the pre-test (Mn= 2.181, Sd= 2.16), did not show significant results (Mn= 0.469, Sd= 2.39) p=0.054, t=1.960. Results according to gender also did not provide significant results (see Table 7.6).

Table 7.6: MRT Results

MRT Pre –Post Results (Meand and SD)

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	PostMRT	2.6515	66	2.53281	.31177
	PreMRT	2.1818	66	2.16908	.26699

MRT Paired Samples Test

		Paired Differences							Significance	
					95% Confidence Interval of the Difference					
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
Pair 1	PostMRT – PreMRT	.46970	1.94715	.23968	-.00897	.94837	1.960	65	.027	.054

MRT Results by Game

			Paired Differences							Significance	
						95% Confidence Interval of the Difference					
games			Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
Discovery	Pair 1	PostMRT – PreMRT	.75000	2.26820	.50719	-.31155	1.81155	1.479	19	.078	.156
In The Wild	Pair 1	PostMRT – PreMRT	.60000	2.43242	.48648	-.40405	1.60405	1.233	24	.115	.229
Journey	Pair 1	PostMRT – PreMRT	.04762	.21822	.04762	-.05171	.14695	1.000	20	.165	.329

MRT Results According to Gender

			Paired Differences							Significance	
						95% Confidence Interval of the Difference					
gender			Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
female	Pair 1	PostMRT – PreMRT	.28000	1.96893	.39379	-.53273	1.09273	.711	24	.242	.484
male	Pair 1	PostMRT – PreMRT	.58537	1.94905	.30439	-.02983	1.20056	1.923	40	.031	.062

The comparative analysis of the PFT showcased significant positive results (Mn= 0.393, Sd= 1.58) p=0.04, t=2.016. The results from the comparative study (pre and post) according to the game also provided a significant positive result for PF an Augmented Journey (Mn= 0.333, Sd= 0.57) p=0.01, t=2.646, while the other did not showcase any significance.

The gender comparative studies also showed a significant positive result for the male participants (Mn= 4.390, Sd= 1.361) p=0.04, t=2.065, while the female participants did not show any significance (see Table 7.7).

As stated before, these results are exploratory and guide us toward future studies to validate the benefits of the games towards the development of spatial skills, thus facilitating the learning process of topics within the chemistry domain.

Table 7.7: Paper Folding Results

Paper Folding Test Results (Mean and SD)

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	PostPaperFolding	3.2879	66	1.68034	.20684
	PrePaperFolding	2.8939	66	1.82402	.22452

Paper Folding Test Results

		Paired Differences							Significance	
					95% Confidence Interval of the Difference					
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
Pair 1	PostPaperFolding - PrePaperFolding	.39394	1.58725	.19538	.00375	.78413	2.016	65	.024	.048

Paper Folding Results by Gender

			Paired Differences							Significance	
						95% Confidence Interval of the Difference					
gender			Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
female	Pair 1	PostPaperFolding - PrePaperFolding	.32000	1.93046	.38609	-.47685	1.11685	.829	24	.208	.415
male	Pair 1	PostPaperFolding - PrePaperFolding	.43902	1.36104	.21256	.00943	.86862	2.065	40	.023	.045

Paper Folding Result by Game

			Paired Differences							Significance	
						95% Confidence Interval of the Difference					
games			Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	One-Sided p	Two-Sided p
Discovery	Pair 1	PostPaperFolding - PrePaperFolding	.30000	1.75019	.39135	-.51911	1.11911	.767	19	.226	.453
In The Wild	Pair 1	PostPaperFolding - PrePaperFolding	.52000	2.02320	.40464	-.31514	1.35514	1.285	24	.106	.211
Journey	Pair 1	PostPaperFolding - PrePaperFolding	.33333	.57735	.12599	.07053	.59614	2.646	20	.008	.016

Qualitative results

The qualitative results from the observational notes, video analysis, and structured interview contributed to support the result of the quantitative data about the participant's engagement and emotions towards the games, providing insights into technical issues with the systems as well.

Results from observational notes and video analysis

According to the observational notes and video analysis, participants showed engagement with the content. The players' overall attitudes were enthusiastic and eager to uncover the information. They constantly made positive comments and smiled during the interactions. We describe the qualitative findings from the observations and video in more detail below.

While using **PF Discovery**, two participants stood up and moved the mobile closer to the cubes to observe the character's animations, commenting,*"This is cool!"*. Some participants showed satisfaction with their performance: *"I just made water!"*, *"Did you see this?*. Participants also collaborated by giving tips regarding how some chemical reactions could be obtained. The eagerness to view the information was displayed by comments such as: *"I bet that Oxygen is going to create air"*; *"I am only missing the Chlorine story"*.

This was also reflected in the manipulation of the cubes (quick and constant movement to scan the facet). The students also enjoyed the stories and the characters: *"Hydrogen just burped"(Laughter); "The characters are so cute!"*. While playing AR PF Discovery, the comments show that the game promotes chemistry literacy and symbolic representation: *"Hydrogen is floating!"; "Whoa! I just saw Carbon waiving at me"; "Now I have to put together Nitrogen!"the "N"and Oxygen, the "O"*.

PF An Augmented Journey - At the beginning of the game, two students struggle to anchor the 3D digital map within actual space, showing frustration. While playing the game, they lamented that the 3D digital world had moved too far and needed to change positions. Most participants seemed immersed in exploring the 3D AR world and showed empathy with the characters: *"Whoa! I will play with nitrogen since he seems cool"; "I will play with oxygen; I like the color, and it is cute"* (this was related to the possibility of selecting a main character for the game), *"Oh! Only five characters are leaving the planet; what happens to the other ones?"* The aesthetics of the animations supported the learning content: *"This is cool! And very pretty"; "Oxygen is swimming!"(Laughter); "I can see the balloons* (atoms in a chemical structure) *joining together!"; "Amazing! It is now creating a diamond!"; "I need to use another reaction to go over the bridge!"; "This character* (referring to zinc) *just gave me a piece of the spacecraft."*

PF in the Wild - The participants paid attention to the instructions, gathering one chemical element at a time to create specific substances individually. However, this process became a collaborative and competitive effort. The participants formed groups of two or three, communicating the location of the elements needed to finish each task first. Some of their comments were: *"We just finished creating ammonia!!! Let's go!"; "You need to scan hydrogen twice!"; "Go to the bottle of peroxide to collect the oxygen!"; "We only need three more substances to finish!"; "Have you seen the animations?"*

Interview results

The analysis of the participants' interviews showed that the stories and characters played an important role in engaging the children with PF Discovery: *"I enjoy viewing the stories"; "I think that the characters and animations were amazing!"; "I will put shoes on the characters"; "Oxygen is cool"*. The children realized that playing the game could enhance their future chemistry classes: *"I like looking at the molecules... this will prepare me for my future classes"; "I think this game is going to be useful for my classes"*. The game also appeals to the participants: *"I liked everything"; "I like it, can I download it?"*.

As in PF Discovery, the characters in PF An Augmented Journey played critical roles in the emotional connection: *"At the end, I would like to take all the characters in the spacecraft with me!"; "I loved the characters"*. The satisfaction was noticeable: *"I enjoyed everything!"; "I would not make any changes"*. The macro and micro representations were of interest: *"I like seeing the transformation of the chemical solutions* (chemical structures of water in this case) *into the actual product"*. The usefulness of the game for chemistry curriculum and content knowledge was foreseen: *"This is fun and a good way to learn"; "I want to use this game in my future chemistry classes"; "I learned that diamonds are made of carbon"*. A technical issue compromised the experience of one student: *"I lost the 3D map In the middle of the game, and I did not like that"*.

The children were highly confident and satisfied with the learning experience of PF in the Wild: *"I like it because I learn things that I did not know, like the products that have some of these elements"; "I enjoy it because I learn by playing"*. The game was defined as useful, encouraging an active learning attitude: *"I think it is fun and good to learn about the elements"; "I will enjoy using the game during my chemistry classes"*. Other positive player responses: *"I enjoyed this game, and I think it is well done"; "Can I download the game?"; "The characters are cute and cool!"*.

7.4 PF in the Wild Summary of Lessons Learned

While this study encompasses all Periodic Fable games, we first single out PF in the Wild evaluation and analysis of its effectiveness as an educational tool. Subsequently, we will compare these findings to the other games with a comprehensive discussion about the affordances and outcomes based on the study results for all three games.

As we analyzed PF in the Wild, there are some similarities with the other PF games that account for the positive results:

- Employs tangible real-world products that are part of the children's reality, such as a bike helmet, bleach, a bottle of water, and party balloons to provide awareness of chemistry as part of their world and not only as a school subject. As said previously, the more the students perception that the Periodic Table is part of their reality and the knowledge can be applied to their context, their engagement and sense of usefulness increases.
- Provides a collaborative and competitive environment (activity moving around the physical space to scan and combine chemical elements), promotes inquiry, active observation, reciprocal teaching through colleagues, and peripheral participation with multiple modes of representation. Also, working with peers allows participants to acquire information (e.g., which chemical elements to join) that is assimilated and accommodated into their existing knowledge (need to combine elements to create substances) and to adapt this information to their real world (problem-solving to overcome the challenge), thus contributing to their cognitive development. This process is aligned with Piaget's constructivism idea of equilibration, which claims that when presented with new or unexpected knowledge, we try to assimilate it by rearranging it in a manner that can be accommodated to make sense, leading to a cognitive adaptation [127, 306]. According to Piaget and Vygotsky, activities

that provide the opportunity for social interaction and language adaptation can facilitate the child's cognitive transition from concrete to formal operational stage [250, 347, 234].

- The reinforcement of the learning content is provided by using repetitive actions at different moments: gathering the chemical element through scanning the product, the mini-game to reconstruct or create new substance/reactions, and viewing and manipulating the element on the molecular structure of such substance.
- The movement within the real space to gather the elements situated in different parts of the room can also contribute to the development of spatial orientation. According to Yakimanskaya (1991), spatial thinking skills develop through identifying properties and relationships of space using problem-solving activities [363].

7.4.1 Discussion

In this study, we reflected on designing and developing the three AR serious games to support and engage 9- to 13-year-old children with abstract scientific concepts related to the Periodic Table. Our approach leverages human factors (participatory design approach), a multi-mode or multi-level chemistry representation, and AR technology with game-based learning (see Figure 1.1). The study allows us to understand how children can engage with chemistry content through AR serious gameplay interactions and tangible interfaces. The results were optimistic, showing significant positive learning outcomes. The increase in positive affects towards chemistry and the decrease in negative ones indicates that PF games can engage children with content knowledge and improve their attitudes, thus facilitating learning.

The qualitative data from observational notes, video analysis, and interviews demonstrated that aesthetics, storytelling, and character development could support learning content through analogies (mimicking chemical elements) and animations, contributing significantly to the child's curiosity and interest. Like, Panagiotis Sarantopoulos and Georgios Tsaparlt's work [288], using these methods appeals to children and facilitates the connection with the learning objectives. The learning achieved through the gameplay mechanics by joining elements to create chemical reactions and substances can promote children's confidence, satisfaction, and chemistry literacy, which as per A. Bandura [31] can lead to self-efficiency and increase intrinsic motivation. The participants' acceptance is also evident in their perception of the games as useful and valuable for their future chemistry classes.

When comparing the games' performance, PF An Augmented Journey had the lowest scores. Several factors, ranging from design strategies to usability issues, may contribute to this, for example:

- Compared to the other games, PF An Augmented Journey lacks relatedness (use real-world products/substances). PF Discovery and PF in the Wild complement the information about the chemical elements by linking the content to the preteen's context, making it relevant and useful with real-life applications. As previous research indicates, using everyday objects can help successfully transfer information because it provides cues that the learner associates with the new skill or knowledge [273, 263]. If the learning content and the scientific literacy are associated with the daily life and situations of the student, the higher their interest.

- PF an Augmented Journey also lacks tactile support. PF Discovery uses tangible cubes, and PF in the Wild uses product containers, adding an extra layer to the learning process. The ability to physically grab, rotate, and manipulate these objects reinforces learning by providing an extra cue in the learning process. This approach also offers an innovative method of controlling the virtual space, which can be particularly appealing to preteens and more effective in facilitating active collaboration. Furthermore, unlike the other games, PF in the Wild used the physical space combined with the tangible interface and seemed more engaging toward competitive and collaborative behavior. The results demonstrated that while interacting with PF in the Wild, participants swiftly formed groups, engaging in communication and idea exchange to be the first to complete the game and achieve the highest scores.

  In this note, AR technology design strategies, whereas the focus of the activity heavily depends on the virtual information, can prevent collaborative environments, as per the supra-cited "tunneling effect"by Ann Morrison [221]. PF an Augmented Journey gameplay, required the children to make quick decisions based on the displayed virtual information (exploration of the digital map and selection-observation of the reactions), preventing the users from interacting with other participants. We also believe that, in addition, this game provided an extra layer to learning content (the sustainability of the chemical elements), increasing the amount of information to understand, which can lead to cognitive overload.

- When exploring the multi-level understanding of chemistry, PF in the Wild substituted a visual representation (animation /video) to provide a Macro-level understanding using real-world world products. The game was also heavier in the symbolic representation, showcasing the atoms and equation of the combined elements more often than PF Discovery and PF an Augmented Journey. While not part of this study, this could be a factor that led to a better performance of the participants that interacted with the game. However, further studies need to be conducted to validate this statement.

- Finally, regarding the game's technical stability, marker base technology seems adequate to our users, providing fewer technical disruptions within the game flow. In the case of PF an Augmented Journey, the anchoring of the 3D world and position within the virtual world was compromised by sudden movements and excitement of the students. The system's need to continue reading the patterns within the real world to allocate the digital information, which is done through the mobile device's camera, requires the steadiness of the equipment. The activity needs to be conducted in spaces with floor plans that incorporate distinct strong patterns/shapes and colors or design the activity pacing the movements of the users to avoid the disruption of the flow leading to frustration. However, we also believe this issue may be resolved with the continuing investment and research of AR technology.

We can also conclude that the overall success of AR interventions depends not only on the technology's technical characteristics; its success is also associated with the pedagogical strategies used to implement them. The participatory design approach helps design and customize the learning objectives and balance game elements to engage and create a better learning experience. Using several elements from animations, character design, storytelling, and gamification helped achieve positive game dynamics that led to acquiring the learning goals. In this context, the human element and learning levels of chemistry (microscopic, macroscopic, and symbolic) need to be investigated according to students' characteristics to improve learning attitudes and achievements in this domain.

Chapter 8

Discussion and Contributions

This chapter reflects on the results of the research questions, which are aligned with our research contribution.

By analyzing the literature review, there is a lack of clearly defined strategies that consider the connection between learning attributes and game elements to achieve a balance between learning chemistry and play. This is because a limited amount of evidence-based research compares various game designs with a specific pedagogical model in chemistry or vice versa. As a result, educators who want to incorporate games into the classroom feel uneasy about selecting serious games that can effectively incorporate specific learning goals within the classroom context. While AR serious games provided positive empirical results in the understanding and engagement of students with scientific concepts, teachers' lack of time, technical training, and resources create a barrier to its adoption in the domain of chemistry. Furthermore, research on AR and Serious Games in chemistry mainly addressed older students. Limited research is provided on strategies, methods, and tools to gather a younger population's interest in chemistry. The body of work presented in this thesis provides an overview of the need to further conduct chemistry research to demystify preteens' negative perception of chemistry, increasing their interest, and motivation towards this subject, thus increasing their academic achievement and future career choices in the field.

To this end, we contribute with the design and development of three novel AR serious games artifacts: Periodic Fable Discovery, Periodic Fable An Augmented Journey, and, finally, Periodic Fable in the Wild, developed to facilitate the learning of abstract concepts about the Periodic Table while engaging preteens with chemistry.

The design and development of these systems followed Alex Johnstone's (chemistry understanding) and Benjamin Bloom's (taxonomy of learning) theoretical approach; human factors (teachers and game designers' contribution) and game elements align with pedagogic.

These artifacts were evaluated, iterated, and analyzed, providing insights into the benefits and limitations of AR Serious Games to facilitate and engage preteens (9 to 13 years old) in learning abstract scientific content. It also provides insights to distill guidelines to help researchers design and develop effective AR serious games for teaching/learning chemistry while engaging the students with the content.

The rest of this chapter provides the research contributions guided by the research questions.

- **RQ1** *How can Augmented Reality game design balance: aesthetic, story, gameplay, technology and pedagogical methods facilitate the learning process of abstract scientific concepts encountered in the Periodic Table*
- **RQ2** *What design considerations-guidelines should be taken into account in the development of Augmented Reality (AR) serious games to effectively support science education?*
- **RQ3** *Can AR Serious Games improve children's affects on chemistry and facilitate the learning of abstract content about the Periodic Table?*

RQ1 -How can Augmented Reality game design balance: aesthetic, story, gameplay, technology, and pedagogical methods facilitate the learning process of abstract scientific concepts encountered in the Periodic Table?

By analyzing the results from the participant's interactions with PF experiences, we can argue that game elements balance and gamification are critical to captivating and engaging children with learning content. Each game component, from the aesthetics, storytelling, mechanics, technology, and pedagogic, influences the game's dynamics and contributes to the overall experience. All the conducted studies showcased the participant's empathy with the characters and engagement with the stories, providing insight into how cognitive and emotional attachment can incite problem-solving skills while acquiring scientific content knowledge. The bonding of the participant with the character can maintain the player's desire to reach the final goal of the game, leading to exploring all the selected learning content about the Periodic Table. The qualitative studies also provide an overview of the players' attachment to the character's visual appearance and personality reflected through their animations. These results validated our design solution for character development, which, while having an entertainment intention, also provided learning information through the analogies to represented chemical elements. Chemical elements are part of the substances and all of which matter is composed; however, they are abstract concepts represented by symbols (unknown or unfamiliar to children). Using an analogy in the form of characters can facilitate the cognitive and emotional connection with the Periodic Table, leading to an effective learning experience.

Likewise, the results of our studies showed that the stories portrayed on PF Discovery and PF An Augmented Journey fostered player immersion, meaning that the participants felt part of the narrative. This also provides an easiness and a more friendly environment where children explore the learning content freely. Supported by previous research, while preteens felt transported into a story world, the events and actions within the narrative seemed closer and more personal, leading to a more memorable experience [224]. Since the actions and events of the stories of PF games evolved around the learning content, we believe that the more memorable and more likely preteens are to remember the concepts.

Roselli Fabrigaret et al. argues that attitudes based on cognitive and emotional foundations are more persistent over time ([104]. The interviews and observation notes prove that PF games created an emotional connection with the overall aesthetics, character, and story plot, leading to increased interest and a positive attitude towards chemistry, which can benefit preteens' perceptions and future intervention with the domain.

Each technology offers unique possibilities and limitations, making them more suited for some jobs and activities than others. Earlier on, an extended body of work indicated the affordance of AR in facilitating the learning process in STEM domains. This is eminent in the case of the visualization of abstract concepts in chemistry by providing valuable benefits for the student's cognitive process and attitudes. Visualizing the information from different perspectives by rotating a cube or walking around a space, besides being interesting according to the results, was allusive and exciting to the participants. In several studies, students commented on the "revealing"of information as being engaging, which prompted their curiosity and desired to keep exploring the learning information by either scanning the facet of the cubes in the case of PF Discovery, exploring the 3D AR map using PF an Augmented Journey or by scanning the product on the shelves in PF in the Wild. The children's enthusiasm and eagerness to uncover the information suggest that they were actively interested in visualizing the information and invested in the learning process. Additionally, the fact that they commented on their achievements at each disclosure indicates that they were taking pride in their progress and feeling a sense of accomplishment as they gained new knowledge. As previously cited [31], the sense of self-efficiency increases intrinsic motivation, promotes performance gains, and sustains engagement. These factors have previously been linked to students' positive learning outcomes and academic achievement [261], which our results support.

AR can also allow designers to creatively use other mediums, like animations, 2D data, sound, and video, to complement the information provided in the content in the context of chemistry (significant for understanding phenomena that happen at different levels).

Finally, mechanics and gameplay in a serious game need to be in accordance with the learning goal. Designing and developing PF games towards this goal was complex and led to many interactions, from the concept stage to the final product. Designing and developing mechanics/gameplay aimed to provide engagement with the interactive environment while incorporating strategies, actions, and rules that deliver the defined learning goals. While balancing other elements, the positive results from our research rely heavily on how to implement the pedagogics within the gameplay in parallel to how it will affect the Game Dynamics. We summarize the insights from the design and development of PF Discovery, PF and Augmented Journey, and PF in the Wild; each developed with unique mechanics in RQ3.

Regarding the **pedagogical methods** as per Bloom's Taxonomy, learning is an overlapping of skills domains – by thinking, doing, and feeling [180]. In this sense, PF games elements contributed to different levels of learning by allowing preteens to think (making sure that the information was adapted to their cognitive development), by doing (using constructivism and a situated learning approach), and finally by feeling (using game elements like aesthetics, storytelling, and gameplay elements to create empathy and engage our users).

As previously stated, teachers' pedagogical practice and continued involvement with preteens provide opportunities to adapt strategies and methods used within the context of science classes in PF games, resulting in different benefits showcased in our studies towards the learning process:

Utilizing a preteen's existing knowledge and experiences can serve as a foundation for establishing meaningful connections with new content. In science education, concepts such as photosynthesis, the circulatory blood system, pollution, and climate change can offer a contextual backdrop for comprehending the Periodic Table. By identifying and leveraging these relevant elements, the cognitive learning process can be facilitated, fostering a stronger connection and understanding of the content. Also, by integrating children's reality, from objects that are part of their daily routine to the game's activities, science becomes closer to the student making chemistry part of their world and not only a school subject.

Considering the child's environment, providing activities where the participant moves around their physical space (in the case of PF to scan and combine chemical elements), and using other senses promoting inquiry, active observation, reciprocal teaching through colleagues, and peripheral participation with multiple modes of representation. Providing a physical activity linked to a conceptual understanding of the educational content helps with its visuospatial comprehension supporting Shelton and Hedley's findings [297].

Promoting activities where preteens can discover and explore the information (Constructivism approach) with continued feedback and guided learning tasks. PF game mechanics allowed preteens to explore the content at their own pace and time. Several factors were considered within the design of PF games to provide the participants the freedom and also the desire to explore the learning content:

1. Selecting and dividing the information throughout the games in a form that is not overwhelming for the user and can easily be assimilated.

2. Using repetitive actions, a pedagogical method, showed benefits within the class

context to retain and help remember the information for a more extended period of time. As a gameplay instrument, it also optimizes the process of conveying information. Using similar actions throughout the game decreases the complexity and need for skill acquisition of game mechanics.

3. Using natural, easy, and intuitive mechanics that do not subordinate the cognitive learning process. By using simple mechanics, preteens engaged in the learning content without having to focus their attention on how to use or manipulate the technology, also avoiding cognitive overload. Furthermore, using multi-modal platforms (PF Discovery and in the Wild), besides being an activity that is natural, provides an extra layer in the learning process (tactile information). We also believe that PF games can promote learning through epistemic actions using trial and error.

4. Providing continuous feedback within the games to convey information on the successful execution of each action and offering updates on progress and achievements (gamification elements). This facilitates preteens in adapting their strategies, instilling a sense of security and accomplishment.

The overall positive study results showcased that the participants felt a sense of accomplishment when able to follow the instructions and finish each task, increasing their motivation, interest, and enjoyment. However, the technology must also be constant to provide the information without breaking the flow. Qualitative results showed that in a few cases, the inconsistency in the tracking of the AR technology created frustration. While we believe that the continued development of the technology will improve and minimize these situations, the AR system needs to be consistent, accurate, and quick since any interruption or delay can break and disrupt the experience.

Designing collaborative experiences within the learning environment using AR Serious. As said before, AR Serious Games can promote collaborative learning environments [144, 201], which benefits students employing reciprocal teaching. However, this affordance depends on the mechanism and activities inherent to the technology. In PF in the Wild, the children move within the space (using their entire body) as part of the mechanics to view the AR information, resulting in the gathering of small groups that worked collaboratively and competitively to be the first to solve the tasks (with significant positive results). In the case of PF Discovery, the mechanics were more restricted (manipulation of the cube to gather the AR information), decreasing collaborative interactions. Lastly, although PF and Augmented Journey mechanics also rely on the participant's movement within the real space, the activity-heavy dependency on the digital world did provide the condition for children to work collaboratively. While viewing the dialogues, exploring the AR map, and following instructions to finish the game, the players did not connect or interact with other participants but instead concentrated on the game. Overall, AR collaborative and competitive environments depend on the design activity and methods to reach the learning objectives.

Finally, designing to "learn by feeling"involves engaging participants emotionally and affective with the content. The body of work and study results presented in this thesis demonstrated that the influence of emotions and affects is a powerful tool in learning. Emotions towards a domain, discipline, or topic can change the student's attitudes and behavior, leading to willingness and interest.

RQ2 - What design considerations-guidelines should be taken into account in the development of Augmented Reality (AR) serious games to effectively support science education?

Guidelines help designers and researchers understand users' learning process and make reasonable decisions about designing effective tools for education. In the following, we share our guidelines, derived from the design and development process, iteration, and evaluation of PF Games. We aim to inform and contribute to the research of AR Serious Games intended to effectively engage preteens and facilitate their understanding of scientific content in the domain of chemistry.

G1 *Using AR display for multi-level understanding (Macro, Micro, and Symbolic representation)*

PF game technology supports different digital formats, providing flexibility to the transition between the different levels of chemistry representation in an ongoing game event. As per Johnstone and other theorists, the interactions between these levels should be explicitly taught [138, 91, 258, 330], providing a deeper understanding of chemistry. The display of the reactions/substances through AR animations (macro), while simultaneously showcasing the symbolic representative information of the chemical equation involved, helps to create a mental connection between both. The visualization and interaction with a 3D AR molecular structure at a micro-level allow for displaying the spatial relationship between the chemical elements. While our results are provided in the domain of chemistry, AR adaptability can help the understanding of abstract phenomena in other STEM subjects by demonstrating concepts within a system and not as an isolated item of information, helping children to attain an understanding connected at different levels and expanding their mental connection and retrieval learning process. This is also supported by the spatial contiguity effect, which indicates that students learn better and more effectively when multiple representations of the same information are presented simultaneously rather than separated in time [169].

G2 *Providing guided learning tasks*

From a constructivist perspective, learning needs to be an active contextual process leading to the construction of knowledge [311]. The task is to find a suitable level for learners to bridge their past knowledge with new knowledge [359, 345]. PF games follow constructivist strategies: exploring and discovering information in easy steps (progressively revealing more information), provided in segments to avoid cognitive overload and increase the students' curiosity. A participatory design approach can help identify real and attainable learning goals while providing the exploration of pedagogical methods to facilitate the process. AR mechanics complexity must be considered and decreased to focus on skill acquisition and learning content. In the case of PF Discovery and PF in the Wild, the reinforcement of the learning content is provided by using repetitive actions (gathering the chemical element through scanning the product, use of the same elements to create substances, and viewing and manipulating the element on the molecular structure of such substance). PF an Augmented Journey also uses repetitive action to provide the learning content while supporting the story plot (explore the map, find an obstacle, use the content knowledge about chemical reactions, dialogue with character, and obtain a reward). Gamification elements can also reinforce learning acquisition by providing reinforcement and feedback.

G3 *Connecting context and content*

Prior STEM research explored the use of everyday objects to make the content relevant to students, facilitating the learning process [166]. However, limited work has focused on exploring how those objects can be used for chemistry learning. PF in the Wild uses tangible everyday routine products within the game mechanics. At the same time, PF Discovery provides a connection with the children's context by displaying 3D AR digital objects/substances, increasing relevance and bringing science closer to the student's everyday life and interests as per Vygotsky's theory of cultural context of knowledge [46]. In the case of PF in the Wild, it employs tangible real-world products that are part of the children's reality, such as a bike helmet, bleach, a bottle of water, and party balloons to provide awareness of chemistry as part of their world and not only as a school subject.

This bridge between educational content and the real-world context of the children creates a meaningful connection, facilitating retention and adding relevance to the topic explored (Periodic Table). Moreover, it also enables a conceptual connection between abstract and concrete representation. This assumption is supported by several authors, according to whom the proper connection of abstract concepts with physical objects can help to support both memory and the understanding of symbolic representations [332, 252, 263].

While the gameplay in PF an Augmented Journey does not include real objects per se, exploring the 3D map by moving in the real world as part of the gameplay increases the children's immersion. In addition, this promotes kinesthetic abilities (physically performing an activity to facilitate the learning process). This aspect has yet to be explored in great detail with Augmented Reality [147]. According to previous research, using AR manipulation to align the information with different points of the virtual 3D map (accessed by moving in the physical space) can aid the memory retrieval process [192]. Following Shelton and Hedley's research, PF an Augmented Journey promotes the interaction between the real world and digital information, simultaneously providing a physical activity that is linked to conceptual understanding of the educational content, helping with its visuospatial comprehension [297]. Moreover, PF games promote meaningful connections, relevance, and a sense of usefulness (important for student's personal development by improving learning in chemistry). They can promote interest in chemistry, going beyond their initial novelty. However, further research is needed to sustain this hypothesis.

G4 *Employing Character and Storytelling*

Previous research demonstrates that character embodiment can promote exploration and discovery in science learning [293]. PF games support this approach by using the story plot to create empathy with the characters, inciting problem-solving and maintaining the child's desire to reach the game's final goal while acquiring scientific knowledge. PF an Augmented Journey exploits visual storytelling and character design, promoting the full involvement of the child in the activities and providing the sense of being part of the narrative (immersion). Furthermore, using a storyline with an altruistic approach, where the children are presented with the opportunity to help solve a problem (fix the spacecraft to help the characters return to their planet) while acquiring content knowledge, seems effective. Moreover, storytelling to promote student interest in chemistry has received increasing attention, proving a valuable pedagogical method. PF Discovery stories' narrative revolves around the chemical elements' covalent bonding, portrayed through fun and engaging situations with the characters. Short stories that, while providing learning content, are fun and relatable to the children's universe (e.g., action on a water park with a character sliding on a toboggan, burping of one of the characters, a superhero story) can captivate their interest.

G5 *Providing Multi-sensory opportunities*

Gathering information by rotating and scanning the physical cubes and manipulating the product containers allows the child to control the type of content and time dedicated to such information. In the particular case of PF Discovery, the manipulation of tangible interfaces (cubes) allowing the rotation of the molecular structure at any angle can develop the student's ability to see, think, and relate the structures of molecules with their properties. This activity encourages participants to actively explore the content and view the information, promoting a constructivist learning approach. The richness of the haptic experience in unveiling information creates a sense of anticipation. It stimulates a student's curiosity, leading him or her to acquire more information about the content of the Periodic Table. Besides being intuitive and easy to use – only grabbing and rotating – the physical tangibles give children a stronger sense of direct stimuli and a realistic feeling by interacting directly with the virtual world. AR games that leverage the child's natural interaction in the physical world (moving around to change perspective, moving closer/farther to change scale) are appropriate for education and can reduce the cognitive mental workload associated with learning new technologies. Since the cognitive process generated by cognitive activities that are not directly related to the learning goal is reduced, the learning effects of the experience increase. We also believe that PF games can promote learning through epistemic actions, that is, actions performed to uncover complex information to compute mentally, sometimes through trial-and-error [201]. Besides providing feedback, the audio cues used in the games promote chemistry literacy by repeating the names of the elements selected in the covalent bonding.

G6 *Promoting collaboration*

Augmented Reality techniques can develop different interfaces, providing a collaborative learning environment. PF in the Wild offered a collaborative environment, where the virtual and real space interactions promoted communication behaviors, leading the children to perform the game tasks together. While each participant had access to the game using their mobile phone, students gathered and directed each other to overcome game challenges associated with the educational content. According to research, collaborative experiences provide deeper learning since children consider various perspectives and direct each other to study different aspects of the educational content [201, 67].

In the case of PF in the Wild, the game supports a collaborative and competitive environment (activity moving around the physical space to scan and combine chemical elements). It promotes inquiry, active observation, reciprocal teaching through colleagues, and peripheral participation with multiple modes of representation. Also, working with peers allows participants to acquire information (e.g., which chemical elements to join) that is assimilated and accommodated into their existing knowledge (need to combine elements to create substances) and to adapt this information to their real world (problem-solving to overcome the challenge), thus contributing to their cognitive development. This process is aligned with Piaget's constructivism idea of equilibration, which claims that when presented with new or unexpected knowledge, we try to assimilate it by rearranging it in a manner that can be accommodated to make sense, leading to a cognitive adaptation [127, 306]. According to Piaget and Vygotsky, activities that provide the opportunity for social interaction and language adaptation can facilitate the child's cognitive transition from concrete to formal operational stage [250, 345, 234].

Nevertheless, while PF in the Wild and PF Discovery fostered a collaborative environment, PF an Augmented Journey gameplay activities, which required a greater focus on AR information, did not provide such interactions. Consequently, to establish a collaborative setting, it is imperative to design AR technology to facilitate activities enabling this kind of collaboration.

RQ3- Can AR Serious Games improve children's affects on chemistry and facilitate the learning of abstract content about the Periodic Table?

AR Serious Games can potentially facilitate the learning of concepts of the Periodic Table. All quantitative results demonstrated a significant positive improvement in the learning outcome of the participants, with one of the studies showing a correlation between the motivation and engagement of the participants and the learning outcome. Using a framework that integrates Chemistry's multi-level of understanding, applying learning by thinking, feeling, and doing approach, and balancing game elements with pedagogical methods can positively affect the student's performance in chemistry. While the games displayed new and abstract concepts, the use of the game's pedagogical approach described previously seems effective.

AR Serious games can help demystify children's perceptions of the complexity of chemistry and encourage them to continue their studies with an open mind. After interacting with PF games, all our studies showed a significant positive change in the affects of chemistry. Quantitative results showcase an increase in the positive affects and decreasing in the negative affects. Our qualitative results from observational notes, video analyses, and interviews reaffirm these results; besides showing enjoyment while interacting with the games, preteens voice their opinions about chemistry being interesting and useful.

Overall, we believe that the results from the conducted studies during this thesis showcase the potential of the PF games to facilitate the learning and understanding the basic concept of the Periodic Table. In this manner, PF games enabled us to address the complexity of chemistry in all its representational modes to facilitate its understanding while engaging and promoting the interest of preteens.

Chapter 9

Conclusion, Limitations, and Future Work

The final chapter of this thesis discusses the research conclusions, limitations, future research directions, and final remarks.

This research thesis's initially stated overarching aim was to investigate how AR serious games can facilitate and engage preteen students with chemistry and STEM domains. Based on the previous body of work, we identified a need for more scientific design principles and more application with an assessment of the pedagogical methods to analyze the efficacy of these tools and their impact on younger students. We designed and developed three novel AR serious games to support teaching and learning chemistry, namely: PF Discovery, PF an Augmented Journey, and finally, PF in the Wild. The games were iterated, tested, and refined, providing the opportunity to analyze and find evidence of the potential of AR Serious Games to engage and enhance preteens' understanding of chemistry concepts employing the Research through Design methodology. This was achieved by providing adapted learning content, using game elements (balancing technology, mechanics, pedagogy, aesthetics, and storytelling), and finally, providing assessment and iterations according to the game dynamics in both formal and informal learning contexts.

The thesis contribution is centered around the design and lessons learned while producing three novel AR serious game artifacts. The research outcomes provide guidelines that can be implemented by game designers and developers aiming to create educational Augmented Reality (AR) Serious Games.

In this context, participatory and collaborative design approaches can shape key methods, including pedagogical and game elements strategies, to provide effective and meaningful learning impact. Balancing game elements and incorporating gamification elements are crucial to captivating and engaging children with the learning content. Each game component, including aesthetics, storytelling, mechanics, technology, and pedagogical methods, influences the game's dynamics and impacts the overall experience and learning.

While the overall study results of the presented thesis were optimistic, several limitations in this research could be addressed in the future.

Logistics and the Covid-19 pandemic limited the opportunity to engage more children in the co-design and incremental development of the games. We aim to expand on this missed opportunity in the future.

The games were coded/developed for a non-responsive specific aspect ratio, limiting the apps to run on the Samsung Edge 7 mobile device. As a result, the number of participants who interacted with the games at the time was limited by the available equipment (10 mobile phones). This led to the study design considering other activities to keep some students occupied while waiting for their turn to interact with the games. It also increased the time and human resources needed to conclude each study.

Conducting studies at school premises while providing the opportunity for larger sample groups limits the number of studies according to student class and teacher availability. During the school year, there are specific moments when teachers and coordinators can dedicate time to extracurricular activities, such as before the end of the school year or just before a long holiday (like Christmas or Easter). While the recall or week-after-study could provide insights into the retention of content knowledge, the school time restrictions (in our case, the end of the school year) limited the gathering of this data. A similar situation occurs in a non-formal learning school context, where children's attendance is optional, and only a limited number of participants came back for a follow-up study to gather week-after data. We aim to collaborate with designated teachers and schools to conduct several studies throughout the school year that can be integrated into their lessons.

We also believe that the PF AR gameplay (rotation of the cube to gather information and movement within the space to collect elements or navigate the 3D world) can benefit preteens' development of spatial skills. However, while we attempted to correlate the interaction of PF games, participants' spatial skills, and learning outcomes, only one study was conducted, and these claims need to be validated. In the future, we intend to conduct a longitudinal study, allowing participants to interact with the games at several points, gather data, and analyze their effects. The collaboration with designated schools will also allow us to assess the novelty effect, which can be a factor influencing participants' engagement.

Finally, in the future, we aim to include more chemical elements within the games to expand the content regarding the Periodic Table and increase the replayability of the games.

In conclusion, we recommend the symbiosis of pedagogical experience and technical expertise to fully leverage the potential of AR serious games. The success of these tools is based on more than just the technology's technical characteristics but on the effective implementation of pedagogical strategies. Designers and developers can contribute their technical skills and knowledge to ensure the usability and engagement of the participants, while teachers provide pedagogical guidance regarding the content. Combining these two aspects can create impactful and engaging AR serious games for educational purposes.

Bibliography

[1] M. Abdinejad, B. Talaie, H. S. Qorbani, and S. Dalili. "Student perceptions using augmented reality and 3d visualization technologies in chemistry education". In: *Journal of Science Education and Technology* 30 (2021), pp. 87–96 (cit. on p. 48).

[2] C. C. Abt. "Serious Games. New York: Viking, 1970, 176 pp.,lc 79-83234". In: *Am. Behav. Sci* 14.1 (1970), p. 129. URL: https://doi.org/10.1177/000276427001400113 (cit. on p. 13).

[3] E. Adams. *Fundamentals of construction and simulation game design*. New Riders, 2013 (cit. on p. 24).

[4] K. Adbo and C. Vidal Carulla. "Learning about science in preschool: Play-based activities to support children's understanding of chemistry concepts". In: *International Journal of Early Childhood* 52.1 (2020), pp. 17–35 (cit. on p. 58).

[5] S. Agrewal, A. M. D. Simon, S. Bech, K. B. Baerentsen, and S. Forchammer. "Defining immersion:: literature review and implications for research on audiovisual experiences". In: *Journal of the Audio Engineering Society* 68.6 (2020), pp. 404–417 (cit. on p. 36).

[6] V. Aleven, E. Myers, M. Easterday, and A. Ogan. "Toward a framework for the analysis and design of educational games". In: *2010 third IEEE international conference on digital game and intelligent toy enhanced learning*. IEEE. 2010, pp. 69–76 (cit. on p. 34).

[7] J. An, L.-P. Poly, and T. A. Holme. "Usability testing and the development of an augmented reality application for laboratory learning". In: *Journal of Chemical Education* 97.1 (2019), pp. 97–105. URL: https://doi.org/10.1021/acs.jchemed.9b00453 (cit. on p. 48).

[8] R. Andrea, S. Lailiyah, F. Agus, and R. Ramadiani. ""Magic Boosed" an elementary school geometry textbook with marker-based augmented reality". In: *TELKOMNIKA (Telecommunication Computing Electronics and Control)* 17.3 (2019), pp. 1242–1249 (cit. on p. 44).

[9] M. Appel and M. Mara. "The persuasive influence of a fictional character's trustworthiness". In: *Journal of Communication* 63.5 (2013), pp. 912–932 (cit. on p. 115).

[10] C. Arcos, W. Fuertes, C. Villacís, M. Zambrano, T. Noboa, A. Tacuri, H. Aules, and T. Toulkeridis. "Playful and interactive environment-based augmented reality to stimulate learning of children". In: *2016 18th Mediterranean Electrotechnical Conference (MELECON)*. IEEE. 2016, pp. 1–6. URL: https://doi.org/10.1109/MELCON.2016.7495421 (cit. on p. 26).

[11] D. Ardura, Á. Zamora, and A. Pérez-Bitrián. "The role of motivation on secondary school students' causal attributions to choose or abandon chemistry". In: *Chemistry Education Research and Practice* 22.1 (2021), pp. 43–61. URL: doi.org/10.1039/D0RP00168F (cit. on pp. 2, 15).

[12] J. Arguëllo and R. E. Dempski. *Fast, simple, student generated augmented reality approach for protein visualization in the classroom and home study*. 2020 (cit. on p. 47).

[13] S. Arnab, T. Lim, M. B. Carvalho, F. Bellotti, S. De Freitas, S. Louchart, N. Suttie, R. Berta, and A. De Gloria. "Mapping learning and game mechanics for serious games analysis". In: *British Journal of Educational Technology* 46.2 (2015), pp. 391–411. URL: https://doi.org/10.1111/bjet.12113 (cit. on p. 34).

[14] H. C. Arnseth. "Activity theory and situated learning theory: contrasting views of educational practice". In: *Pedagogy, Culture & Society* 16.3 (2008), pp. 289–302 (cit. on p. 121).

[15] T. Arvanitis, A. Petrou, and J. F. Knight. "Human factors and qualitative pedagogical evaluation of a MAR system for science education used by learners with physical disabilities". In: *Personal and ubiquitous computing* 13 (2009), pp. 243–250 (cit. on p. 44).

[16] P. M. Asaro. "Transforming society by transforming technology: the science and politics of participatory design". In: *Accounting, Management and Information Technologies* 10.4 (2000), pp. 257–290 (cit. on p. 53).

[17] P. Aubusson, D. Treagust, and A. Harrison. "Learning and teaching science with analogies and metaphors". In: *The World of Science Education*. Brill, 2009, pp. 199–216. URL: 10.1163/9789087909291_014 (cit. on p. 82).

[18] N. R. Augustine, P. R. Vagelos, and W. Wulf. "Rising above the gathering storm: Energizing and employing America for a brighter economic future". In: *National Academies Statements on Science, Technology, and Global Economic Competitiveness to the 109th Congress (First Session)*. 2005. URL: https://doi.org/10.17226/11463 (cit. on p. 18).

[19] G. A. Austin. *A study of thinking*. Routledge, 2017. URL: https://doi.org/10.4324/9781315083223 (cit. on pp. 26, 32).

[20] S. Avargil, Z. Kohen, and Y. J. Dori. "Trends and perceptions of choosing chemistry as a major and a career". In: *Chemistry Education Research and Practice* 21.2 (2020), pp. 668–684. URL: https://doi.org/10.1039/C9RP00158A (cit. on p. 15).

[21] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre. "Recent advances in augmented reality". In: *IEEE computer graphics and applications* 21.6 (2001), pp. 34–47. URL: https://doi.org/10.1109/38.963459 (cit. on p. 20).

[22] R. T. Azuma. "A survey of augmented reality". In: *Presence: teleoperators & virtual environments* 6.4 (1997), pp. 355–385 (cit. on p. 20).

[23] Z. Babakr, P. Mohamedamin, and K. Kakamad. "Piaget's cognitive developmental theory: Critical review". In: *Education Quarterly Reviews* 2.3 (2019). URL: https://doi.org/10.31014/aior.1993.02.03.84 (cit. on pp. 12, 14).

[24] J. L. Bacca Acosta, S. M. Baldiris Navarro, R. Fabregat Gesa, S. Graf, et al. "Augmented reality trends in education: a systematic review of research and applications". In: *Journal of Educational Technology and Society, 2014, vol. 17, núm. 4, p. 133-149* (2014) (cit. on pp. 44, 85).

[25] A. Bagiati, S. Y. Yoon, D. Evangelou, and I. Ngambeki. "Engineering curricula in early education: Describing the landscape of open resources." In: *Early Childhood Research & Practice* 12.2 (2010), n2 (cit. on p. 15).

[26] R. Baillargeon, J. Li, Y. Gertner, and D. Wu. *How do infants reason about physical events?* Wiley-Blackwell, 2011. URL: https://doi.org/10.1002/9781444325485.ch1 (cit. on p. 13).

[27] F. Bakri, O. Marsal, and D. Muliyati. "Textbooks equipped with augmented reality technology for physics topic in high-school". In: *Jurnal Penelitian & Pengembangan Pendidikan Fisika* 5.2 (2019), pp. 113–122 (cit. on p. 45).

[28] A. T. Balaban and D. J. Klein. "Is chemistry'The Central Science'? How are different sciences related? Co-citations, reductionism, emergence, and posets". In: *Scientometrics* 69.3 (2006), pp. 615–637. URL: https://doi.org/10.1007/s11192-006-0173-2 (cit. on p. 15).

[29] R. Ballon. *Breathing life into your characters*. Penguin, 2009 (cit. on p. 31).

[30] T. Bancroft. *Creating characters with personality*. Watson-Guptill, 2016 (cit. on p. 31).

[31] A. Bandura and S. Wessels. *Self-efficacy*. Vol. 4. na, 1994 (cit. on pp. 17, 136, 141).

[32] G. M. Battle, G. M. Ferrence, and F. H. Allen. "Applications of the Cambridge Structural Database in chemical education". In: *Journal of Applied Crystallography* 43.5 (2010), pp. 1208–1223 (cit. on p. 48).

[33] D. Beck, L. Morgado, and P. O'Shea. "Finding the gaps about uses of immersive learning environments: a survey of surveys". In: *Journal of Universal Computer Science* 26 (2020), pp. 1043–1073 (cit. on p. 37).

[34] L. A. Beck. *Csikszentmihalyi, Mihaly.(1990). Flow: The psychology of optimal experience*. 1992 (cit. on p. 25).

[35] C. Beşevli, E. Salman, T. Goksun, H. Urey, and O. Özcan. "MaR-T: Designing a projection-based mixed reality system for nonsymbolic math development of preschoolers: Guided by theories of cognition and learning". In: *Proceedings of the 18th ACM International Conference on Interaction Design and Children*. 2019, pp. 280–292 (cit. on p. 46).

[36] T. Bi and S. Song. "Problems and solutions of educational game development". In: *2011 International Conference on Consumer Electronics, Communications and Networks (CECNet)*. IEEE. 2011, pp. 3364–3367 (cit. on p. 50).

[37] M. Billinghurst, A. Clark, G. Lee, et al. "A survey of augmented reality". In: *Foundations and Trends® in Human–Computer Interaction* 8.2-3 (2015), pp. 73–272. URL: DOI:%2010.1561/1100000049 (cit. on pp. 21, 23, 45, 72, 100).

[38] M. Billinghurst, H. Kato, and I. Poupyrev. "The magicbook-moving seamlessly between reality and virtuality". In: *IEEE Computer Graphics and applications* 21.3 (2001), pp. 6–8 (cit. on p. 44).

[39] C. Boletsis and S. McCallum. "The table mystery: An augmented reality collaborative game for chemistry education". In: *Serious Games Development and Applications: 4th International Conference, SGDA 2013, Trondheim, Norway, September 25-27, 2013. Proceedings 4*. Springer. 2013, pp. 86–95 (cit. on p. 49).

[40] E. Bonsignore, A. J. Quinn, A. Druin, and B. B. Bederson. "Sharing stories "in the wild" a mobile storytelling case study using storykit". In: *ACM Transactions on Computer-Human Interaction (TOCHI)* 20.3 (2013), pp. 1–38 (cit. on p. 74).

[41] M. C. Bottia, E. Stearns, R. A. Mickelson, and S. Moller. "Boosting the numbers of STEM majors? The role of high schools with a STEM program". In: *Science Education* 102.1 (2018), pp. 85–107. URL: https://doi.org/10.1002/sce.21318 (cit. on pp. 13, 14).

[42] M. Bower, C. Howe, N. McCredie, A. Robinson, and D. Grover. "Augmented Reality in education–cases, places and potentials". In: *Educational Media International* 51.1 (2014), pp. 1–15. URL: https://doi.org/10.1080/09523987.2014.889400 (cit. on pp. 2, 27, 44).

[43] B. Brathwaite and I. Schreiber. *Challenges for game designers*. Course Technology/Cengage Learning Boston, Massachusetts, 2009 (cit. on p. 27).

[44] K. Brenneman. "Assessment for Preschool Science Learning and Learning Environments." In: *Early Childhood Research & Practice* 13.1 (2011), n1 (cit. on p. 13).

[45] S. L. Britner and F. Pajares. "Sources of science self-efficacy beliefs of middle school students". In: *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching* 43.5 (2006), pp. 485–499 (cit. on p. 57).

[46] J. Britton. "Vygotsky's contribution to pedagogical theory". In: *English in Education* 21.3 (1987), pp. 22–26. URL: https://doi.org/10.1111/j.1754-8845.1987.tb00951.x (cit. on pp. 13, 27, 145).

[47] R. Brunken, R. Moreno, and J. L. Plass. *Cognitive load theory*. Cambridge University Press, 2010 (cit. on p. 76).

[48] B. Bucat and M. Mocerino. "Learning at the sub-micro level: Structural representations". In: *Multiple representations in chemical education* (2009), pp. 11–29. URL: https://doi.org/10.1007/978-1-4020-8872-8_2 (cit. on p. 16).

[49] D. Buckingham. *Media education: Literacy, learning and contemporary culture*. John Wiley & Sons, 2013 (cit. on p. 2).

[50] R. W. Bybee and B. Fuchs. "Preparing the 21st century workforce: A new reform in science and technology education." In: (2006). URL: https://doi.org/10.1002/tea.20147 (cit. on p. 15).

[51] S. Cai, F.-K. Chiang, Y. Sun, C. Lin, and J. J. Lee. "Applications of augmented reality-based natural interactive learning in magnetic field instruction". In: *Interactive Learning Environments* 25.6 (2017), pp. 778–791 (cit. on p. 46).

[52] S. Cai, X. Wang, and F.-K. Chiang. "A case study of Augmented Reality simulation system application in a chemistry course". In: *Computers in human behavior* 37 (2014), pp. 31–40. URL: https://doi.org/10.1016/j.chb.2014.04.018 (cit. on pp. 3, 45, 47, 72).

[53] P. Cairns, A. L. Cox, M. Day, H. Martin, and T. Perryman. "Who but not where: The effect of social play on immersion in digital games". In: *International Journal of Human-Computer Studies* 71.11 (2013), pp. 1069–1077. URL: https://doi.org/10.1016/j.ijhcs.2013.08.015 (cit. on p. 26).

[54] S. Camara, V. Nisi, and T. Romão. "Enhancing Children Spatial Skills with Augmented Reality Serious Games". In: *Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play*. 2021, pp. 94–100 (cit. on p. 8).

[55] S. M. Camara Olim, V. Nisi, and E. Rubegni. ""Periodic Fable Discovery" Using Tangible Interactions and Augmented Reality to Promote STEM Subjects". In: *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction*. 2023, pp. 1–15 (cit. on p. 8).

[56] S. M. Câmara Olim, V. Nisi, and E. Rubegni. "Periodic Fable Augmenting Chemistry with Technology, Characters and Storytelling". In: *Interaction Design and Children*. 2022, pp. 123–136 (cit. on p. 8).

[57] E. Campos-Pajuelo, L. Vargas-Hernandez, F. Sierra-Liñan, J. Zapata-Paulini, and M. Cabanillas-Carbonell. "Learning the chemical elements through an augmented reality application for elementary school children". In: *Advances in Mobile Learning Educational Research* 2.2 (2022), pp. 493–501. URL: 10.25082/AMLER.2022.02.018 (cit. on p. 49).

[58] J. Cerqueira, B. Cleto, J. M. Moura, and C. Sylla. "Visualizing platonic solids with augmented reality". In: *Proceedings of the 17th ACM Conference on Interaction Design and Children*. 2018, pp. 489–492. URL: https://doi.org/10.1145/3202185.3210761 (cit. on p. 33).

[59] E. J. Chappin, X. Bijvoet, and A. Oei. "Teaching sustainability to a broad audience through an entertainment game–The effect of Catan: Oil Springs". In: *Journal of cleaner production* 156 (2017), pp. 556–568 (cit. on p. 24).

[60] S. Chatterjee, A. Mohanty, and B. Bhattacharya. "Peer collaboration, facilitator intervention, and learning styles in computer game-based learning: Initial findings from an empirical study". In: *Proceedings of the European conference on games based learning*. 2011, pp. 683–690 (cit. on p. 42).

[61] J. Chen. "Flow in games (and everything else)". In: *Communications of the ACM* 50.4 (2007), pp. 31–34 (cit. on p. 25).

[62] J.-J. Chen, Y. Hsu, W. Wei, and C. Yang. "Continuance intention of augmented reality textbooks in basic design course". In: *Education Sciences* 11.5 (2021), p. 208 (cit. on p. 44).

[63] K. Chen. "An Interactive Design Framework for Children's Apps for Enhancing Emotional Experience". In: *Interacting with Computers* (2022) (cit. on p. 61).

[64] P. Chen, X. Liu, W. Cheng, and R. Huang. "A review of using Augmented Reality in Education from 2011 to 2016". In: *Innovations in smart learning* (2017), pp. 13–18. URL: https://doi.org/10.1007/978-981-10-2419-1_2 (cit. on p. 22).

[65] S.-Y. Chen and S.-Y. Liu. "Using augmented reality to experiment with elements in a chemistry course". In: *Computers in Human Behavior* 111 (2020), p. 106418. URL: https://doi.org/10.1016/j.chb.2020.106418 (cit. on p. 3).

[66] C.-H. Cheng and C.-H. Su. "A Game-based learning system for improving student's learning effectiveness in system analysis course". In: *Procedia-Social and Behavioral Sciences* 31 (2012), pp. 669–675. URL: https://doi.org/10.1016/j.sbspro.2011.12.122 (cit. on p. 2).

[67] M. T. Chi. "Active-constructive-interactive: A conceptual framework for differentiating learning activities". In: *Topics in cognitive science* 1.1 (2009), pp. 73–105 (cit. on p. 147).

[68] S. Chi, Z. Wang, X. Liu, and L. Zhu. "Associations among attitudes, perceived difficulty of learning science, gender, parents' occupation and students' scientific competencies". In: *International Journal of Science Education* 39.16 (2017), pp. 2171–2188. URL: https://doi.org/10.1080/09500693.2017.1366675 (cit. on p. 15).

[69] R. Christensen and G. Knezek. "Relationship of middle school student STEM interest to career intent". In: *Journal of education in science environment and health* 3.1 (2017), pp. 1–13. URL: https://doi.org/10.21891/jeseh.275649 (cit. on p. 15).

[70] C. A. Clark. "Serious games". In: *New York: Viking* (1970) (cit. on p. 26).

[71] R. E. Clark. "Reconsidering research on learning from media". In: *Review of educational research* 53.4 (1983), pp. 445–459 (cit. on p. 36).

[72] D. H. Clements and J. Sarama. "Math, science, and technology in the early grades". In: *The Future of Children* (2016), pp. 75–94. URL: https://doi.org/10.1353/foc.2016.0013 (cit. on p. 18).

[73] R. Cobo-Rendón, M. V. Pérez-Villalobos, D. Páez-Rovira, and M. Gracia-Leiva. "A longitudinal study: Affective wellbeing, psychological wellbeing, self-efficacy and academic performance among first-year undergraduate students". In: *Scandinavian Journal of Psychology* 61.4 (2020), pp. 518–526. URL: https://doi.org/10.1111/sjop.12618 (cit. on p. 14).

[74] O. M. Colakoglu and O. Akdemir. "Motivational measure of the instruction compared: Instruction based on the ARCS motivation theory vs traditional instruction in blended courses". In: *Turkish Online Journal of Distance Education* 11.2 (2010), pp. 73–89 (cit. on p. 85).

[75] B. Cold, A. Kolstad, and S. Larssæther. *Aesthetics, well-being and health: Abstracts on theoretical and empirical research within environmental aesthetics*. Norsk form, 1998 (cit. on p. 31).

[76] N. R. Council et al. *Learning science in informal environments: People, places, and pursuits*. National Academies Press, 2009 (cit. on p. 14).

[77] N. Cross. "Design research: A disciplined conversation". In: *Design issues* 15.2 (1999), pp. 5–10 (cit. on p. 52).

[78] K. Danielsson and C. Wiberg. "Participatory design of learning media: Designing educational computer games with and for teenagers". In: *Interactive Technology and Smart Education* 3.4 (2006), pp. 275–291 (cit. on p. 55).

[79] S. Dargan, S. Bansal, M. Kumar, A. Mittal, and K. Kumar. "Augmented Reality: A Comprehensive Review". In: *Archives of Computational Methods in Engineering* 30.2 (2023), pp. 1057–1080. URL: https://doi.org/10.1007/s11831-022-09831-7 (cit. on p. 22).

[80] V. V. Davydov. "The influence of LS Vygotsky on education theory, research, and practice". In: *Educational researcher* 24.3 (1995), pp. 12–21. URL: https://doi.org/10.3102/0013189X024003012 (cit. on p. 13).

[81] E. L. Deci and R. M. Ryan. *Handbook of self-determination research*. University Rochester Press, 2004 (cit. on p. 35).

[82] N. K. DeJarnette. "Implementing STEAM in the early childhood classroom." In: *European Journal of STEM Education* 3.3 (2018), p. 18. URL: https://doi.org/10.20897/ejsteme/3878 (cit. on p. 15).

[83] S. Deterding, D. Dixon, R. Khaled, and L. Nacke. "From game design elements to gamefulness: defining"gamification"". In: *Proceedings of the 15th international academic MindTrek conference: Envisioning future media environments*. 2011, pp. 9–15. URL: https://doi.org/10.1145/2181037.2181040 (cit. on p. 35).

[84] C. Dewi, P. Pahriah, and A. Purmadi. "The urgency of digital literacy for generation Z students in chemistry learning". In: *International Journal of Emerging Technologies in Learning (iJET)* 16.11 (2021), pp. 88–103. URL: https://doi.org/10.3991/ijet.v16i11.19871 (cit. on pp. 13, 14).

[85] F. Dobal and V. Lalioti. "Circular Species: Designing critical thinking into children's science education through biomaterials and augmented reality". In: *Interaction Design and Children*. 2021, pp. 8–17 (cit. on pp. 118, 120).

[86] A. Donker, P. Markopoulos, et al. "A comparison of think-aloud, questionnaires and interviews for testing usability with children". In: *People and Computers* (2002), pp. 305–316 (cit. on p. 79).

[87] A. Druin. "The role of children in the design of new technology". In: *Behaviour and information technology* 21.1 (2002), pp. 1–25 (cit. on pp. 37, 55, 79).

[88] X. Duan, S.-J. Kang, J. I. Choi, and S. K. Kim. "Mixed reality system for virtual chemistry lab". In: *KSII Transactions on Internet and Information Systems (TIIS)* 14.4 (2020), pp. 1673–1688 (cit. on p. 49).

[89] M. Dunleavy and C. Dede. "Augmented reality teaching and learning". In: *Handbook of research on educational communications and technology* (2014), pp. 735–745 (cit. on pp. 21, 46, 47).

[90] M. Dunleavy, C. Dede, and R. Mitchell. "Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning". In: *Journal of science Education and Technology* 18 (2009), pp. 7–22. URL: DOI:%2010.1007/s10956-008-9119-1 (cit. on pp. 27, 99, 121).

[91] J. V. Ebenezer. "A hypermedia environment to explore and negotiate students' conceptions: Animation of the solution process of table salt". In: *Journal of science Education and Technology* 10 (2001), pp. 73–92 (cit. on pp. 16, 144).

[92] C. Ebesutani, J. Regan, A. Smith, S. Reise, C. Higa-McMillan, and B. F. Chorpita. "The 10-item positive and negative affect schedule for children, child and parent shortened versions: application of item response theory for more efficient assessment". In: *Journal of Psychopathology and behavioral Assessment* 34 (2012), pp. 191–203 (cit. on p. 129).

[93] L. Edomwonyi-Otu and A. Avaa. "The challenge of effective teaching of chemistry: A case study". In: *Leonardo Electronic Journal of Practices and Technologies* 10.18 (2011), pp. 1–8 (cit. on p. 48).

[94] S. Egenfeldt-Nielsen. "Overview of research on the educational use of video games". In: *Nordic journal of digital literacy* 1.3 (2006), pp. 184–214 (cit. on p. 42).

[95] S. B. Ehrlich, S. C. Levine, and S. Goldin-Meadow. "The importance of gesture in children's spatial reasoning." In: *Developmental psychology* 42.6 (2006), p. 1259 (cit. on p. 122).

[96] I. Eilks and A. Hofstein. *Relevant chemistry education: From theory to practice*. Springer, 2015 (cit. on p. 15).

[97] H. Elmunsyah, W. Hidayat, and K. Asfani. "Interactive learning media innovation: utilization of augmented reality and pop-up book to improve user's learning autonomy". In: *Journal of Physics: Conference Series*. Vol. 1193. 1. IOP Publishing. 2019, p. 012031 (cit. on p. 45).

[98] M. Eraut. "Non-formal learning and tacit knowledge in professional work". In: *British journal of educational psychology* 70.1 (2000), pp. 113–136. URL: https://doi.org/10.1348/000709900158001 (cit. on p. 11).

[99] C. Erbas and V. Demirer. "The effects of augmented reality on students' academic achievement and motivation in a biology course". In: *Journal of Computer Assisted Learning* 35.3 (2019), pp. 450–458. URL: https://doi.org/10.1111/jcal.12350 (cit. on p. 2).

[100] D. G. Erbil. "A review of flipped classroom and cooperative learning method within the context of Vygotsky theory". In: *Frontiers in Psychology* 11 (2020), p. 1157. URL: https://doi.org/10.3389/fpsyg.2020.01157 (cit. on p. 14).

[101] S. Erhel and E. Jamet. "Digital game-based learning: Impact of instructions and feedback on motivation and learning effectiveness". In: *Computers & education* 67 (2013), pp. 156–167. URL: https://doi.org/10.1016/j.compedu.2013.02.019 (cit. on p. 26).

[102] K. Eriksen, B. E. Nielsen, and M. Pittelkow. *Visualizing 3D molecular structures using an augmented reality app*. 2020 (cit. on p. 47).

[103] A. Ewais and O. D. Troyer. "A usability and acceptance evaluation of the use of augmented reality for learning atoms and molecules reaction by primary school female students in Palestine". In: *Journal of Educational Computing Research* 57.7 (2019), pp. 1643–1670. URL: 10.1177/0735633119855609 (cit. on pp. 48, 49).

[104] L. R. Fabrigar and R. E. Petty. "The role of the affective and cognitive bases of attitudes in susceptibility to affectively and cognitively based persuasion". In: *Personality and social psychology bulletin* 25.3 (1999), pp. 363–381 (cit. on p. 141).

[105] H. Faridi, N. Tuli, A. Mantri, G. Singh, and S. Gargrish. "A framework utilizing augmented reality to improve critical thinking ability and learning gain of the students in Physics". In: *Computer Applications in Engineering Education* 29.1 (2021), pp. 258–273 (cit. on p. 46).

[106] A. Fatemah, S. Rasool, and U. Habib. "Interactive 3D visualization of chemical structure diagrams embedded in text to aid spatial learning process of students". In: *Journal of Chemical Education* 97.4 (2020), pp. 992–1000 (cit. on p. 47).

[107] J. Fernandes, T. Brandão, S. M. Almeida, and P. Santana. "An educational game to teach children about air quality using augmented reality and tangible interaction with sensors". In: *International Journal of Environmental Research and Public Health* 20.5 (2023), p. 3814 (cit. on p. 46).

[108] S. Q. Fernandes and C. M. R. Madhuranthakam. "Molecular Dynamics Simulation of a Superhydrophobic Cellulose Derivative Targeted for Eco-Friendly Packaging Material". In: *Macromolecular Theory and Simulations* 30.1 (2021), p. 2000056. URL: https://doi.org/10.1002/mats.202000056 (cit. on p. 48).

[109] C. A. Ferraz, A. C. A. Sousa, D. Caramelo, F. Delgado, A. P. de Oliveira, and M. R. Pastorinho. "Chemical profile and eco-safety evaluation of essential oils and hydrolates from Cistus ladanifer, Helichrysum italicum, Ocimum basilicum and Thymbra capitata". In: *Industrial Crops and Products* 175 (2022), p. 114232 (cit. on pp. 106, 119).

[110] B. Ferrell, M. M. Phillips, and J. Barbera. "Connecting achievement motivation to performance in general chemistry". In: *Chemistry Education Research and Practice* 17.4 (2016), pp. 1054–1066. URL: https://doi.org/10.1039/C6RP00148C (cit. on pp. 2, 15).

[111] C. Fisher. *Designing games for children: Developmental, usability, and design considerations for making games for kids*. CRC Press, 2014 (cit. on p. 24).

[112] P. Fissler, I.-T. Kolassa, and C. Schrader. "Educational games for brain health: revealing their unexplored potential through a neurocognitive approach". In: *Frontiers in psychology* 6 (2015), p. 1056 (cit. on p. 26).

[113] J. H. Flavell. "Development of children's knowledge about the mental world". In: *International journal of behavioral development* 24.1 (2000), pp. 15–23. URL: https://doi.org/10.1080/016502500383421 (cit. on p. 17).

[114] M. Fleer and N. Pramling. "A Cultural-Historical study of children learning Science". In: *Dordrecht and New York: Springer* (2014). URL: https://doi.org/10.1007/978-94-017-9370-4 (cit. on pp. 13, 14).

[115] J. Forlizzi, J. Zimmerman, and E. Stolterman. "From design research to theory: Evidence of a maturing field". In: *Proceedings of IASDR* 9 (2009), pp. 2889–2898 (cit. on p. 52).

[116] A. Foster and M. Shah. "PCaRD: A model for teachers to integrate games in their classrooms". In: *Society for Information Technology & Teacher Education International Conference*. Association for the Advancement of Computing in Education (AACE). 2012, pp. 2525–2533 (cit. on p. 24).

[117] L. Frankel and M. Racine. "The complex field of research: For design, through design, and about design". In: (2010) (cit. on p. 52).

[118] B. L. Fredrickson. "Positive emotions broaden and build". In: *Advances in experimental social psychology*. Vol. 47. Elsevier, 2013, pp. 1–53. URL: https://doi.org/10.1016/B978-0-12-407236-7.00001-2 (cit. on p. 14).

[119] A. Frick and W. Möhring. "Mental object rotation and motor development in 8-and 10-month-old infants". In: *Journal of experimental child psychology* 115.4 (2013), pp. 708–720 (cit. on p. 122).

[120] D. B. Fried, P. P. Tinio, A. Gubi, and J. P. Gaffney. "Enhancing elementary science learning through organic chemistry modeling and visualization". In: *European Journal of Science and Mathematics Education* 7.2 (2019), pp. 73–82. URL: https://doi.org/10.30935/scimath/9535 (cit. on p. 3).

[121] D. Gabel. "Improving teaching and learning through chemistry education research: A look to the future". In: *Journal of Chemical education* 76.4 (1999), p. 548. URL: https://doi.org/10.1021/ed076p548 (cit. on p. 16).

[122] J. Gallardo and P. Gallardo. "Teorías del juego como recurso educativo". In: *Conferencia llevada a cabo en el IV Congreso Internacional sobre Innovación Pedagógica y Praxis Educativa, Sevilla, España. Recuperado de https://www. innovagogia.es/innovagogia-2018.* 2018 (cit. on p. 24).

[123] A. Gardeli and S. Vosinakis. "ARQuest: A tangible augmented reality approach to developing computational thinking skills". In: *2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*. IEEE. 2019, pp. 1–8 (cit. on p. 45).

[124] H. Gardner. "Using multiple intelligences to improve negotiation theory and practice". In: *Negotiation journal* 16.4 (2000), pp. 321–324. URL: https://doi.org/10.1111/j.1571-9979.2000.tb00760.x (cit. on p. 11).

[125] D. L. Gelman. *Design for kids: digital products for playing and learning*. Rosenfeld Media, 2014 (cit. on p. 61).

[126] J. L. Gillin. *Homo Ludens: A Study of the Play-Element in Culture.* 1951. URL: https://doi.org/10.2307/2087716 (cit. on p. 24).

[127] H. P. Ginsburg and S. Opper. *Piaget's theory of intellectual development*. Prentice-Hall, Inc, 1988 (cit. on pp. 135, 147).

[128] J. Glynn Jr et al. "The effects of a flipped classroom on achievement and student attitudes in secondary chemistry". In: (2013) (cit. on p. 57).

[129] A. Gomes and A. J. Mendes. "An environment to improve programming education". In: *Proceedings of the 2007 international conference on Computer systems and technologies*. 2007, pp. 1–6 (cit. on p. 41).

[130] T. Göttel. "ProBoNO: transferring knowledge of virtual environments to real world situations". In: *Proceedings of the 6th international conference on Interaction design and children*. 2007, pp. 81–88 (cit. on pp. 23, 45, 46).

[131] J. Green, G. Nelson, A. J. Martin, and H. Marsh. "The Causal Ordering of Self-Concept and Academic Motivation and Its Effect on Academic Achievement." In: *International Education Journal* 7.4 (2006), pp. 534–546 (cit. on p. 85).

[132] M. C. Green and T. C. Brock. "The role of transportation in the persuasiveness of public narratives." In: *Journal of personality and social psychology* 79.5 (2000), p. 701 (cit. on p. 115).

[133] R. Green. "The role of relational structures in indexing for the humanities". In: *Information services & use* 17.2-3 (1997), pp. 85–100 (cit. on p. 30).

[134] G. Groenhof. "Introduction to QM/MM simulations". In: *Biomolecular simulations: methods and protocols* (2013), pp. 43–66 (cit. on p. 48).

[135] A. Gupta, B. R. Lin, S. Ji, A. Patel, and D. Vogel. "Replicate and reuse: Tangible interaction design for digitally-augmented physical media objects". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–12. URL: https://doi.org/10.1145/3313831.3376139 (cit. on p. 23).

[136] J. Hammer, A. To, K. Schrier, S. L. Bowman, and G. Kaufman. "Learning and role-playing games". In: *Role-Playing Game Studies*. Routledge, 2018, pp. 283–299 (cit. on p. 26).

[137] M. D. Hanus and J. Fox. "Assessing the effects of gamification in the classroom: A longitudinal study on intrinsic motivation, social comparison, satisfaction, effort, and academic performance". In: *Computers & education* 80 (2015), pp. 152–161. URL: https://doi.org/10.1016/j.compedu.2014.08.019 (cit. on p. 35).

[138] A. G. Harrison and D. F. Treagust. "Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in grade 11 chemistry". In: *Science education* 84.3 (2000), pp. 352–381. URL: https://doi.org/10.1002/(SICI)1098-237X(200005)84:3%3C352::AID-SCE3%3E3.0.CO;2-J (cit. on pp. 16, 144).

[139] T. J. Harviainen. "The multi-tier game immersion theory." In: *As Larp Grows Up–Theory and Methods in Larp*. 2003, electronic–version (cit. on p. 33).

[140] P. J. Hay, R. L. Martin, and G. Schreckenbach. "Theoretical studies of the properties and solution chemistry of AnO22+ and AnO2+ aquo complexes for An= U, Np, and Pu". In: *The Journal of Physical Chemistry A* 104.26 (2000), pp. 6259–6270 (cit. on p. 48).

[141] J. C. Hayes and D. J. Kraemer. "Grounded understanding of abstract concepts: The case of STEM learning". In: *Cognitive research: principles and implications* 2.1 (2017), pp. 1–15. URL: https://doi.org/10.1186/s41235-016-0046-z (cit. on p. 12).

[142] J. Herskovitz, J. Wu, S. White, A. Pavel, G. Reyes, A. Guo, and J. P. Bigham. "Making mobile augmented reality applications accessible". In: *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility*. 2020, pp. 1–14 (cit. on p. 22).

[143] M. Host'oveckỳ, I. Salgovic, and R. Virágh. "Serious game in science education: How we can develop mathematical education". In: *2018 16th International Conference on Emerging eLearning Technologies and Applications (ICETA)*. IEEE. 2018, pp. 191–196. URL: 10.1109/ICETA.2018.8572158 (cit. on p. 26).

[144] Y.-H. Hung, C.-H. Chen, and S.-W. Huang. "Applying augmented reality to enhance learning: a study of different teaching materials". In: *Journal of Computer Assisted Learning* 33.3 (2017), pp. 252–266 (cit. on pp. 91, 143).

[145] R. Hunicke, M. LeBlanc, R. Zubek, et al. "MDA: A formal approach to game design and game research". In: *Proceedings of the AAAI Workshop on Challenges in Game AI*. Vol. 4. 1. San Jose, CA. 2004, p. 1722 (cit. on pp. 28, 30, 36).

[146] M. B. Ibáñez, Á. Di Serio, D. Villarán, and C. D. Kloos. "Experimenting with electromagnetism using augmented reality: Impact on flow student experience and educational effectiveness". In: *Computers & Education* 71 (2014), pp. 1–13 (cit. on p. 46).

[147] M. Z. Iqbal, E. Mangina, and A. G. Campbell. "Exploring the use of augmented reality in a kinesthetic learning application integrated with an intelligent virtual embodied agent". In: *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. IEEE. 2019, pp. 12–16 (cit. on p. 145).

[148] K. Isbister. *Better game characters by design: A psychological approach*. CRC Press, 2022 (cit. on p. 31).

[149] K. Isbister. "Enabling social play: A framework for design and evaluation". In: *Evaluating user experience in games: Concepts and methods* (2010), pp. 11–22 (cit. on p. 55).

[150] H. Ishii and B. Ullmer. "Tangible bits: towards seamless interfaces between people, bits and atoms". In: *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. 1997, pp. 234–241. URL: https://doi.org/10.1145/258549.258715 (cit. on p. 23).

[151] L. Z. Jaber and S. BouJaoude. "A macro–micro–symbolic teaching to promote relational understanding of chemical reactions". In: *International Journal of Science Education* 34.7 (2012), pp. 973–998. URL: https://doi.org/10.1080/09500693.2011.569959 (cit. on p. 16).

[152] H. Jang. "Identifying 21st century STEM competencies using workplace data". In: *Journal of science education and technology* 25 (2016), pp. 284–301. URL: https://doi.org/10.48550/ARXIV.1511.05858 (cit. on p. 2).

[153] A. Järvinen. *Games without frontiers: Theories and methods for game studies and design*. Tampere University Press, 2008 (cit. on p. 33).

[154] S. Jegede. "Students' anxiety towards the learning of chemistry in some Nigerian secondary schools". In: *Educational Research and Review* 2.7 (2007), pp. 193–197. URL: https://doi.org/10.18844/cjes.v14i2.2564 (cit. on p. 17).

[155] X. Jiang and K. Perkins. "A Conceptual Paper on the Application of the Picture Word Inductive Model Using Bruner's Constructivist View of Learning and the Cognitive Load Theory." In: *Interdisciplinary journal of teaching and learning* 3.1 (2013), pp. 8–17 (cit. on p. 76).

[156] L. Jiao, J. Li, L. L. Richard, Q. Sun, T. Stracensky, E. Liu, M. T. Sougrati, Z. Zhao, F. Yang, S. Zhong, et al. "Chemical vapour deposition of Fe–N–C oxygen reduction catalysts with full utilization of dense Fe–N4 sites". In: *Nature materials* 20.10 (2021), pp. 1385–1391 (cit. on p. 57).

[157] O. Jimenez, D. Arena, and U. Acholonu. "Tug-of-War: A card game for pulling students to fractions fluency". In: *Proceedings of the 7th international conference on Games+ Learning+ Society Conference*. 2011, pp. 119–127 (cit. on p. 24).

[158] R. T. Johnson and D. W. Johnson. "Active learning: Cooperation in the classroom". In: *The annual report of educational psychology in Japan* 47 (2008), pp. 29–30 (cit. on p. 27).

[159] M. C. Johnson-Glenberg. "Immersive VR and education: Embodied design principles that include gesture and hand controls". In: *Frontiers in Robotics and AI* (2018), p. 81 (cit. on p. 45).

[160] A. H. Johnstone. “Chemistry teaching-science or alchemy? 1996 Brasted lecture”. In: *Journal of chemical education* 74.3 (1997), p. 262. URL: https://doi.org/10.1021/ed074p262 (cit. on pp. 3, 16, 107).

[161] A. H. Johnstone. “Teaching of chemistry-logical or psychological?” In: *Chemistry Education Research and Practice* 1.1 (2000), pp. 9–15. URL: https://doi.org/10.1039/A9RP90001B (cit. on pp. 3, 5, 16, 72).

[162] A. H. Johnstone. “Why is science difficult to learn? Things are seldom what they seem”. In: *Journal of computer assisted learning* 7.2 (1991), pp. 75–83. URL: https://doi.org/10.1111/j.1365-2729.1991.tb00230.x (cit. on p. 16).

[163] R. P. Jolley, Z. Zhi, and G. V. Thomas. “How focus of interest in pictures changes with age: A cross-cultural comparison”. In: *International Journal of Behavioral Development* 22.1 (1998), pp. 127–149 (cit. on p. 31).

[164] O. A. Jones, M. Spichkova, and M. J. Spencer. *Chirality-2: Development of a multilevel mobile gaming app to support the teaching of introductory undergraduate-level organic chemistry*. 2018. URL: https://doi.org/10.1021/acs.jchemed.7b00856 (cit. on p. 48).

[165] G. Kalmpourtzis. *Educational Game Design Fundamentals: A journey to creating intrinsically motivating learning experiences*. CRC Press, 2018. URL: https://doi.org/10.1201/9781315208794 (cit. on p. 29).

[166] N.-H. Kang. “A review of the effect of integrated STEM or STEAM (science, technology, engineering, arts, and mathematics) education in South Korea”. In: *Asia-Pacific Science Education* 5.1 (2019), pp. 1–22. URL: DOI:%2010.1186/s41029-019-0034-y (cit. on pp. 21, 23, 145).

[167] S. Kang, E. Shokeen, V. L. Byrne, L. Norooz, E. Bonsignore, C. Williams-Pierce, and J. E. Froehlich. “ARMath: augmenting everyday life with math learning”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 2020, pp. 1–15. URL: https://doi.org/10.1145/3313831.3376252 (cit. on p. 23).

[168] R. Karplus. “Chemical phenomena in elementary school science”. In: *Journal of Chemical Education* 43.5 (1966), p. 267. URL: https://doi.org/10.1021/ed043p267 (cit. on p. 14).

[169] H. Kaufmann and A. Dünser. “Summary of usability evaluations of an educational augmented reality application”. In: *Virtual Reality: Second International Conference, ICVR 2007, Held as part of HCI International 2007, Beijing, China, July 22-27, 2007. Proceedings 2*. Springer. 2007, pp. 660–669 (cit. on pp. 21, 144).

[170] J. M. Keller. “Strategies for stimulating the motivation to learn”. In: *Performance and instruction* 26.8 (1987), pp. 1–7 (cit. on p. 85).

[171] N. S. KL, P. S. Chavan, and S. Murthy. “StereoChem: Augmented reality 3D molecular model visualization app for teaching and learning stereochemistry”. In: *2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT)*. IEEE. 2018, pp. 252–256 (cit. on p. 47).

[172] M. Koehler and P. Mishra. “What is technological pedagogical content knowledge (TPACK)?” In: *Contemporary issues in technology and teacher education* 9.1 (2009), pp. 60–70. URL: https://doi.org/10.1177/002205741319300303 (cit. on pp. 34, 35).

[173] A. Y. Kolb and D. A. Kolb. “Learning styles and learning spaces: Enhancing experiential learning in higher education”. In: *Academy of management learning & education* 4.2 (2005), pp. 193–212. URL: https://doi.org/10.5465/amle.2005.17268566 (cit. on p. 12).

[174] V. K. Kolil, S. Muthupalani, and K. Achuthan. “Virtual experimental platforms in chemistry laboratory education and its impact on experimental self-efficacy”. In: *International Journal of Educational Technology in Higher Education* 17.1 (2020), pp. 1–22. URL: https://doi.org/10.1186/s41239-020-00204-3 (cit. on p. 14).

[175] J. Kolko. *Thoughts on interaction design*. Morgan Kaufmann, 2010 (cit. on p. 60).

[176] K. D. Könings, T. Seidel, and J. J. van Merriënboer. “Participatory design of learning environments: integrating perspectives of students, teachers, and designers”. In: *Instructional Science* 42 (2014), pp. 1–9 (cit. on p. 53).

[177] R. Koster. *Theory of fun for game design*. "O’Reilly Media, Inc.", 2013 (cit. on pp. 25, 26).

[178] M. Kozhevnikov and R. Thornton. “Real-time data display, spatial visualization ability, and learning force and motion concepts”. In: *Journal of Science Education and Technology* 15.1 (2006), pp. 111–132 (cit. on p. 13).

[179] R. Kraleva. “Designing an Interface For a Mobile Application Based on Children’s Opinion.” In: *Int. J. Interact. Mob. Technol.* 11.1 (2017), pp. 53–70 (cit. on p. 79).

[180] D. R. Krathwohl. “A revision of Bloom’s taxonomy: An overview”. In: *Theory into practice* 41.4 (2002), pp. 212–218. URL: https://doi.org/10.1207/s15430421tip4104_2 (cit. on pp. 11, 142).

[181] H. Kritzenberger, T. Winkler, and M. Herczeg. “Collaborative and constructive learning of elementary school children in experiental learning spaces along the virtuality continuum”. In: *Mensch & Computer 2002: Vom interaktiven Werkzeug zu kooperativen Arbeits-und Lernwelten* (2002), pp. 115–124. URL: DOI:%2010.1007/978-3-322-89884-5_12 (cit. on pp. 2, 11).

[182] A. W. Kruglanski. “Motivated social cognition: Principles of the interface.” In: (1996) (cit. on p. 32).

[183] P. Lameras, S. Arnab, I. Dunwell, C. Stewart, S. Clarke, and P. Petridis. "Essential features of serious games design in higher education: Linking learning attributes to game mechanics". In: *British journal of educational technology* 48.4 (2017), pp. 972–994. URL: https://doi.org/10.1111/bjet.12467 (cit. on p. 34).

[184] R. N. Landers, E. M. Auer, A. B. Collmus, and M. B. Armstrong. "Gamification science, its history and future: Definitions and a research agenda". In: *Simulation & Gaming* 49.3 (2018), pp. 315–337. URL: https://doi.org/10.1177/1046878118774385 (cit. on p. 36).

[185] P. Lankoski, S. Björk, et al. "Game research methods: An overview". In: (2015) (cit. on p. 52).

[186] P. Lankoski and J. Holopainen. "Game design research: An overview". In: *Online], https://www. researchgate. net/publication/323748642 Game Design Research An Overview (Accessed: 26 June 2019)* (2017) (cit. on p. 52).

[187] A. Large, J. Beheshti, N. Tabatabaei, and V. Nesset. "Developing a visual taxonomy: Children's views on aesthetics". In: *Journal of the American Society for Information Science and Technology* 60.9 (2009), pp. 1808–1822 (cit. on p. 30).

[188] J. Lave and E. Wenger. *Situated learning: Legitimate peripheral participation*. Cambridge university press, 1991 (cit. on p. 11).

[189] G. A. Lee, C. Nelles, M. Billinghurst, and G. J. Kim. "Immersive authoring of tangible augmented reality applications". In: *Third IEEE and ACM international symposium on mixed and augmented reality*. IEEE. 2004, pp. 172–181. URL: https://doi.org/10.1109/ISMAR.2004.34 (cit. on p. 21).

[190] B. Legerén Lago. "Al-Kimia: how to create a video game to help high school students enjoy chemistry". In: *Serious Games and Edutainment Applications: Volume II* (2017), pp. 259–272 (cit. on p. 42).

[191] Y. Li, M. Liang, J. Preissing, N. Bachl, M. M. Dutoit, T. Weber, S. Mayer, and H. Hussmann. "A meta-analysis of tangible learning studies from the tei conference". In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 2022, pp. 1–17 (cit. on p. 23).

[192] H.-N. Liang, F. Lu, Y. Shi, V. Nanjappan, and K. Papangelis. "Evaluating the effects of collaboration and competition in navigation tasks and spatial knowledge acquisition within virtual reality environments". In: *Future Generation Computer Systems* 95 (2019), pp. 855–866 (cit. on p. 146).

[193] H.-s. Lin, B.-r. Shiau, and F. Lawrenz. "The effectiveness of teaching science with pictorial analogies". In: *Research in Science Education* 26 (1996), pp. 495–511. URL: https://doi.org/10.1007/BF02357457 (cit. on p. 61).

[194] B. Lindahl. "A longitudinal study of students' attitudes towards science and choice of career". In: *NARST Annual Conference, April 15-18, 2007, New Orleans*. 2007 (cit. on pp. 18, 49).

[195] K. Loderer, R. Pekrun, and J. L. Plass. "Emotional foundations of game-based learning." In: (2020) (cit. on pp. 33, 106).

[196] N. Loorbach, O. Peters, J. Karreman, and M. Steehouder. "Validation of the Instructional Materials Motivation Survey (IMMS) in a self-directed instructional setting aimed at working with technology". In: *British journal of educational technology* 46.1 (2015), pp. 204–218 (cit. on pp. 85, 91).

[197] A. S. Lu, T. Baranowski, D. Thompson, and R. Buday. "Story immersion of videogames for youth health promotion: A review of literature". In: *GAMES FOR HEALTH: Research, Development, and Clinical Applications* 1.3 (2012), pp. 199–204 (cit. on p. 106).

[198] A. Lu, C. S. Wong, R. Y. Cheung, and T. S. Im. "Supporting flipped and gamified learning with augmented reality in higher education". In: *Frontiers in education*. Vol. 6. Frontiers Media SA. 2021, p. 623745. URL: https://doi.org/10.3389/feduc.2021.623745 (cit. on p. 33).

[199] D. S. Lubinski and C. P. Benbow. *Sex differences in personal attributes for the development of scientific expertise.* American Psychological Association, 2007. URL: https://doi.org/10.1037/11546-007 (cit. on p. 13).

[200] M. Luraschi, R. Rezzonico, and G. Pellegri. "The chemist, that madman! How children perceive science". In: *Chimia* 66.11 (2012), pp. 820–820. URL: https://doi.org/10.2533/chimia.2012.820 (cit. on pp. 2, 15).

[201] P. P. Maglio and D. Kirsh. "Epistemic action increases with skill". In: *Proceedings of the eighteenth annual conference of the cognitive science society*. Routledge. 2019, pp. 391–396 (cit. on pp. 143, 147).

[202] M. Maguire. "Methods to support human-centred design". In: *International journal of human-computer studies* 55.4 (2001), pp. 587–634 (cit. on p. 89).

[203] P. Maier and G. Klinker. "Augmented chemical reactions: 3D interaction methods for chemistry". In: *International Journal of Online Engineering (iJOE)* 9.S8 (2013), p. 80 (cit. on pp. 47, 99).

[204] T. W. Malone. "Toward a theory of intrinsically motivating instruction". In: *Cognitive science* 5.4 (1981), pp. 333–369 (cit. on p. 88).

[205] P. Markopoulos and M. Bekker. "On the assessment of usability testing methods for children". In: *Interacting with computers* 15.2 (2003), pp. 227–243 (cit. on p. 37).

[206] F. Martin and D. U. Bolliger. "Engagement matters: Student perceptions on the importance of engagement strategies in the online learning environment." In: *Online learning* 22.1 (2018), pp. 205–222 (cit. on p. 85).

[207] J.-F. Martin-SanJose, M. Juan, E. Torres, M. J. Vicent, et al. "Playful interaction for learning collaboratively and individually". In: *Journal of Ambient Intelligence and Smart Environments* 6.3 (2014), pp. 295–311 (cit. on pp. 91, 93).

[208] A. I. Martins, A. F. Rosa, A. Queirós, A. Silva, and N. P. Rocha. "European Portuguese validation of the system usability scale (SUS)". In: *Procedia computer science* 67 (2015), pp. 293–300 (cit. on p. 79).

[209] S. A. Matlin, G. Mehta, H. Hopf, and A. Krief. "The periodic table of the chemical elements and sustainable development". In: *European Journal of Inorganic Chemistry* 2019.39-40 (2019), pp. 4170–4173. URL: https://doi.org/10.1002/ejic.201801409 (cit. on p. 19).

[210] J. T. Mayes and C. J. Fowler. "Learning technology and usability: a framework for understanding courseware". In: *Interacting with computers* 11.5 (1999), pp. 485–497 (cit. on p. 37).

[211] F. Mäyrä and L. Ermi. "Fundamental components of the gameplay experience". In: *Digarec Series* 6 (2011), pp. 88–115 (cit. on p. 33).

[212] E. McCarthy, M. Tiu, and L. Li. "Learning math with curious George and the odd squad: Transmedia in the classroom". In: *Technology, Knowledge and Learning* 23 (2018), pp. 223–246 (cit. on p. 40).

[213] R. McKee. "Story: Substance, Structure, Style and the Principles of Screenwriting. Sivu 79-88."4". In: *Structure and Genre* (1997) (cit. on p. 33).

[214] E. D. Mekler, F. Brühlmann, A. N. Tuch, and K. Opwis. "Towards understanding the effects of individual gamification elements on intrinsic motivation and performance". In: *Computers in Human Behavior* 71 (2017), pp. 525–534. URL: https://doi.org/10.1016/j.chb.2015.08.048 (cit. on p. 36).

[215] K. E. Metz. "Narrowing the gulf between the practices of science and the elementary school science classroom". In: *The Elementary School Journal* 109.2 (2008), pp. 138–161. URL: https://doi.org/10.1086/590523 (cit. on p. 18).

[216] L. Y. Midak, I. Kravets, O. Kuzyshyn, L. Baziuk, and K. V. Buzhdyhan. "Specifics of using image visualization within education of the upcoming chemistry teachers with augmented reality technology". In: *Journal of Physics: Conference Series*. Vol. 1840. 1. IOP Publishing. 2021, p. 012013. URL: 10.1088/1742-6596/1840/1/012013 (cit. on p. 49).

[217] P. Milgram, H. Takemura, A. Utsumi, and F. Kishino. "Augmented reality: A class of displays on the reality-virtuality continuum". In: *Telemanipulator and telepresence technologies*. Vol. 2351. Spie. 1995, pp. 282–292. URL: https://doi.org/10.1117/12.197321 (cit. on p. 20).

[218] J. M. Montejo Bernardo and A. Fernández González. "Chemical battleship: discovering and learning the periodic table playing a didactic and strategic board game". In: *Journal of Chemical Education* 98.3 (2021), pp. 907–914 (cit. on p. 24).

[219] C. Morais. "Storytelling with chemistry and related hands-on activities: Informal learning experiences to prevent "chemophobia" and promote young children's scientific literacy". In: *Journal of Chemical Education* 92.1 (2015), pp. 58–65. URL: https://doi.org/10.1021/ed5002416 (cit. on p. 2).

[220] A. Morrison, A. Oulasvirta, P. Peltonen, S. Lemmela, G. Jacucci, G. Reitmayr, J. Näsänen, and A. Juustila. "Like bees around the hive". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (ACM Conferences), Dan R. Olsen (Ed.). ACM, New York, NY*. Vol. 1898. 1889. URL: https://doi.org/10.1145/1518701.1518991 (cit. on p. 22).

[221] A. Morrison, A. Oulasvirta, P. Peltonen, S. Lemmela, G. Jacucci, G. Reitmayr, J. Näsänen, and A. Juustila. "Like bees around the hive: a comparative study of a mobile augmented reality map". In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2009, pp. 1889–1898 (cit. on p. 137).

[222] E. Moyer-Gusé. "Toward a theory of entertainment persuasion: Explaining the persuasive effects of entertainment-education messages". In: *Communication theory* 18.3 (2008), pp. 407–425. URL: https://doi.org/10.1111/j.1468-2885.2008.00328.x (cit. on p. 113).

[223] J. A. Naese, D. McAteer, K. D. Hughes, C. Kelbon, A. Mugweru, and J. P. Grinias. *Use of augmented reality in the instruction of analytical instrumentation design*. 2019. URL: https://doi.org/10.1021/acs.jchemed.8b00794 (cit. on p. 48).

[224] E. Naul and M. Liu. "Why story matters: A review of narrative in serious games". In: *Journal of Educational Computing Research* 58.3 (2020), pp. 687–707. URL: https://doi.org/10.1177/0735633119859904 (cit. on pp. 33, 141).

[225] I. Nayfeld, K. Brenneman, and R. Gelman. "Science in the classroom: Finding a balance between autonomous exploration and teacher-led instruction in preschool settings". In: *Early Education & Development* 22.6 (2011), pp. 970–988. URL: https://doi.org/10.1080/10409289.2010.507496 (cit. on p. 13).

[226] P. Nechypurenko, T. Starova, T. Selivanova, A. Tomilina, and A. Uchitel. "Use of augmented reality in chemistry education". In: *Memoires of 1st International Workshop on Augmented Reality in Education*. 2018. URL: DOI:%2010.31812/pedag.v51i0.3650 (cit. on p. 48).

[227] V. Nesset and A. Large. “Children in the information technology design process: A review of theories and their applications”. In: *Library & Information Science Research* 26.2 (2004), pp. 140–161 (cit. on p. 79).

[228] B. M. Newman and P. R. Newman. *Theories of adolescent development*. Academic Press, 2020 (cit. on p. 1).

[229] A. G. Nichele and G. do Nascimento. “Augmented Reality in Teaching Chemistry”. In: *INTED2017 Proceedings*. IATED. 2017, pp. 8736–8743 (cit. on p. 48).

[230] J. Nielsen and R. Molich. “Heuristic evaluation of user interfaces”. In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. 1990, pp. 249–256 (cit. on p. 59).

[231] M. Nieminen. “Psychology in character design: Creation of a Character Design Tool”. In: (2017) (cit. on p. 31).

[232] P. Nikken and M. Schols. “How and why parents guide the media use of young children”. In: *Journal of child and family studies* 24 (2015), pp. 3423–3435 (cit. on p. 13).

[233] N. C. Nilsson, R. Nordahl, and S. Serafin. “Immersion revisited: A review of existing definitions of immersion and their relation to different theories of presence”. In: *Human technology* 12.2 (2016), pp. 108–134 (cit. on p. 37).

[234] S. K. O’Dell. “Design thinking for the development of formal operations: A team-based middle school design curriculum”. In: (2016). URL: https://doi.org/10.25772/HWKG-9B46 (cit. on pp. 58, 136, 147).

[235] S. Olim, V. Nisi, and T. Romão. “Periodic fable discovery: an augmented reality serious game to introduce and motivate young children towards chemistry”. In: *Multimedia Tools and Applications* (Nov. 2023). DOI: 10.1007/s11042-023-17526-9 (cit. on p. 8).

[236] S. C. Olim and V. Nisi. “Augmented reality towards facilitating abstract concepts learning”. In: *Entertainment Computing–ICEC 2020: 19th IFIP TC 14 International Conference, ICEC 2020, Xi’an, China, November 10–13, 2020, Proceedings 19*. Springer. 2020, pp. 188–204 (cit. on p. 8).

[237] S. C. Olim, V. Nisi, and T. Romão. “Towards Identifying Augmented Reality Unique Attributes to Facilitate Chemistry Learning”. In: *IFIP Conference on Human-Computer Interaction*. Springer. 2021, pp. 513–516 (cit. on p. 8).

[238] M. B. Oliver, N. D. Bowman, J. K. Woolley, R. Rogers, B. I. Sherrick, and M.-Y. Chung. “Video games as meaningful entertainment experiences.” In: *Psychology of popular media culture* 5.4 (2016), p. 390. URL: https://doi.org/10.1037/ppm0000066 (cit. on p. 26).

[239] J. Osborne and J. Dillon. *Science education in Europe: Critical reflections*. Vol. 13. London: The Nuffield Foundation, 2008 (cit. on p. 14).

[240] O. S. Oyelekan, S. S. Jolayemi, and J. E. Upahi. "Relationships among Senior School Students' Self-Efficacy, Metacognition and Their Achievement in Chemistry." In: *Cypriot Journal of Educational Sciences* 14.2 (2019), pp. 208–221 (cit. on p. 17).

[241] H. Özmen. "The effectiveness of conceptual change texts in remediating high school students' alternative conceptions concerning chemical equilibrium". In: *Asia Pacific Education Review* 8 (2007), pp. 413–425. URL: https://doi.org/10.1007/BF03026470 (cit. on pp. 16, 18).

[242] A. Paivio. "Abstractness, imagery, and meaningfulness in paired-associate learning". In: *Journal of Verbal Learning and Verbal Behavior* 4.1 (1965), pp. 32–38 (cit. on pp. 11, 12).

[243] D. Palmer. "Students' alternative conceptions and scientifically acceptable conceptions about gravity". In: *International Journal of Science Education* 23.7 (2001), pp. 691–706. URL: https://doi.org/10.1080/09500690010006527 (cit. on p. 48).

[244] S. Papert. "The children's machine: Rethinking school in the age of the computer". In: *New York* (1993) (cit. on p. 15).

[245] E. A. Patall, S. Hooper, A. C. Vasquez, K. A. Pituch, and R. R. Steingut. "Science class is too hard: Perceived difficulty, disengagement, and the role of teacher autonomy support from a daily diary perspective". In: *Learning and Instruction* 58 (2018), pp. 220–231. URL: https://doi.org/10.1016/j.learninstruc.2018.07.004 (cit. on p. 2).

[246] M. Perez-Sanagustin, D. Hernández-Leo, P. Santos, C. D. Kloos, and J. Blat. "Augmenting reality and formality of informal and non-formal settings to enhance blended learning". In: *IEEE Transactions on Learning Technologies* 7.2 (2014), pp. 118–131. URL: DOI:%2010.1109/TLT.2014.2312719 (cit. on p. 22).

[247] A. Permana, D. Muliyati, F. Bakri, B. Dewi, and D. Ambarwulan. "The development of an electricity book based on augmented reality technologies". In: *Journal of Physics: Conference Series*. Vol. 1157. 3. IOP Publishing. 2019, p. 032027 (cit. on p. 45).

[248] M. Peters and C. Battista. "Applications of mental rotation figures of the Shepard and Metzler type and description of a mental rotation stimulus library". In: *Brain and cognition* 66.3 (2008), pp. 260–264 (cit. on p. 126).

[249] M. H. Phan, J. R. Keebler, and B. S. Chaparro. "The development and validation of the game user experience satisfaction scale (GUESS)". In: *Human factors* 58.8 (2016), pp. 1217–1247 (cit. on p. 38).

[250] J. Piaget. *Language and thought of the child: Selected works*. Vol. 5. Routledge, 2005. URL: https://doi.org/10.4324/9780203992739 (cit. on pp. 23, 26, 58, 136, 147).

[251] J. Piaget. *Possibility and necessity*. Vol. 2. U of Minnesota Press, 1987 (cit. on p. 14).

[252] A. C. Pires, F. González Perilli, E. Bakała, B. Fleisher, G. Sansone, and S. Marichal. "Building blocks of mathematical learning: Virtual and tangible manipulatives lead to different strategies in number composition". In: *Frontiers in Education*. Vol. 4. Frontiers Media SA. 2019, p. 81 (cit. on p. 145).

[253] I. Polycarpou, J. Krausea, C. Rader, C. Kembel, C. Poupore, and E. Chiu. "Math-City: An educational game for K-12 mathematics". In: *Procedia-Social and Behavioral Sciences* 9 (2010), pp. 845–850 (cit. on p. 40).

[254] H. Qin, P.-L. Patrick Rau, and G. Salvendy. "Measuring player immersion in the computer game narrative". In: *Intl. Journal of Human–Computer Interaction* 25.2 (2009), pp. 107–133. URL: https://doi.org/10.1080/10447310802546732 (cit. on p. 33).

[255] I. Radu. "Augmented reality in education: a meta-review and cross-media analysis". In: *Personal and ubiquitous computing* 18 (2014), pp. 1533–1543. URL: https://doi.org/10.1007/s00779-013-0747-y (cit. on p. 22).

[256] I. Radu and B. Schneider. "What can we learn from augmented reality (AR)? Benefits and drawbacks of AR for inquiry-based learning of physics". In: *Proceedings of the 2019 CHI conference on human factors in computing systems*. 2019, pp. 1–12. URL: https://doi.org/10.1145/3290605.3300774 (cit. on p. 22).

[257] P. Ralph and K. Monu. "Toward a unified theory of digital games". In: *The Computer Games Journal* 4 (2015), pp. 81–100. URL: https://doi.org/10.1007/s40869-015-0007-7 (cit. on p. 30).

[258] A. Raviolo. "Assessing students' conceptual understanding of solubility equilibrium". In: *Journal of Chemical Education* 78.5 (2001), p. 629. URL: https://doi.org/10.1021/ed078p629 (cit. on pp. 16, 144).

[259] J. C. Read and S. MacFarlane. "Using the fun toolkit and other survey methods to gather opinions in child computer interaction". In: *Proceedings of the 2006 conference on Interaction design and children*. 2006, pp. 81–88 (cit. on pp. 80, 112).

[260] S. E. Reed, O. Kreylos, S. Hsi, L. H. Kellogg, G. Schladow, M. B. Yikilmaz, H. Segale, J. Silverman, S. Yalowitz, and E. Sato. "Shaping watersheds exhibit: An interactive, augmented reality sandbox for advancing earth science education". In: *AGU Fall Meeting Abstracts*. Vol. 2014. 2014, ED34A–01 (cit. on p. 47).

[261] J. Reeve. "A self-determination theory perspective on student engagement". In: *Handbook of research on student engagement*. Springer, 2012, pp. 149–172. URL: https://doi.org/10.1007/978-1-4614-2018-7_7 (cit. on pp. 35, 141).

[262] K. Reinecke and K. Z. Gajos. “Quantifying visual preferences around the world”. In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2014, pp. 11–20 (cit. on p. 31).

[263] A. Reinschlüssel, D. Alexandrovsky, T. Döring, A. Kraft, M. Braukmüller, T. Janßen, D. Reid, E. Vallejo, A. Bikner-Ahsbahs, and R. Malaka. “Multimodal algebra learning: From math manipulatives to tangible user interfaces”. In: *i-com* 17.3 (2018), pp. 201–209 (cit. on pp. 137, 145).

[264] D. Resnyansky. “Augmented reality-supported tangible gamification for debugging learning”. In: *2020 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE)*. IEEE. 2020, pp. 377–383. URL: https://doi.org/10.1109/TALE48869.2020.9368410 (cit. on p. 23).

[265] G. Riva, J. Waterworth, and D. Murray. *Interacting with Presence: HCI and the Sense of Presence in Computer-mediated Environments*. Walter de Gruyter GmbH & Co KG, 2014. URL: https://doi.org/10.2478/9783110409697 (cit. on p. 27).

[266] T. Roberts, C. Jackson, M. J. Mohr-Schroeder, S. B. Bush, C. Maiorca, M. Cavalcanti, D. Craig Schroeder, A. Delaney, L. Putnam, and C. Cremeans. “Students’ perceptions of STEM learning after participating in a summer informal learning experience”. In: *International journal of STEM education* 5.1 (2018), pp. 1–14. URL: https://doi.org/10.1186/s40594-018-0133-4 (cit. on p. 13).

[267] L. Rodrigues, F. D. Pereira, A. M. Toda, P. T. Palomino, M. Pessoa, L. S. G. Carvalho, D. Fernandes, E. H. Oliveira, A. I. Cristea, and S. Isotani. “Gamification suffers from the novelty effect but benefits from the familiarization effect: Findings from a longitudinal study”. In: *International Journal of Educational Technology in Higher Education* 19.1 (2022), pp. 1–25. URL: https://doi.org/10.1186/s41239-021-00314-6 (cit. on p. 36).

[268] Y. Rogers, S. Price, G. Fitzpatrick, R. Fleck, E. Harris, H. Smith, C. Randell, H. Muller, C. O’Malley, D. Stanton, et al. “Ambient wood: designing new forms of digital augmentation for learning outdoors”. In: *Proceedings of the 2004 conference on Interaction design and children: building a community*. 2004, pp. 3–10 (cit. on p. 45).

[269] M. Romero-Ternero, R. García-Robles, D. Cagigas-Muñiz, O. Rivera-Romero, and M. Romero-Ternero. “Participant Observation to Apply an Empirical Method of Codesign with Children”. In: *Advances in Human-Computer Interaction* 2022 (2022) (cit. on p. 79).

[270] J. Ross, L. Nunez, and C. C. Lai. “Partial least squares structural equation modeling of chemistry attitude in introductory college chemistry”. In: *Chemistry Education Research and Practice* 19.4 (2018), pp. 1270–1286 (cit. on p. 2).

[271] V. Rossano, F. Mangialardo, and T. Roselli. "Math is magic: an adaptive serious game to reinforce math competences". In: *Ninth International Conference on Technological Ecosystems for Enhancing Multiculturality (TEEM'21)*. 2021, pp. 162–166 (cit. on p. 41).

[272] F. Rosselli, J. J. Skelly, and D. M. Mackie. "Processing rational and emotional messages: The cognitive and affective mediation of persuasion". In: *Journal of experimental social psychology* 31.2 (1995), pp. 163–190. URL: https://doi.org/10.1006/jesp.1995.1008 (cit. on p. 33).

[273] W.-M. Roth. *Authentic school science: Knowing and learning in open-inquiry science laboratories*. Vol. 1. Springer Science & Business Media, 2012 (cit. on p. 137).

[274] W.-M. Roth and G. M. Bowen. "Knowing and interacting: A study of culture, practices, and resources in a grade 8 open-inquiry science classroom guided by a cognitive apprenticeship metaphor". In: *Cognition and instruction* 13.1 (1995), pp. 73–128 (cit. on p. 27).

[275] J. Rowe, B. Mott, S. McQuiggan, J. Robison, S. Lee, and J. Lester. "Crystal island: A narrative-centered learning environment for eighth grade microbiology". In: *workshop on intelligent educational games at the 14th international conference on artificial intelligence in education, Brighton, UK*. 2009, pp. 11–20 (cit. on p. 41).

[276] S. Ruan, J. He, R. Ying, J. Burkle, D. Hakim, A. Wang, Y. Yin, L. Zhou, Q. Xu, A. AbuHashem, et al. "Supporting children's math learning with feedback-augmented narrative technology". In: *Proceedings of the Interaction Design and Children Conference*. 2020, pp. 567–580 (cit. on pp. 107, 119).

[277] C. M. Rubilar. "Designing of augmented reality teaching-learning sequences to promote the accessibility and vizualization of complex contents in Chemistry". In: *EDULEARN19 Proceedings*. IATED. 2019, pp. 8299–8303 (cit. on p. 47).

[278] R. M. Ryan and E. L. Deci. "Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being." In: *American psychologist* 55.1 (2000), p. 68 (cit. on p. 17).

[279] A. Sadeghi-Niaraki and S.-M. Choi. "A survey of marker-less tracking and registration techniques for health & environmental applications to augmented reality and ubiquitous geospatial information systems". In: *Sensors* 20.10 (2020), p. 2997. URL: https://doi.org/10.3390/s20102997 (cit. on p. 22).

[280] A. H. Safar, A. A. Al-Jafar, and Z. H. Al-Yousefi. "The effectiveness of using augmented reality apps in teaching the English alphabet to kindergarten children: A case study in the State of Kuwait". In: *EURASIA Journal of Mathematics, Science and Technology Education* 13.2 (2016), pp. 417–440 (cit. on p. 44).

[281] N. F. Saidin, N. D. A. Halim, and N. Yahaya. "Framework for Developing a Mobile Augmented Reality for Learning Chemical Bonds." In: *International Journal of Interactive Mobile Technologies* 13.7 (2019). URL: https://doi.org/10.3991/ijim.v13i07.10750 (cit. on pp. 3, 47).

[282] M. Sailer, J. Hense, H. Mandl, and M. Klevers. "Fostering development of work competencies and motivation via gamification". In: *Competence-based vocational and professional education: Bridging the worlds of work and education* (2017), pp. 795–818. URL: https://doi.org/10.1007/978-3-319-41713-4_37 (cit. on p. 36).

[283] M. Sailer and L. Homner. "The gamification of learning: A meta-analysis". In: *Educational Psychology Review* 32.1 (2020), pp. 77–112. URL: https://doi.org/10.1007/s10648-019-09498-w (cit. on p. 36).

[284] K. Saksrisathaporn and P. Sribunthankul. "A Smartphone Game to Promote Self-Learning in Chemistry." In: *International Association for Development of the Information Society* (2019) (cit. on p. 42).

[285] H. Salmi, H. Thuneberg, and M.-P. Vainikainen. "Making the invisible observable by Augmented Reality in informal science education context". In: *International Journal of Science Education, Part B* 7.3 (2017), pp. 253–268. URL: DOI:%2010.1080/21548455.2016.1254358 (cit. on p. 49).

[286] D. R. Sanchez, M. Langer, and R. Kaur. "Gamification in the classroom: Examining the impact of gamified quizzes on student learning". In: *Computers & Education* 144 (2020), p. 103666. URL: https://doi.org/10.1016/j.compedu.2019.103666 (cit. on p. 36).

[287] V. C. Santos and A. Arroio. "The representational levels: Influences and contributions to research in chemical education". In: *Journal of Turkish Science Education* 13.1 (2016). URL: 10.12973/tused.10153a (cit. on p. 16).

[288] P. SARANTOPOULOS and G. TSAPARLIS. "Analogies in chemistry teaching as a means of attainment of cognitive and affective objectives: A longitudinal study in a naturalistic setting, using analogies with a strong social content". In: *Chemistry Education Research and Practice* 5.1 (2004), pp. 33–50 (cit. on pp. 61, 136).

[289] V. T. Sarinho. "Masters of the process: a board game proposal for teaching software management and software development process". In: *Proceedings of the XXXIII Brazilian Symposium on Software Engineering*. 2019, pp. 532–536 (cit. on p. 24).

[290] R. Savi, C. G. Von Wangenheim, V. Ulbricht, and T. Vanzin. "Proposta de um modelo de avaliação de jogos educacionais". In: *Renote* 8.3 (2010) (cit. on p. 85).

[291] M. Scaife and Y. Rogers. "Kids as informants: Telling us what we didn't know or confirming what we knew already". In: *The design of children's technology* (1999), pp. 27–50 (cit. on p. 55).

[292] J. Schell. *The Art of Game Design: A book of lenses*. CRC press, 2008 (cit. on pp. 24, 26, 28, 32–34, 100, 102).

[293] I. Schloss, J. O. Bailey, and S. Tripathi. ""I'm in his belly!": Children's Responses to Different Types of Characters in Virtual Reality". In: *Interaction Design and Children*. 2021, pp. 43–48 (cit. on pp. 74, 118, 146).

[294] D. H. Schunk. *Learning theories an educational perspective*. Pearson Education, Inc, 2012 (cit. on p. 11).

[295] Á. Serrano-Laguna, B. Manero, M. Freire, and B. Fernández-Manjón. "A methodology for assessing the effectiveness of serious games and for inferring player learning outcomes". In: *Multimedia Tools and applications* 77 (2018), pp. 2849–2871. URL: DOI:%2010.1007/s11042-017-4467-6 (cit. on p. 50).

[296] D. R. Shaffer and K. Kipp. *Developmental psychology: Childhood and adolescence*. Cengage Learning, 2013 (cit. on p. 13).

[297] B. E. Shelton and N. R. Hedley. "Exploring a cognitive basis for learning spatial relationships with augmented reality". In: *Technology, Instruction, Cognition and Learning* 1.4 (2004), p. 323 (cit. on pp. 26, 106, 119, 142, 146).

[298] R. N. Shepard and C. Feng. "A chronometric study of mental paper folding". In: *Cognitive psychology* 3.2 (1972), pp. 228–243 (cit. on p. 126).

[299] S. Shirazi. "Student experience of school science". In: *International Journal of Science Education* 39.14 (2017), pp. 1891–1912. URL: doi.org/10.1080/09500693.2017.1356943 (cit. on pp. 2, 15).

[300] G. Shrader, K. Williams, J. Lachance-Whitcomb, L.-E. Finn, and L. Gomez. "Participatory design of science curricula: The case for research for practice". In: *Annual Meeting of the American Educational Research Association, Seattle, WA*. 2001 (cit. on p. 53).

[301] G. Shwartz, O. Shav-Artza, and Y. J. Dori. "Choosing chemistry at different education and career stages: Chemists, chemical engineers, and teachers". In: *Journal of Science Education and Technology* 30.5 (2021), pp. 692–705. URL: https://doi.org/10.1007/s10956-021-09912-5 (cit. on p. 2).

[302] M. Sicart. "Defining game mechanics". In: *Game studies* 8.2 (2008), pp. 1–14 (cit. on p. 33).

[303] N. M. Siew, J. Geofrey, and B. N. Lee. "Students' algebraic thinking and attitudes towards algebra: the effects of game-based learning using Dragonbox 12+ App". In: *The Research Journal of Mathematics and Technology* 5.1 (2016), pp. 66–79 (cit. on p. 41).

[304] M. M. O. da Silva, R. A. Roberto, I. Radu, P. S. Cavalcante, and V. Teichrieb. "Why Don't We See More of Augmented Reality in Schools?" In: *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. IEEE. 2019, pp. 138–143. URL: https://doi.org/10.1109/ISMAR-Adjunct.2019.00-61 (cit. on p. 22).

[305] M. A. R. Silva, A. L. Dias, and J. C. Anacleto. "Using Contextualized Narrative Game to Improve Students and Teachers Communication." In: *CSEDU (2)*. 2010, pp. 232–237. URL: https://doi.org/10.5220/0002787302320237 (cit. on p. 33).

[306] D. Singer and T. Revenson. "A Piaget primer: haw a child thinks". In: *New York: Plume/Penguin* (1996) (cit. on pp. 135, 147).

[307] S. Singhal, S. Bagga, P. Goyal, and V. Saxena. "Augmented chemistry: Interactive education system". In: *International Journal of Computer Applications* 49.15 (2012). URL: doi%2010.5120/7700-1041 (cit. on p. 48).

[308] C. Siry, G. Ziegler, and C. Max. ""Doing science" through discourse-in-interaction: Young children's science investigations at the early childhood level". In: *Science Education* 96.2 (2012), pp. 311–326 (cit. on p. 58).

[309] M. Slater, V. Linakis, M. Usoh, and R. Kooper. "Immersion, presence and performance in virtual environments: An experiment with tri-dimensional chess". In: *Proceedings of the ACM symposium on virtual reality software and technology*. 1996, pp. 163–172 (cit. on p. 25).

[310] E. Smith and P. White. "Where do all the STEM graduates go? Higher education, the labour market and career trajectories in the UK". In: *Journal of Science Education and Technology* 28 (2019), pp. 26–40. URL: https://doi.org/10.1007/s10956-018-9741-5 (cit. on p. 15).

[311] I. So. "Cognitive development in children: Piaget development and learning". In: *Journal, of Research in Science Teaching* 2 (1964), pp. 176–186. URL: https://doi.org/10.1002/tea.3660020306 (cit. on pp. 34, 144).

[312] H. Soares, J. AIKES, and F. MOURATO. "Development of a Serious Game to Improve the Teaching of Chemistry". In: *10th Conference on videogame sciences and arts*. 2018, pp. 109–120 (cit. on p. 49).

[313] D. M. Solano, F. E. Wood, and M. J. Kurth. ""Careers in Chemistry": A course providing students with real-world foundations". In: *Journal of Chemical Education* 88.10 (2011), pp. 1376–1379. URL: https://doi.org/10.1021/ed1001366 (cit. on p. 15).

[314] S. Sorby, N. Veurink, and S. Streiner. "Does spatial skills instruction improve STEM outcomes? The answer is 'yes'". In: *Learning and Individual Differences* 67 (2018), pp. 209–222. URL: https://doi.org/10.1016/j.lindif.2018.09.001 (cit. on p. 16).

[315] M. Sousa. "Modern Serious Board Games: modding games to teach and train civil engineering students". In: *2020 IEEE Global Engineering Education Conference (EDUCON)*. IEEE. 2020, pp. 197–201 (cit. on p. 24).

[316] K. Squire and H. Jenkins. "Harnessing the power of games in education". In: *Insight* 3.1 (2003), pp. 5–33 (cit. on p. 2).

[317] H. Stavridou and D. Marinopoulos. "Water and Air pollution: Primary Students' conceptions about "Itineraries"of Substances". In: *Chemistry Education Research and Practice* 2.1 (2001), pp. 31–41 (cit. on p. 18).

[318] F. Steen and S. Owens. "Evolution's pedagogy: An adaptationist model of pretense and entertainment". In: *Journal of Cognition and Culture* 1.4 (2001), pp. 289–321 (cit. on p. 119).

[319] M. Stuckey, A. Hofstein, R. Mamlok-Naaman, and I. Eilks. "The meaning of 'relevance'in science education and its implications for the science curriculum". In: *Studies in Science Education* 49.1 (2013), pp. 1–34. URL: https://doi.org/10.1080/03057267.2013.802463 (cit. on p. 14).

[320] A. Y. Sung, B. J. Floyd, and D. J. Pagliarini. "Systems biochemistry approaches to defining mitochondrial protein function". In: *Cell metabolism* 31.4 (2020), pp. 669–678. URL: https://doi.org/10.1016/j.cmet.2020.03.011 (cit. on p. 48).

[321] N. Supanchaiyamat and A. J. Hunt. "Conservation of critical elements of the periodic table". In: *ChemSusChem* 12.2 (2019), pp. 397–403. URL: https://doi.org/10.1002/cssc.201802556 (cit. on p. 19).

[322] S. Swink. *Game feel: a game designer's guide to virtual sensation*. CRC press, 2008 (cit. on p. 61).

[323] G. Tavinor. "Definition of videogames". In: *Contemporary Aesthetics (Journal Archive)* 6.1 (2008), p. 16 (cit. on p. 25).

[324] N. Y. K. Tee, H. S. Gan, J. Li, B. H.-P. Cheong, H. Y. Tan, O. W. Liew, and T. W. Ng. "Developing and demonstrating an augmented reality colorimetric titration tool". In: *Journal of Chemical Education* 95.3 (2018), pp. 393–399. URL: https://doi.org/10.1021/acs.jchemed.7b00618 (cit. on p. 48).

[325] K. S. Tekinbas and E. Zimmerman. *Rules of play: Game design fundamentals*. MIT press, 2003 (cit. on p. 24).

[326] M. Teplá, P. Teplý, and P. Šmejkal. "Influence of 3D models and animations on students in natural subjects". In: *International Journal of STEM Education* 9.1 (2022), p. 65 (cit. on p. 103).

[327] M. Teppo, R. Soobard, and M. Rannikmäe. "A study comparing intrinsic motivation and opinions on learning science (grades 6) and taking the international PISA test (grade 9)". In: *Education Sciences* 11.1 (2021), p. 14. URL: https://doi.org/10.3390/educsci11010014 (cit. on pp. 2, 13, 14).

[328] F. Thomas, O. Johnston, and F. Thomas. *The illusion of life: Disney animation*. Hyperion New York, 1995 (cit. on p. 31).

[329] B. Tillman. *Creative character design*. Crc Press, 2012 (cit. on pp. 31, 32).

[330] D. Treagust, G. Chittleborough, and T. Mamiala. "The role of submicroscopic and symbolic representations in chemical explanations". In: *International journal of science education* 25.11 (2003), pp. 1353–1368. URL: https://doi.org/10.1080/0950069032000070306 (cit. on pp. 16, 144).

[331] E. Tribble, R. Skariah, E. Tran, and O. Gulacar. "Exploring the Effects of a Neglected Area: The United Nations Sustainable Development Goals in Science Education". In: *Journal of College Science Teaching* 51.3 (2022), pp. 37–42 (cit. on p. 14).

[332] B. Tversky. "Structures of mental spaces: How people think about space". In: *Environment and behavior* 35.1 (2003), pp. 66–80 (cit. on p. 145).

[333] M. Üce and İ. Ceyhan. "Misconception in Chemistry Education and Practices to Eliminate Them: Literature Analysis." In: *Journal of Education and Training Studies* 7.3 (2019), pp. 202–208. URL: https://doi.org/10.11114/jets.v7i3.3990 (cit. on pp. 17, 102, 103).

[334] D. H. Uttal, D. I. Miller, and N. S. Newcombe. "Exploring and enhancing spatial thinking: Links to achievement in science, technology, engineering, and mathematics?" In: *Current Directions in Psychological Science* 22.5 (2013), pp. 367–373. URL: https://doi.org/10.1177/0963721413484756 (cit. on pp. 13, 16).

[335] A. Uysal and I. G. Yildirim. "Self-determination theory in digital games". In: *Gamer psychology and behavior* (2016), pp. 123–135. URL: https://doi.org/10.1007/978-3-319-29904-4_8 (cit. on p. 34).

[336] A. Vahldick, P. R. Farah, M. J. Marcelino, and A. J. Mendes. "A blocks-based serious game to support introductory computer programming in undergraduate education". In: *Computers in Human Behavior Reports* 2 (2020), p. 100037 (cit. on p. 41).

[337] R. B. Valimont, D. A. Vincenzi, S. N. Gangadharan, and A. Majoros. "The effectiveness of augmented reality as a facilitator of information acquisition". In: *Proceedings. The 21st Digital Avionics Systems Conference*. Vol. 2. IEEE. 2002, pp. 7C5–7C5. URL: https://doi.org/10.1109/DASC.2002.1052926 (cit. on p. 21).

[338] D. Van Krevelen and R. Poelman. "A survey of augmented reality technologies, applications and limitations". In: *International journal of virtual reality* 9.2 (2010), pp. 1–20. URL: https://doi.org/10.20870/IJVR.2010.9.2.2767 (cit. on p. 20).

[339] J. C. Vega Garzón, M. L. Magrini, and E. Galembeck. "Using augmented reality to teach and learn biochemistry". In: *Biochemistry and molecular biology education* 45.5 (2017), pp. 417–420. URL: https://doi.org/10.1002/bmb.21063 (cit. on p. 48).

[340] C. Vidal Carulla. "Children's emergent chemistry in the preschool". PhD thesis. Linnaeus University Press, 2020 (cit. on p. 58).

[341] P. Vilia and A. A. Candeias. "Attitude towards the discipline of physics-chemistry and school achievement: revisiting factor structure to assess gender differences in Portuguese high-school students". In: *International Journal of Science Education* 42.1 (2020), pp. 133–150. URL: https://doi.org/10.1080/09500693.2019.1706012 (cit. on p. 16).

[342] S. M. Villafañe and J. E. Lewis. "Exploring a measure of science attitude for different groups of students enrolled in introductory college chemistry". In: *Chemistry Education Research and Practice* 17.4 (2016), pp. 731–742. URL: https://doi.org/10.1039/C5RP00185D (cit. on p. 2).

[343] A. Villanueva, Z. Zhu, Z. Liu, K. Peppler, T. Redick, and K. Ramani. "Meta-AR-app: an authoring platform for collaborative augmented reality in STEM classrooms". In: *Proceedings of the 2020 CHI conference on human factors in computing systems*. 2020, pp. 1–14. URL: https://doi.org/10.1145/3313831.3376146 (cit. on p. 21).

[344] P. Vlachogianni and N. Tselios. "Perceived usability evaluation of educational technology using the System Usability Scale (SUS): A systematic review". In: *Journal of Research on Technology in Education* 54.3 (2022), pp. 392–409 (cit. on p. 38).

[345] L. S. Vygotsky. "Play and its role in the mental development of the child". In: *Soviet psychology* 5.3 (1967), pp. 6–18. URL: https://doi.org/10.2753/RPO1061-040505036 (cit. on pp. 26, 145, 147).

[346] L. S. Vygotsky. *Thought and language*. MIT press, 2012 (cit. on p. 27).

[347] L. S. Vygotsky. "Play and Its Role in the Mental Development of the Child." In: *International Research in Early Childhood Education* 7.2 (2016), pp. 3–25 (cit. on p. 136).

[348] H. Wang, J. Bowerman, and F. Yang. "Do learning websites reflect users' aesthetic preferences". In: *Tenth International Conference on the Arts in Society*. 2015, pp. 1–5 (cit. on p. 31).

[349] X. Wang. "Why students choose STEM majors: Motivation, high school learning, and postsecondary context of support". In: *American Educational Research Journal* 50.5 (2013), pp. 1081–1121. URL: https://doi.org/10.3102/0002831213488622 (cit. on pp. 13, 14).

[350] D. Watson, L. A. Clark, and A. Tellegen. "Development and validation of brief measures of positive and negative affect: the PANAS scales." In: *Journal of personality and social psychology* 54.6 (1988), p. 1063 (cit. on p. 111).

[351] D. Weintrop, E. Beheshti, M. Horn, K. Orton, K. Jona, L. Trouille, and U. Wilensky. "Defining computational thinking for mathematics and science classrooms". In: *Journal of science education and technology* 25 (2016), pp. 127–147 (cit. on p. 41).

[352] C. Weng, A. Rathinasabapathi, A. Weng, and C. Zagita. "Mixed reality in science education as a learning support: a revitalized science book". In: *Journal of Educational Computing Research* 57.3 (2019), pp. 777–807 (cit. on p. 45).

[353] N. Whitton. *Learning with digital games: A practical guide to engaging students in higher education*. Routledge, 2009 (cit. on p. 40).

[354] P. Wijdenes, D. Borkenhagen, J. Babione, I. Ma, and G. Hallihan. "Leveraging augmented reality training tool for medical education: A case study in central venous catheterization". In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–7. URL: https://doi.org/10.1145/3170427.3174361 (cit. on p. 21).

[355] E. V. Wilson and S. Djamasbi. "Measuring mobile user experience instruments for research and practice". In: *Communications of the Association for Information Systems* 44.1 (2019), p. 8 (cit. on p. 79).

[356] B. M. Winn. "The design, play, and experience framework". In: *Handbook of research on effective electronic gaming in education*. IGI Global, 2009, pp. 1010–1024. URL: https://doi.org/10.4018/978-1-59904-808-6.ch058 (cit. on pp. 26, 55).

[357] B. G. Witmer and M. J. Singer. "Measuring presence in virtual environments: A presence questionnaire". In: *Presence* 7.3 (1998), pp. 225–240 (cit. on p. 36).

[358] W. Wolf. "Aesthetic illusion". In: *Immersion and Distance*. Brill, 2013, pp. vii–63 (cit. on p. 61).

[359] E. Wood and J. Attfield. *Play, Learning, and t he Early Childhood Curriculum*. 2005. URL: https://doi.org/10.4135/9781446280393 (cit. on pp. 13, 145).

[360] J.-Y. Wu, Y.-C. Hsiao, and M.-W. Nian. "Using supervised machine learning on large-scale online forums to classify course-related Facebook messages in predicting learning achievement within the personal learning environment". In: *Interactive Learning Environments* 28.1 (2020), pp. 65–80. URL: https://doi.org/10.1080/10494820.2017.1294608 (cit. on p. 48).

[361] P. Wyeth and H. C. Purchase. "Tangible programming elements for young children". In: *CHI'02 extended abstracts on Human factors in computing systems*. 2002, pp. 774–775. URL: https://doi.org/10.1145/506443.506591 (cit. on p. 23).

[362] X. Xu and J. E. Lewis. "Refinement of a chemistry attitude measure for college students". In: *Journal of Chemical Education* 88.5 (2011), pp. 561–568. URL: https://doi.org/10.1021/ed900071q (cit. on p. 16).

[363] I. S. Yakimanskaya. *The Development of Spatial Thinking in Schoolchildren. Soviet Studies in Mathematics Education. Volume 3.* ERIC, 1991 (cit. on p. 136).

[364] S. Yang, B. Mei, and X. Yue. *Mobile augmented reality assisted chemical education: insights from elements 4D*. 2018 (cit. on pp. 47, 48).

[365] S. Yoon, E. Anderson, J. Lin, and K. Elinich. "How augmented reality enables conceptual understanding of challenging science content". In: *Journal of Educational Technology & Society* 20.1 (2017), pp. 156–168 (cit. on p. 46).

[366] H. Yu. "What Pokémon Go's Success Means for the Future of Augmented Reality". In: *Fortune* 23 (2016), p. 16 (cit. on p. 43).

[367] Z. Yu, M. Gao, and L. Wang. "The effect of educational games on learning outcomes, student motivation, engagement and satisfaction". In: *Journal of Educational Computing Research* 59.3 (2021), pp. 522–546. URL: https://doi.org/10.1177/0735633120969214 (cit. on p. 2).

[368] J. Zimmerman, J. Forlizzi, and S. Evenson. "Research through design as a method for interaction design research in HCI". In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. 2007, pp. 493–502. URL: https://doi.org/10.1145/1240624.1240704 (cit. on pp. 4, 52, 53).

[369] L. Zimmermann, L. Foster, R. M. Golinkoff, and K. Hirsh-Pasek. "Spatial Thinking and STEM: How Playing with Blocks Supports Early Math." In: *American Educator* 42.4 (2019), pp. 22–27 (cit. on p. 104).

[370] F. Zünd, M. Ryffel, S. Magnenat, A. Marra, M. Nitti, M. Kapadia, G. Noris, K. Mitchell, M. Gross, and R. W. Sumner. "Augmented creativity: bridging the real and virtual worlds to enhance creative play". In: *SIGGRAPH Asia 2015 Mobile Graphics and Interactive Applications*. 2015, pp. 1–7 (cit. on p. 21).

[371] G. Zurita and M. Nussbaum. "A constructivist mobile learning environment supported by a wireless handheld network". In: *Journal of computer assisted learning* 20.4 (2004), pp. 235–243 (cit. on p. 121).

Appendix A

Secretary of Education Ethical Approval

This Appendix contains the documents that are required to obtain Ethical Approval by the Secretary of Education.

Projeto “A Fábula Periódica”

NOTA METODOLÓGICA

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Introdução

Estudos prévios demonstram que a criança tem uma perceção da disciplina de físico/química como sendo difícil e complexa, mesmo antes de ter contacto com as mesmas por meio dos programas curriculares (Luraschi et al., 2012)(Morais, 2015). Um dos fatores identificados para esta perceção é a utilização de conceitos abstratos os quais, não sendo observáveis a olho nu, tornam a sua compreensão mais difícil (Treagust et al., 2003) (Bucat & Mocerino, 2009).

Esta perceção pode contribuir para a desmotivação e fraco desempenho nesta área pelos alunos, podendo até influenciar em futuras escolhas a nível profissional. Estudos também indicam que os alunos que têm contacto precoce com áreas das ciências no geral, em contexto formal e informal, demonstram melhores prestações e mais sucesso a nível académico e, mais importante, maior incidência na escolha de uma profissão nestas áreas (Fleer & Pramling, 2015)(Teppo et al., 2021)(Dewi et al., 2021). Por outro lado, a tecnologia de Realidade Aumentada permite a visualização de informação digital no mundo real, possibilitando a observação de conteúdos e fenômenos das áreas das ciências que de outra forma não seria possível, facilitando o processo de aprendizagem. Outra ferramenta que tem demonstrado ser eficaz e versátil na administração de conteúdos educativos é os jogos digitais. Estes permitem adaptar diferentes métodos pedagógicos nas suas mecânicas de jogos, facilitando o processo de aprendizagem e motivando os alunos para diversas disciplinas escolares, de acordo com as habilidades dos alunos (Prensky, 2001).

Nesta perspetiva, o projeto "A Fábula Periódica" tem como intuito promover o interesse dos alunos, com idades compreendidas entre os 9 aos 13 anos, antes de estes terem contacto com o conteúdo da Tabela Periódica o qual, em contexto escolar e no âmbito curricular de Físico/Química, deve acontecer no 8º ano de escolaridade. O critério de seleção é ainda baseado no desenvolvimento cognitivo da criança, que nesta faixa etária já tem capacidade de compreensão de conceitos abstratos.

A Fábula Periódica é composta por três jogos didáticos, desenhados e desenvolvidos utilizando a tecnologia da Realidade Aumentada (AR), como ferramentas de investigação: *" Descoberta da Fábula Periódica", "Fábula Periódica uma Viagem Aumentada", e finalmente "A Fábula Periódica no Meio".* Cada jogo apresenta a mesma informação ou conteúdo educativo. Porém, a sua abordagem pedagógica, a qual está integrada na própria mecânica dos jogos, é diferente (ver anexo I – Descrição dos jogos). O nosso estudo visa investigar a eficácia destas ferramentas na aprendizagem de conceitos abstratos sobre a Tabela Periódica e o seu efeito a nível da motivação e interesse pela química.

Metodologia

Participantes

O estudo está a decorrer nas Escola Básicas dos 2º e 3º Ciclo da Região Autónoma da Madeira (ver anexo II – Lista nominal das escolas). Tem como principal objetivo a recolha de dados sobre eficácia dos jogos educativos em Realidade Aumentada (AR) na aprendizagem de conceitos abstratos sobre a Tabela Periódica e quais são os efeitos destas ferramentas no âmbito da perceção sobre a disciplina da química.

Nesta primeira etapa, as crianças (alunos do 5º ao 7º ano) cujos encarregados de educação autorizarem a participar no estudo (ver Anexo III - Consentimento Informado Encarregados Educação), serão convidados ao preenchimento de inquéritos e a interagir com um dos jogos da Fábula Periódica. Esta atividade será realizada em dois blocos de 45 minutos e acompanhada pelo professor responsável da turma, o investigador principal e dois assistentes do investigador.

Descrição do estudo

O estudo irá ser implementado usando um desenho experimental "Intra-Sujeitos" (ou medidas repetitivas), exemplificado pelo cenário proposto na Figura 1.

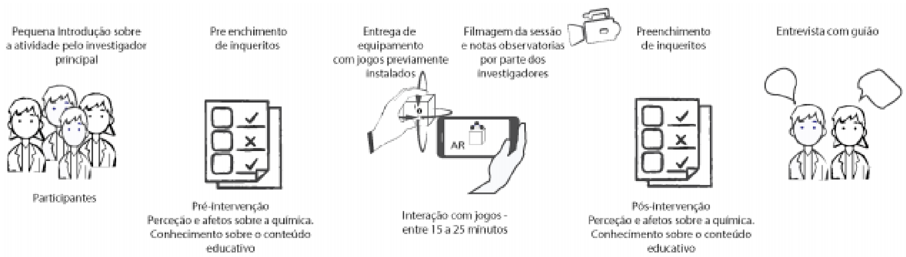

Figura 1 – Cenário proposto para estudo

Serão recolhidos dados quantitativos, nomeadamente: *dados demográficos* (gênero, idade, experiência prévia com a tecnologia e com o conteúdo, método ensino/aprendizagem preferido), *dados sobre a compreensão do conteúdo* (elaborados e validados por professores da área), e finalmente *perceção sobre a química como disciplina* (utilizando como instrumento uma adaptação a escala de PANAS (Ebesutani et al., 2012). *Entrevistas, notas de observação* (sobre as expressões faciais dos participantes, movimentos e interação com os jogos, comentários, e dificuldades durante a atividade *e filmagens* serão utilizados como dados qualitativos. Os resultados dos inquéritos pré e pós intervenção serão comparados utilizando a ferramenta estatística IBM Spss.

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Processo

No início do estudo, os professores responsáveis pela turma, em conjunto com a investigadora principal, farão uma breve apresentação da atividade. A investigadora principal fará ainda uma breve introdução sobre o projeto de forma muito geral e indicará as diferentes etapas do processo inerente ao estudo. Seguidamente, será colocado em cada aluno um autocolante com um código identificativo (atribuído pelos investigadores), permitindo a comparação dos resultados dos inquéritos de pré e pós intervenção a serem preenchidos durante a atividade.

Uma vez apresentada a atividade, os participantes terão que responder um pré-inquérito (ver em Anexo IV).

Seguidamente serão recolhidos os pré-inquéritos, e os alunos serão convidados pelo investigador a interagir com os jogos. A atribuição do jogo a ser explorado será indicado pelo investigador principal. Os participantes, com ajuda do tutorial presente no início do jogo, serão guiados para diversas tarefas lúdico-didáticas onde poderão explorar informações sobre as propriedades dos elementos químicos (número atômico, peso, simbologia); a sua localização na Tabela Periódica; produtos e objetos do quotidiano que apresentam estes elementos na sua composição; atividade de junção covalente que visam a criação de substâncias e visualização da estrutura molecular das substâncias criadas. A intervenção será gravada (vídeo e áudio) de modo a possibilitar catalogação de: comportamentos, emoções, expressões orais, entre outros. No caso de pelo menos um encarregado de Educação da turma em intervenção não permitir a gravação de áudio do seu educando este passo será ignorado para esta turma. Neste caso concreto, serão feitas só as anotações por parte dos investigadores em sala de: comportamentos, emoções, expressões orais, entre outros, para futura análise.

A interação com os jogos será feita usando um telemóvel Samsung Edge S7, propriedade do Instituto de Investigação ITI, com os jogos previamente instalados. Este equipamento, será entregue aos alunos pelos investigadores e recolhido pelos mesmos após a intervenção (interação com os jogos). Enquanto os participantes interagem com as aplicações, será filmada as interações dos mesmos e os investigadores tiraram notas.

Após a interação com os jogos, os participantes deverão responder a um pós-inquérito com as mesmas perguntas que o pré-inquérito mais organizadas de forma aleatória (ver anexo V). Será ainda realizada uma entrevista para recolher informação sobre usabilidade e para aferir a opinião dos alunos sobre os sistemas lúdicos e sua importância e pertinência para a aprendizagem da química (ver anexo VI).

Com a análise dos dados recolhidos através de análise estatística, espera-se conseguir perceber:

- Benefícios e limitações da Realidade Aumentada no âmbito da aprendizagem da química.
- Se existem dados significativos que demonstram que os jogos de Realidade Aumentada podem melhorar os resultados da aprendizagem do conteúdo educativo.

- Se a utilização desta ferramenta pode promover o interesse e melhorar a perceção dos alunos sobre a química.

Bibliografia

Bucat, B., & Mocerino, M. (2009). Learning at the Sub-micro Level: Structural Representations. In J. K. Gilbert & D. Treagust (Eds.), *Multiple Representations in Chemical Education* (Vol. 4, pp. 11–29). Springer Netherlands. https://doi.org/10.1007/978-1-4020-8872-8_2

Dewi, C. A., Pahriah, P., & Purmadi, A. (2021). The Urgency of Digital Literacy for Generation Z Students in Chemistry Learning. *International Journal of Emerging Technologies in Learning (IJET)*, *16*(11), 88. https://doi.org/10.3991/ijet.v16i11.19871

Fleer, M., & Pramling, N. (2015). *A Cultural-Historical Study of Children Learning Science: Foregrounding Affective Imagination in Play-based Settings* (1st ed. 2015). Springer Netherlands : Imprint: Springer. https://doi.org/10.1007/978-94-017-9370-4

Luraschi, M., Rezzonico, R., & Pellegri, G. (2012). The Chemist, that Madman! How Children Perceive Science. *CHIMIA*, *66*(11), 820. https://doi.org/10.2533/chimia.2012.820

Morais, C. (2015). Storytelling with Chemistry and Related Hands-On Activities: Informal Learning Experiences To Prevent "Chemophobia" and Promote Young Children's Scientific Literacy. *Journal of Chemical Education*, *92*(1), 58–65. https://doi.org/10.1021/ed5002416

Prensky, M. (2001). *Digital game-based learning*. McGraw-Hill.

Teppo, M., Soobard, R., & Rannikmäe, M. (2021). A Study Comparing Intrinsic Motivation and Opinions on Learning Science (Grades 6) and Taking the International PISA Test (Grade 9). *Education Sciences*, *11*(1), 14. https://doi.org/10.3390/educsci11010014

Treagust, D., Chittleborough, G., & Mamiala, T. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25*(11), 1353–1368. https://doi.org/10.1080/0950069032000070306

Anexos

Anexo I - Jogos Lúdico-Educativos "A Fábula Periódica"

A Fábula Periódica é um conjunto de três jogos educativos em Realidade Aumentada, direcionada a crianças com idades compreendidas entre os 9 e os 13 anos, com o intuito de motivar e facilitar a aprendizagem de conceitos básicos sobre a Tabela Periódica. O conjunto de jogos dispõe de diferentes abordagens pedagógicas (como a utilização de analogias, histórias e animações) para que a transposição e assimilação dos conceitos educativos seja feita de uma forma lúdica. Cada uma das personagens representa um elemento químico, num total de dez elementos abordados nesta fase do desenvolvimento.

Descrição dos jogos

1º Jogo – "Descoberta da Fábula Periódica"

Jogo com uma vertente construtivista onde a aprendizagem é feita pela exploração e aquisição de informação (com recurso a um telemóvel e à interface física de um cubo).

A experiência inicia-se com um tutorial que indica a mecânica do jogo - exploração das fases do cubo com recurso à câmara do telemóvel para visualizar a informação (animações, modelos tridimensionais, áudio, texto, etc.). A cada cubo (cinco) é atribuído um elemento químico: oxigénio, hidrogénio, nitrogénio, cloro e carbono. Cada um destes elementos químicos possibilita diferentes áreas de exploração: propriedades do elemento químico, produtos que contêm esse elemento, histórias, localização do elemento na tabela periódica, combinações de elementos para criar reações e, finalmente, o mapa que dá acesso a uma recompensa (Selfie).

2º Jogo – "Fábula Periódica uma Viagem Aumentada"

É um jogo de aventura que se desenvolve em prol de uma narrativa para a introdução do conteúdo educativo. O jogo inicia-se com a exibição da história - personagens a navegar no espaço, desvio e queda num planeta. Após esta introdução, o jogador é convidado a ajudar a personagem principal a explorar um mundo em 3D, dialogar com outros personagens (elementos químicos em fase de extinção pelo sua sobre-exploração), ultrapassar obstáculos com a utilização de reações químicas e recuperar peças da nave.

3º Jogo – "Fábula Periódica no Meio"

Esta experiência é baseada na utilização de produtos do nosso quotidiano como parte da mecânica do jogo. O jogo inicia-se com um tutorial que indica aos participantes que utilizem a câmara do dispositivo móvel para "capturar" átomos que fazem parte dos compostos de alguns objetos/substâncias (como lixívia, água, um capacete, baterias e outros). Após a aquisição dos átomos, os jogadores usam um mini-jogo que permite que juntem os átomos e criem moléculas/compostos químicos e os visualizem em 3D. Ao finalizar o jogo, a criança recebe uma mensagem de parabéns e a oportunidade de tirar um selfie com todas as personagens do jogo.

https://periodicfable.m-iti.org/

Vídeos sobre a interação dos dois primeiros jogos.

Anexo II – Lista Nominal das Escolas onde se pretende realizar os estudos

Tabela 1 – Lista nominal de possíveis escolas dos 2º e 3º Ciclo da Região Autónoma da Madeira onde se pretende realizar os estudos

Escola	Ano
Escola Básica dos 2º e 3º Ciclo do Caniço	5º, 6º e 7º ano de escolaridade
Escola BS de Santa Cruz	5º, 6º e 7º ano de escolaridade
Escola BS Dr. Ângelo Augusto da Silva	5º, 6º e 7º ano de escolaridade
Escola BS de Machico	5º, 6º e 7º ano de escolaridade
Escola BS Gonçalves Zarco	5º, 6º e 7º ano de escolaridade
Escola Básica dos 2º e 3º Ciclos Dr. Horácio Bento Gouveia	5º, 6º e 7º ano de escolaridade
Escola Básica dos 2º e 3º Ciclos da Torre	5º, 6º e 7º ano de escolaridade
Escola BS da Ponta do Sol	5º, 6º e 7º ano de escolaridade
Escola BS Padre Manuel Álvares	5º, 6º e 7º ano de escolaridade

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Anexo III – Consentimento Informado

Projecto "A Fábula Periódica"

Consentimento: Informação aos Pais

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Título do Estudo: A Realidade Aumentada como ferramenta para motivar e facilitar a aprendizagem de conceitos sobre a Tabela Periódica dos elementos químicos.

Objetivo do Estudo: O objetivo deste estudo é tentar compreender se a utilização de jogos educativos em realidade aumentada, em âmbito educativo formal e informal, podem promover e motivar as crianças para a área da química, assim como facilitar a aprendizagem e retenção de conceitos básicos sobre Tabela Periódica.

Caro encarregado de Educação,

O grupo de investigação do Interactive Technology Institute (Madeira Tecnopolo) irá colaborar com a *nome da escola* durante o dia *data do estudo,* no contexto do projeto "A Fábula Periódica".

A utilização de conceitos abstratos em disciplinas como a matemática, ciências e outras, apresentam-se como um obstáculo para alguns alunos. Neste sentido, métodos que facilitem esta aprendizagem no ensino básico podem ser úteis.

A Realidade Aumentada (RA) é uma tecnologia que apresenta a possibilidade de interação entre o mundo físico e o digital, facilitando a visualização de conteúdos mais complexos. Esta tecnologia pode ainda facilitar o papel de educadores e professores, motivar a aprendizagem ativa dos alunos nas escolas e ajudá-los na retenção e aprendizagem de diversos conteúdos.

Com a intenção de analisar a eficácia desta ferramenta, foram desenvolvidas três aplicações em Realidade Aumentada pelos investigadores sobre os conceitos básicos dos elementos da Tabela Periódica. Neste âmbito, será pedido ao seu educando para interagir com um dos jogos, a fim de explorar informação relacionada com as propriedades dos elementos químicos; a sua localização na Tabela Periódica; produtos e objetos do quotidiano que apresentam estes elementos na sua composição e, finalmente, uma atividade que visa a criação digital de substâncias químicas. No fim do jogo, o seu educando terá a opção de tirar um selfie com uma das suas personagens preferidas (como compensação por finalizar o jogo), ficando esta informação alocada no equipamento e disponível ao aluno para partilhar com amigos ou familiares só no momento do estudo. Os selfies serão permanentemente apagados do equipamento após o estudo. Será ainda pedido ao seu educando para responder alguns inquéritos e fazer uma pequena entrevista após a utilização da aplicação. O estudo irá decorrer durante a *aula de ou atividade escolar*, *local ou sala* e terá uma duração de 1 h – 1h 30 min, aproximadamente. A atividade será explicada de forma acessível às crianças. O seu educando poderá recusar-se a participar no estudo ou desistir do mesmo a qualquer momento, sem ter que apresentar alguma justificação.

Riscos: Não existem riscos associados a esta experiência, sendo que esta é uma atividade similar à dos participantes numa sala de aulas.

Benefícios: Ao participar nesta experiência estará a melhorar as técnicas para aumentar o interesse e a aprendizagem de conceitos sobre a química pelas crianças, utilizando ferramentas digitais.

Compensações e Custos: Não existem custos nem compensações por participar neste estudo

Confidencialidade: Esta declaração de consentimento será arquivada nas instalações do Interactive Technologies Institute e não será divulgada a terceiros. Durante o estudo serão recolhidos dados sobre todas as escolhas que o(a) seu(ua) educando(a) fizer usando as aplicações disponibilizada com conteúdos relativos aos elementos químicos, questionário apresentado e entrevista. Será também recolhido material de áudio, vídeo e imagem para posterior análise. ***O material recolhido não será colocado online nem publicitado de nenhuma forma. Os dados destinam-se apenas a análise estatística***. Os dados recolhidos só poderão ser divulgados em revistas, eventos científicos ou em contexto educativo. Cada participante irá ser identificado através de um código aleatório, que não permitirá identificá-lo(a) a si ou ao(à) seu(ua) educando(a) pessoalmente. Todos os dados recolhidos serão mantidos em anonimato e serão armazenados num servidor do ITI-Interactive Technology Institute, ao qual apenas

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os investigadores envolvidos neste estudo poderão aceder até ao final de 2024. O tratamento dos dados será feito pela investigadora Sandra Câmara Olim (S.Olim@campus.fct.unl.pt).

A recolha e tratamento de dados pessoais, no âmbito do estudo em causa, está de acordo coma legislação em vigor, nomeadamente, a Lei nº. 58/2019 de 8 de agosto, que assegura a execução, na ordem jurídica nacional, do Regulamento Geral de Proteção de Dados (EU) 2016/679 do Parlamento e do Conselho, de 27 de abril de 2016, relativo à proteção das pessoas singulares no que diz respeito ao tratamento de dados pessoais e à livre circulação desses dados.

Direitos: A qualquer momento o(a) Sr(a) responsável pela educação da criança poderá pedir para aceder aos dados do seu educando, bem como pedir para remover os seus dados da nossa base de dados ou até mesmo apresentar reclamação junto da CNPD (Comissão Nacional de Proteção de Dados) http://www.cnpd.pt/. Tem ainda o direito de retirar consentimento em qualquer altura, sem comprometer a licitude do tratamento efetuado com base no consentimento previamente dado. A recusa em participar ou interrupção da participação não resultará em qualquer penalização ou perda de eventuais benefícios ou direitos. O investigador principal poderá decidir, de forma fundamentada, interromper a participação do interveniente neste estudo. Mesmo neste caso, não haverá qualquer penalização ou perda de eventuais benefícios ou direitos. Se o interveniente tiver dúvidas sobre este estudo, desejar obter mais informações ou pretender interromper a sua participação no estudo, poderá entrar em contato com o Investigador Principal (por e-mail). A informação de contato está disponível no início da primeira página deste documento.

Menores: Os menores (indivíduos com idade inferior a 18 anos) não podem legalmente dar o consentimento para participar em estudos de investigação. O consentimento só pode ser dado pelo pai/mãe do participante ou responsável legal.

Consentimento Voluntário

Entendo que os investigadores podem querer usar fotografias, vídeo ou áudio para ilustrar apresentações e/ou publicações deste trabalho, para fins científicos ou educativos. Dou autorização para fazê-lo, desde que o nome e rosto do meu educando não sejam identificáveis: ______SIM ______NÃO

Ao assinar este documento, o participante confirma que leu a informação acima descrita sobre este estudo e que todas as suas perguntas foram respondidas. Mesmo assim, o participante poderá fazer perguntas adicionais a qualquer momento durante o estudo e mesmo após este ter terminado. Ao assinar este documento, concorda que o seu filho participe neste estudo de investigação.

______________________________ ______________

ASSINATURA DO PAI/MÃE/RESPONSÁVEL LEGAL DATA

NOME DO MENOR: ____

Investigador que obtém o consentimento: Como membro da equipa de investigação, confirmo que expliquei ao participante acima referido a natureza e finalidade deste estudo de investigação, e que esclarece quais os potenciais benefícios e eventuais riscos da participação no estudo. Todas as perguntas foram respondidas e estou disponível para esclarecer quaisquer dúvidas que possam surgir ao longo do estudo.

ASSINATURA DO INVESTIGADOR DATA

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Anexo IV - Pré-inquérito

Periodic Fable

Jogo a Fábula Periódica Pré-inquérito

A Fábula Periódica é um conjunto de três jogos educativos em Realidade Aumentada, desenhados e desenvolvidos com o intuito de motivar e facilitar a aprendizagem de conceitos básicos sobre a Tabela Periódica.

Para avaliar a eficácia desta ferramenta, pedimos que sejam respondidas as seguintes perguntas:

ID do participante número no autocolante: ______________

Género: *masculino* ☐ *feminino* ☐

Idade: ______ *Ano de escolaridade:* ________

1. Conhece ou já utilizou a tecnologia de Realidade Aumentada?

   Sim ☐ Não ☐

2. Já ouviu falar nos elementos químicos da Tabela Periódica?

   Sim ☐ Não ☐

3. Sabe o que é a química?

   Sim ☐ Não ☐

4. O que acha que se aprende na química? ______________________________

5. Nesta pergunta pode escolher mais do que uma resposta. Acha que a química é:

difícil	☐	fácil	☐
interessante	☐	simples	☐
divertida	☐	complexa	☐
inútil	☐	útil	☐
aborrecida	☐	maçadora	☐

6. Tem outra opinião sobre a química? ______________________________

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7. Qual é o método de ensino / aprendizagem que prefere? Pode escolher mais do que uma resposta

Que o professor explique a matéria / conteúdo	☐
Explorar o conteúdo por conta própria, utilizando a internet ou um jogo	☐
Aprender por meio de histórias	☐
Nenhuma das opções acima indicadas	☐

Conhecimento prévio sobre a Tabela Periódica

Vamos começar por identificar se tem algum conhecimento prévio deste conteúdo. Por vezes, já ouvimos falar, sabemos alguma coisa, ou não sabemos nada sobre o tema, o que é perfeitamente normal! Recorde que não há respostas certas ou erradas.

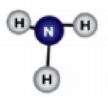
1. O ozono é formado por:

dois oxigénios	☐	cinco carbonos	☐
nitrogénio e hidrogénio	☐	não sei	☐
três oxigénios	☐	outro	☐

2. Qual é o símbolo do nitrogénio, também conhecido por azoto?

N2	Az	N	Ni	Não sei
☐	☐	☐	☐	☐

3. Quantos hidrogénios tem a seguinte molécula?



CL=1	H=4	N=1	H=3	Não sei
☐	☐	☐	☐	☐

4. Qual é o símbolo químico do cloro?

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CO	CL	CH	Lixívia	Não sei
☐	☐	☐	☐	☐

5. Qual é o elemento responsável pela constituição dos diamantes?

Cloro	Carbono	Hidrogénio	Nitrogénio	Não sei
☐	☐	☐	☐	☐

6. Qual destes elementos existe na composição química da água?

Cloro	Nitrogénio	Oxigénio	Platina	Não sei
☐	☐	☐	☐	☐

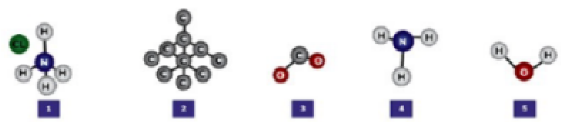
7. Qual é a fórmula química do dióxido de carbono?

CO_2	H_2O	NH_3	O_3	C_2O_2
1	2	3	4	5
☐	☐	☐	☐	☐

8. Qual é a fórmula química da água?

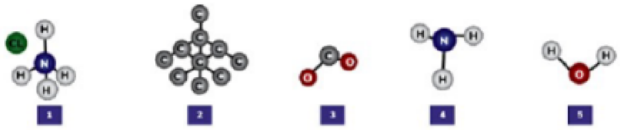
CO_2	H_2O	NH_3	O_3	C_2O_2
1	2	3	4	5
☐	☐	☐	☐	☐

9. Qual destas moléculas está presente na estrutura de um diamante?



☐ ☐ ☐ ☐ ☐

10. Qual destas moléculas representa água?



☐ ☐ ☐ ☐ ☐

Obrigado pela sua participação!

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Anexo IV - Pós-inquérito

Periodic Fable

Jogo a Fábula Periódica Pós-inquérito

ID do participante número no autocolante: ________

1. Nesta pergunta pode escolher mais do que uma resposta. Achas que a química é:

difícil	☐	fácil	☐
interessante	☐	simples	☐
divertida	☐	complexa	☐
inútil	☐	útil	☐
aborrecida	☐	maçadora	☐

2. Tens outra opinião sobre a química? ______________________________

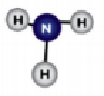
3. Qual é o símbolo do nitrogénio, também conhecido por azoto?

N2	Az	N	Ni	Não sei
☐	☐	☐	☐	☐

4. O ozono é formado por:

dois oxigénios	☐	cinco carbonos	☐
nitrogénio e hidrogénio	☐	não sei	☐
três oxigénios	☐	outro	☐

5. Quantos hidrogénios tem a seguinte molécula?



CL=1	H=4	N=1	H=3	Não sei
☐	☐	☐	☐	☐

6. Qual destes elementos existe na composição química da água?

Cloro	Nitrogénio	Oxigénio	Platina	Não sei
☐	☐	☐	☐	☐

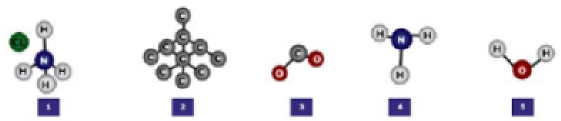
7. Qual é o elemento responsável pela constituição dos diamantes?

Cloro	Carbono	Hidrogénio	Nitrogénio	Não sei
☐	☐	☐	☐	☐

8. Qual é a fórmula química do dióxido de carbono?

CO_2	H_2O	NH_3	O_3	C_2O_2
1	2	3	4	5
☐	☐	☐	☐	☐

9. Qual destas moléculas está presente na estrutura de um diamante?



☐	☐	☐	☐	☐

10. Qual destas moléculas representa água?

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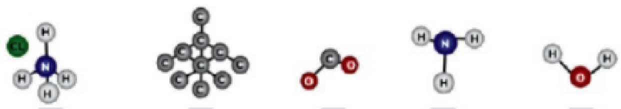

1	2	3	4	5
☐	☐	☐	☐	☐

11. Qual é a fórmula química da água?

CO_2	H_2O	NH_3	O_3	C_2O_2
1	2	3	4	5
☐	☐	☐	☐	☐

Obrigada pela tua participação!

Anexo VI – Guião da Entrevista pós interação com aplicação

1. O que é que mais gostas-te na aplicação com que interagiste?
2. O que é que menos gostas-te no jogo com que interagiste?
3. Voltarias a jogar?
4. Achaste que faltava alguma coisa na aplicação? Se sim, indica o quê?
5. Se tivesses a oportunidade de modificar ou mudar alguma coisa no o jogo, o que séria?
6. Recomendavas o jogo aos teus colegas?
7. Achas que este jogo pode ser útil no teu futuro? Se sim, porque?
8. Ao interagir com o jogo, sentiste alguma dificuldade?

Direção Regional de Educação DSAGO		
SAÍDA	CLASSIF.	DATA
2364	5.13.0	12-12-2022

S. R.

REGIÃO AUTÓNOMA DA MADEIRA
GOVERNO REGIONAL
SECRETARIA REGIONAL DE EDUCAÇÃO, CIÊNCIA E TECNOLOGIA
DIREÇÃO REGIONAL DE EDUCAÇÃO

Exma. Senhora
Dra. Sandra Câmara Olim
s.olim@campus.fct.unl.pt

ASSUNTO: **Pedido de autorização para realização de estudo em escolas da RAM**

Na sequência da vossa solicitação, com entrada nos serviços a 28-12-2022, informa-se Vossa Excia de que, por despacho do Diretor Regional de Educação de 07 de dezembro de 2022, está autorizada a realizar um estudo de âmbito académico, nas Escolas de 2.º e 3.º Ciclos do Ensino Básico da RAM.

O estudo intitulado "A Realidade Aumentada como ferramenta para motivar e facilitar a aprendizagem de conceitos sobre a Tabela Periódica dos elementos químicos" insere-se no Doutoramento em Media Digitais, da Universidade Nova de Lisboa, em parceria com o Instituto de Tecnologias Interativas da Madeira (ITI), sob a orientação da Professora Doutora Valentina Nizi.

No entanto, informa-se que a aplicação do estudo deve atender às observações seguintes:

a) A realização do estudo fica sujeita à autorização das direções dos estabelecimentos de educação e ensino, a contactar para o efeito, a quem compete autorizar a realização de intervenções educativas/desenvolvimento de atividades/programas em meio escolar, junto de alunos em contexto de sala de aula ou em qualquer outro espaço escolar, por ser suscetível de interferir no ato educativo, a quem incumbe, também, a gestão dos recursos humanos, bem como, salvaguardar o direito da confidencialidade dos dados pessoais dos alunos, nos termos do n.º 1 do Artigo 7.º do Decreto Legislativo Regional n.º 21/2013/M, de 28 de junho, que estabelece o Estatuto do Aluno e Ética Escolar da RAM. O estudo em meio escolar deverá fazer-se em estreita articulação com as direções das escolas, que decidirão sobre o modo, o momento e condições de aplicação dos instrumentos de recolha de dados em meio escolar;

b) Autorizada a realização do estudo pelas direções das escolas, fica ao critério de cada docente aceitar ou não a realização do estudo durante a sua aula ou atividade e de

Na resposta indicar a «Nossa Referência». Em cada ofício tratar só de um assunto

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cada encarregado de educação autorizar ou não a participação do seu educando e de cada aluno aceitar ou não participar na investigação;

c) Deve considerar-se o disposto legal em matéria de garantia de anonimato dos implicados, confidencialidade, proteção e segurança dos dados. Considerados os documentos que foram anexados e para efeitos de proteção dos dados pessoais a recolher junto dos participantes, em cumprimento da legislação em vigor (Lei n.º 58/2019, de 8 de agosto, que assegura a execução, na ordem jurídica portuguesa, do Regulamento Geral de Proteção de Dados (EU) 2016/679 do Parlamento e do Conselho, de 27 de abril de 2016, relativo à proteção de pessoas singulares no que diz respeito à proteção de dados pessoais e à sua livre circulação) resultam obrigações que a responsável se propõe cumprir. Destas deve dar conhecimento a todos os inquiridos e a quem intervenha na recolha e tratamento de dados pessoais. É obrigatório recolher as declarações de consentimento informado e esclarecido a utilizar junto dos representantes legais dos titulares dos dados. Não deve haver cruzamento ou associação de dados entre os que são recolhidos pelos instrumentos de inquirição e os constantes das declarações de consentimento informado.

d) A autorização expressa deve vincular-se em exclusivo à aplicação dos instrumentos de inquirição e não a quaisquer outros atos ou medidas da inteira responsabilidade da requerente ou de terceiros.

Com os melhores cumprimentos,

O Diretor de Serviços de Investigação,
Formação e Inovação Educacional

Bernardo Lage Valério

(Bernardo Lage Valério)

GF/LB

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Appendix B

Aesthetics - Environmental Assets


Periodic
Fable
H2O Park
CORONAVÍRUS - SINTOMAS
Periodic
Fable


Oxigénio
Hidrogénio
Cloro
Azoto
Carbono
PRESENTS
Nitrogen
Oxygen

Appendix C

Publications

"Periodic Fable Discovery"

Using Tangible Interactions and Augmented Reality to Promote STEM Subjects

Sandra Câmara Olim
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Valentina Nisi
Instituto Superior Tecnico, University of Lisbon
Lisboa, Portugal and ITI/LARSys
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Elisa Rubegni
Lancaster University
Lancaster, UK
e.rubegni@lancaster.ac.uk

ABSTRACT

This pictorial presents Periodic Fable (PF), an educational game's design and graphic interface that promotes a constructivist approach to engage young children with Science, Technology, Engineering, and Math (STEM) subjects. The game presents children with scientific content supported with an exploratory activity using physical cubes manipulable through Tangible Interaction and Augmented Reality. The game's objective is to entertain children while engaging them with the basics of chemistry and the Periodic Table. We reflect upon the combination of these immersive technologies, game-play mechanics, and aesthetics geared towards conveying accurate scientific information through a ludic and entertaining approach. The quantitative and qualitative results of a study with 20 children, showed significant positive results in the participants' learning outcomes and engagement, thereby encouraging us to continue evaluating our design system as a tool that can promote STEM Education.

Authors Keywords

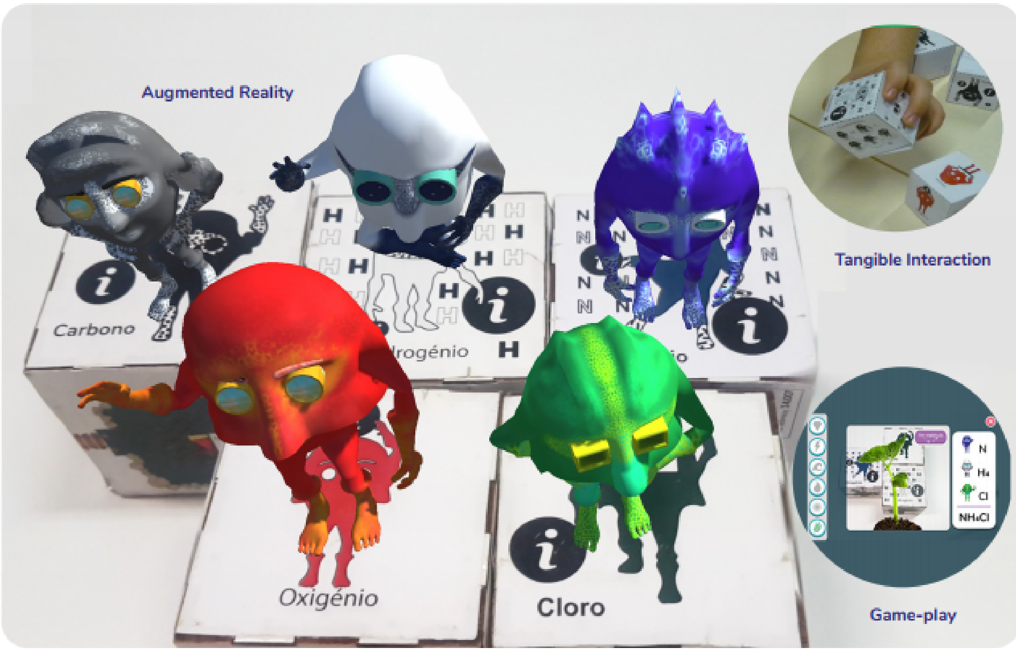
Augmented Reality; Serious Games; Chemistry; Periodic Table; Children.

CSS Concepts

•Human-centered computing~Human computer interaction (HCI)~Interaction paradigms~Mixed / augmented reality

TEI '23, February 26-March 1, 2023, Warsaw, Poland

ACM ISBN 978-1-4503-9977-7/23/02.
https://doi.org/10.1145/3569009.3572804



Periodic Fable use of AR allows children to discern and interact with the real environment while receiving additional digital information from multiple perspectives. The TI is designed so that the child manipulates the cube to capture the graphics of a facet with the mobile device camera. Game play elements are used to actively engage the user with the learning content.

INTRODUCTION

Children perceived chemistry as a difficult and complex subject [13, 38, 46, 61, 63]. This perception, as in other STEM subjects, can affect the student's academic performance and future career choices [19, 29, 45, 61]. In Portugal, like in other countries, this is a concern for the educational community, especially since the student's decision to initiate a trajectory in chemistry or other STEM domain through the school curriculum is usually taken very earlier, when students are around age 14-16 years old [16].

Participants interacting with game character

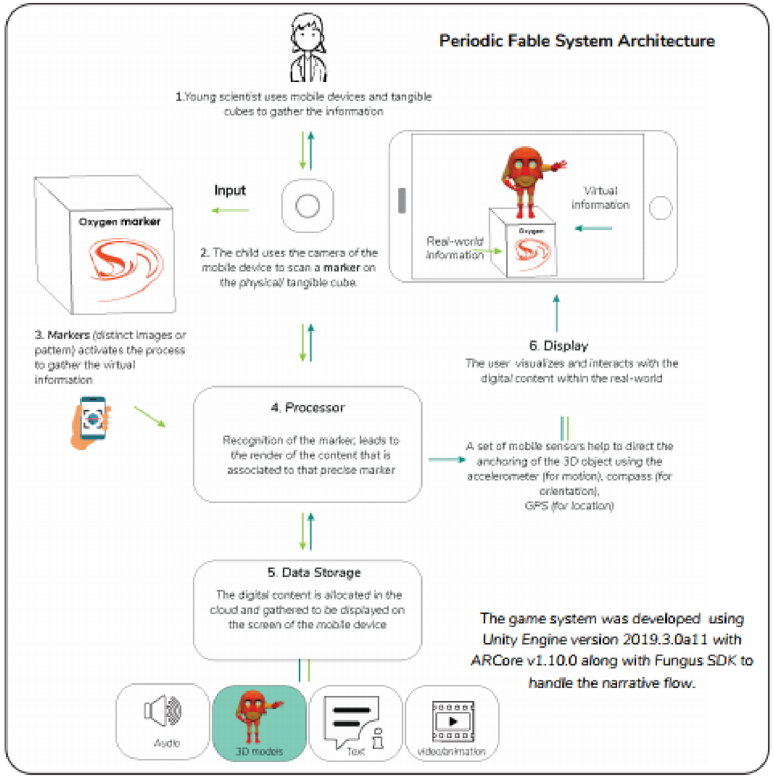
Augmented Reality (AR) allows the superimposition of virtual objects on top of the real world [52]. Such an approach can facilitate individuals' understanding of demanding concepts by means of making them visible and allowing multidimensional perspectives [68]. Through AR simulations' use of images and visual maps to create connections, visual learners and educators can benefit from this approach by allowing the application of theoretical material into the real concept, supporting spatial cognition [39]. Furthermore, these tools have the potential to motivate students toward scientific domains [9, 10, 15, 20, 35].

Game actity to create chemical reactions

When we look at multimodal interactions that combine digital information with tangible interfaces, literature has shown great potential to facilitate the understanding of abstract concepts and scientific phenomena [68]. These tools can combine visual, tactile, and auditory elements into a seamless and natural interface, helping to create a more inclusive learning environment for children with varying levels of abilities. However, research is still limited in the actual impact of immersive technologies on teaching, learning and working in the chemistry domain [14]. While previous research showcased the benefits of AR technology on chemistry education, most of this research is geared towards high school and college students. Further research is needed to investigate the applications of technologies in game-based learning and STEM education [13]. We believe research lacks an approach to multimodal systems (AR and TI affordances) that takes into account the complexity of chemistry understanding (symbolic, microscopic and macroscopic) [34] and the student's characteristics to design and develop effective and engaging tools for chemistry.

This paper contributes by:

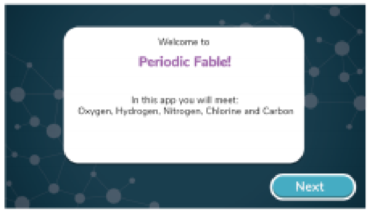
- Providing researchers with our guidepost in the design and development of Periodic Fable (PF) Discovery, a Tangible Interaction (TI) and Augmented Reality (AR) based game that supports the communication between different types of expertise, towards facilitating and engaging young children learning of abstract scientific content about the Periodic Table of chemical elements.
- We reflect upon the contributions of teachers and game designers. We also report the affordances of Tangible Interaction (TI) and Augmented Reality (AR) based games to administer scientific content to young children.
- Finally, we share our findings from a user study with 20 participants (9 to 13 years old children) using a mix-method approach.



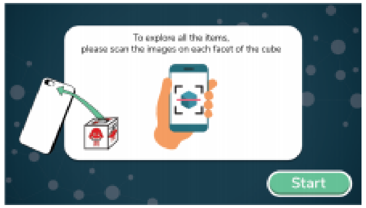
INTERACTION DESIGN

The use of AR and TI created the opportunity to design the game-play that can benefit from a constructive learning approach. The child interacts with the AR content by rotating and scanning the facet of the physical cube (4 cm x 4 cm) at their own pace and time. The game provides instructions that are easy to follow and gives immediate feedback (visual and audio) to guide the player. The game starts with a short tutorial (images 2 - 3) which invites the player to explore all the cube facets freely.

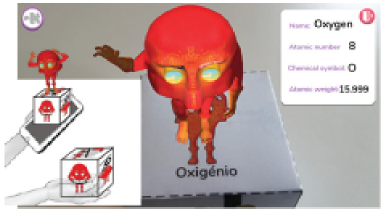
1. We provide the 2D plan of the cubes on our website, allowing the children, teachers and parents to download, print, and assemble each cube creating their own TI.



2. After Periodic Fable Discovery uploads, the user is welcome to meet Oxygen, Hydrogen, Nitrogen, Carbon, and Chlorine

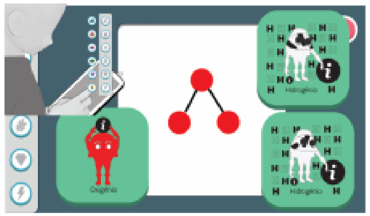


3. The tutorial guides the user to use the camera and point at the facets of the cube to meet the characters and find information

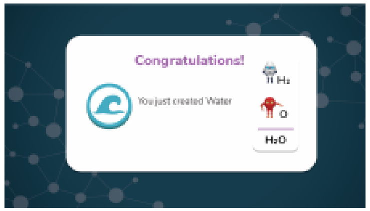


4. The user "captures" the image at the facet of the cube, and the AR systems will display digital information (3D models, animations).

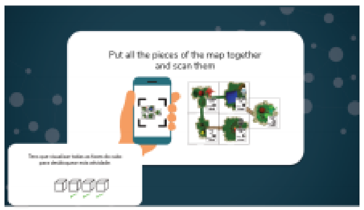
5. Create a chemical compound by joining two or more elements.



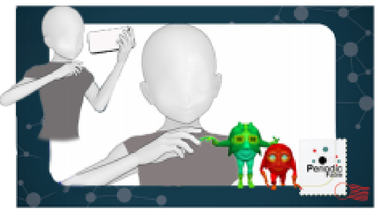
6. The app will showcase the compound or molecular structure



7. A congratulation screen will show the chemical equation created



8. The app will unblock a map puzzle, which, after scanned, unlocks the reward



9. Select your favourite character and take a selfie

LITERATURE REVIEW

Augmented Reality (AR) helps teach and learn STEM concepts and phenomena because of its unique affordance of allowing the coexistence of virtual information within the real world [52]. This provides the opportunity to visualize concepts without physical referend or invisible to the naked eye in different learning contexts. Research emphasizes the constructivist approach of AR because of the ability to provide dynamic representational levels of chemistry and interactive learning environments that allow students to become active learners and construct their knowledge through their experiences while developing problem-solving strategies and conceptual understanding [17]. AR affective factors, such as intrinsic and extrinsic motivation, seem to be the most correlated affects on the student´s performance and achievement in science education in general [9, 10, 15, 43, 55]. However, the success of AR interventions not only depends on the technical characteristics of the technology, but its success is associated with the pedagogical strategies to implement them. In this line, the human factors and learning levels of chemistry (microscopic, macroscopic and symbolic) [34] need to be investigated according to the student's characteristics to improve learning attitudes and achievements in this domain (see Figure 1).

Tangible Interactions (TI) have been shown to facilitate learning and be an excellent alternative to traditional teaching methods [31]. One of the key aspects of TI is the opportunity for young children to learn by using, exploring, and manipulating an actual physical object connected to digital information [5, 47] [53]. Piaget and other developmental psychologists highlighted the importance of manipulating objects, especially for young children in cognitive development [32]. When a child rotates a cube to build a tower, they employ spatial reasoning, allowing their investigation and problem-solving skills to develop further [73]. Besides the visual and auditory senses addresses by some of the more traditional computer interfaces, the haptic sense can provide an extra layer to the learning of the content [54]. One of the most prevalent theoretical accounts for TI is constructivism, which considers the manipulation of an object as a key aspect of aiding children's learning processes [3, 53]. TI has also been demonstrated to be highly effective in supporting educational activities in several topics, including those defined as STEM [25, 49, 56, 60].

Game-Based Learning (GBL) is widespread in the research community because of its potential to motivate and promote academic achievement. These educational games emerge as effective tools for knowledge construction when they include specific learning objectives [33]. Games provide interesting opportunities to build students' mental structures [32], develop abstract thinking [32, 40] and improve some relevant abilities of students like those related to attention, memory, creativity and imagination [6, 40]. Games can be considered a valuable instrument to overcome the conceptual difficulties associated with chemistry by making the content simpler, more dynamic, and enjoyable, developing a positive perception of the domain [22, 44, 64]. It also provides the opportunity to engage students with other mediums such as storytelling, aesthetics and game-play mechanics while providing content knowledge [7]. For an educative game to be effective, it is essential to have a clear learning goal to guide students, have a connection with the curricula and adapt to the knowledge of diverse learners [4]. Educators acting in a facilitating and supporting role can foster learning, particularly in selecting and discussing new information and where higher order skills are involved in the learning outcomes [71].

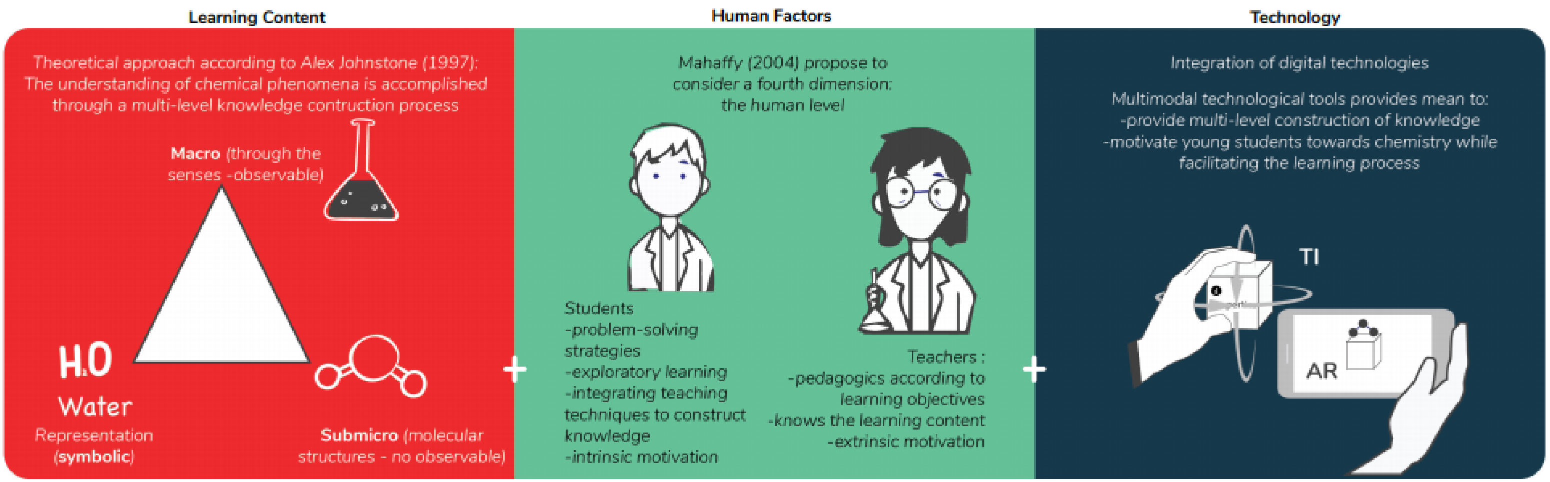


Figure 1. *Factors to consider in the design and development of tools to facilitate and engage students with chemistry*

METHODOLOGY

Our research process is divided into two parts:

I. The design and development of an artefact (PF Discovery) to conduct practice-based research and analyze AR with a TI game base tool to provide accurate scientific content. The design and development process follows several stages:

Stage 1		Stage 2		Stage 3		Stage 4
CONCEPT DESIGN	→	PAPER PROTOTYPE	→	LOW FIDELITY PROTOTYPE	→	HIGH FIDELITY PROTOTYPE

II. Afterwards, we used the high-fidelity prototype to conduct an exploratory study with 20 participants from a public school to evaluate: Can AR with TI system promote positive affects on children's perception of chemistry? How can the design of PF facilitate the learning process according to a multi-level construction of chemistry concepts? And finally, can PF engage young students with chemistry content?

Design and development of Periodic Fable Discovery

Human factors

In its early concept design and development, the system followed an iterative co-design process involving a team of three chemistry and science teachers, a PhD student in chemical biology, and four-game design experts. Children also were part of the evaluation process, refinement of the game mechanics and identification of usability issues. The collaboration was conducted through meetings and emails and yielded several iterations of the game design and concept refinement. Our design and development process follows:

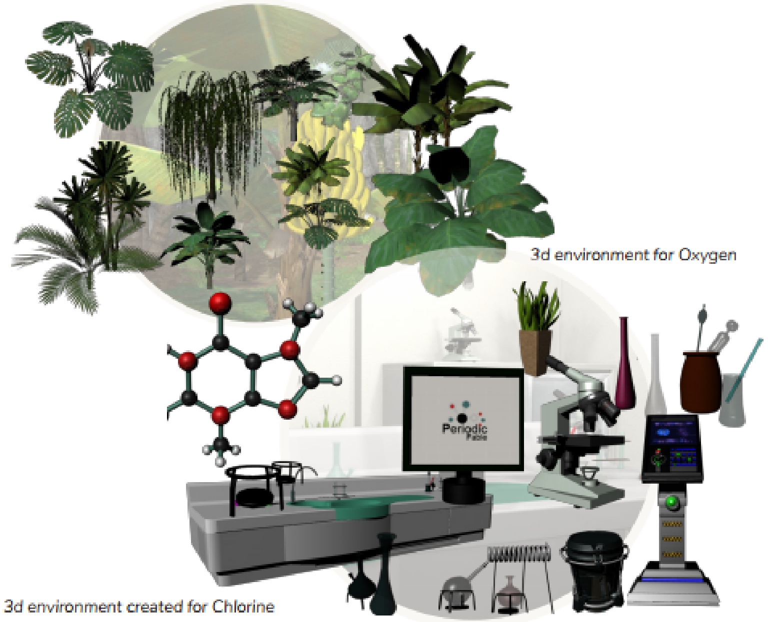
Participants interacting with PF game

Identifying users' characteristics:

Children ages between 9 and 13 years old.

The criteria for this selection are children's cognitive development since at this age can grasp abstract content when provided with appropriate visual aids and activities [1]. We also want to reach the students before they have the topic of the Periodic Table administered through the school curriculum, which happens in Portugal in 8th grade (14 year old). Most of these students have easy access to mobile devices and use them to play digital games, communicate and gather information.

The aesthetics of the game were designed to engage the children and to fit the underline narrative of the stories: the bonding of the chemical elements.



3d environment for Oxygen

3d environment created for Chlorine

The researchers and teachers also decided to showcase products/substances that contain such chemical elements within their composition, creating a connection between the content and the child's real world.

Displaying of real-products chemical compounds

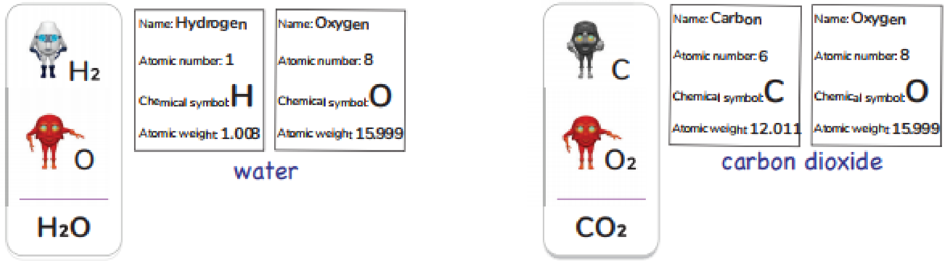
Selecting and validating the content:

The scientific content of the game was designed and verified together with a chemistry researcher (PhD. student in Chemical Biology), as well as a science and two chemistry teachers. The collaboration was conducted through presential meetings and emails and yielded several iterations of the game design and concept refinement. During the concept design stage, teachers helped define the selection of the chemical elements (to start with), the type of information to showcase to our target group (since most will be encountering this topic for the first time), and what type of reaction to showcase.

The educators stressed the need for content tailored specifically around general scientific topics like photosynthesis (oxygen), pollution (carbon dioxide and ozone), and the water cycle (hydrogen). The criteria for the selection were: abundance in the environment and compelling reaction; the teachers highlighted the importance of making children curious about the elements and encouraging them to speculate about possible combinations; the selected elements of oxygen, hydrogen, carbon, nitrogen, and chlorine were considered important because their covalent bond combinations are responsible for most biological molecules on earth.

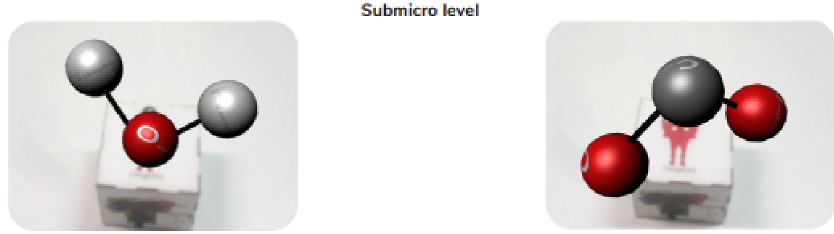
At this point, together with the chemistry experts, the different areas of exploration for our experience were co-designed: the properties of the chemical elements (showcasing a character that will represent the element); the location of such elements within the Periodic Table; display of compound/products that contain such elements; short stories about the combination of some elements; an activity where the participants could experience the joining and visualization of chemical reactions; a final reward (once the user explored all the areas).

Symbolic level



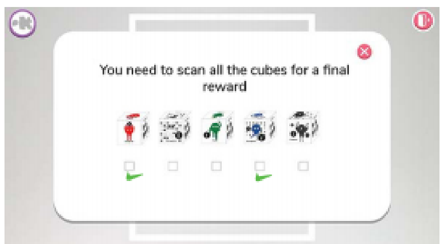
The properties of the element, chemical representation and equation are presented in visual and audio form to increase children's chemistry literacy.

Submicro level

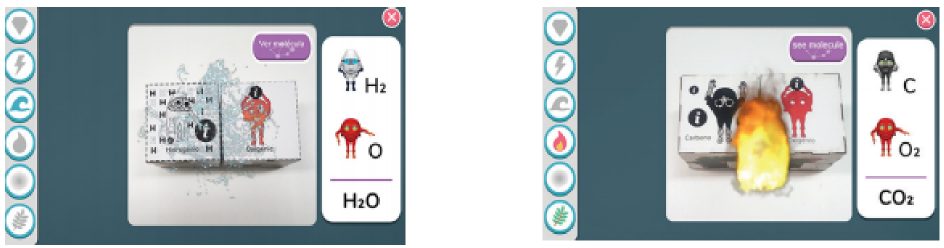


Children can interact with the molecular structure through the AR 3D models and the movement of the cube, similar to previous work by Shuxia Yang et al. (2018) [72] and Morten Fjeld et al. (2003) [21]. This feature is considered of extreme importance since it provides a deeper understanding of the spatial relationship of the element, avoiding some misconceptions associated with the use of more traditional methods of teaching [67].

Macro level

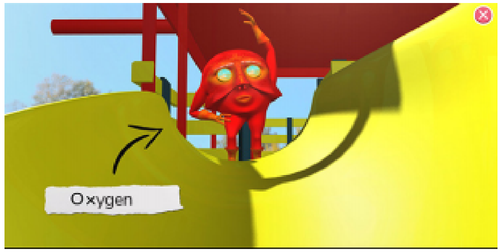


The app gives feedback about the cubes scanned.

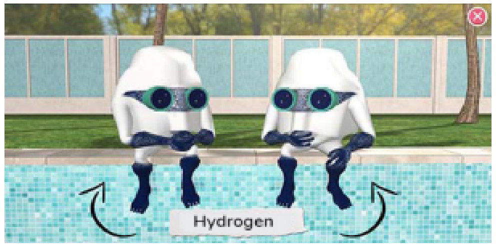


The player can view the reactions/substances that are created once join the element in one of the game activities.

Likewise, the use of short funny stories aims to entertain while administering the content embedded within the plot about the bonding of chemical elements.

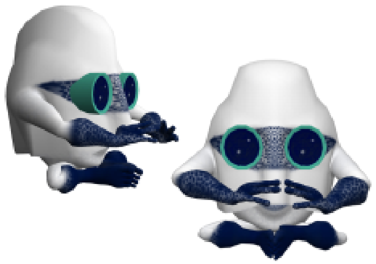


e.g. The underline theme of the element/character hydrogen is its bond with oxygen to create water.



The story revolves around oxygen losing control while coming down on a toboggan and smashing into hydrogens, thus creating water.

The game characters' tri-dimensional aesthetics are inspired by the properties of the elements and the form and colour of the physical molecular model (ball-and-stick). Their colour code follows the standard convention known as CPK colour (Corey, Pauline and Koltun), used to distinguish the atoms of chemical elements in molecular models [28]. The properties of each specific element are reflected in the personality of each character and animations. Some additional accessories were designed to highlight the anthropomorphic personification of the characters. Moreover, using analogies in chemistry teaching methods proves to help students learning process [67].



Hydrogen

Being lighter than air, Hydrogen has a Zen and relaxed attitude towards its surroundings.

Carbon

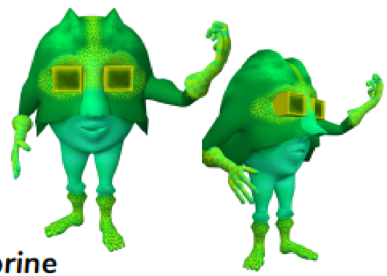
It is a stable bonding element. This trait is reflected in the character personality as a stable and confident creature.

Oxygen

Since Oxygen is highly reactive and capable of bonding with other elements, it is depicted as a friendly creature.

Nitrogen

Nitrogen is a highly active creature since it can release a considerable amount of energy, creating a shock wave through an explosion.



Chlorine

It is portrayed as a heroic figure because of its power to kill bacteria.

Iterations with game experts: The four interaction design researchers were selected among HCI and game design experts at our research institution Interactive Technologies Institute. They were involved in the validation and preliminary evaluation of the design concepts and prototypes regarding the game-play, aesthetics, mechanics, as well as interactions and usability (intuitive, easy, fun). Game designers interacted with the paper prototype (image below) and provided feedback used to iterate the game.

Game experts feedback:

"Children will find the animations of the reactions amusing and engaging."

"Game mechanics seem simple enough for the children to follow-up."

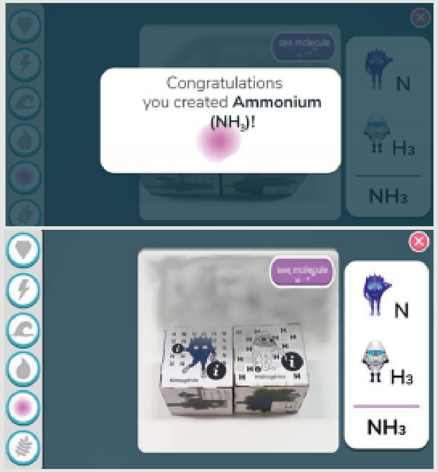
"Graphics and aesthetics are pleasing and age-appropriate."

"The game's playability is endless, and it can be applied to many elements" combinations."

"Needs more information when joining elements."

A congratulation screen was added once the participants gathered the correct elements to create a reaction/substance. This screen was followed by animation, the display of the chemical equation of the elements, audio feedback and a highlight of the icon on the left corner of the screen. If the participant selected the wrong elements, they would be notified with sound feedback to try other chemical elements.

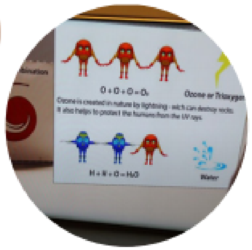
Iteration:



Iterations with teachers: The teachers selected, validated and provided feedback on the methods and mediums used to provide the content. The visualization of the molecules was agreed as the best method to perceive the relationship between the elements in a molecular structure. The use of stories, analogies, and a game-play to join elements (like little alchemy [50]) to reinforce the learning content.

Teachers interaction with the game prototype

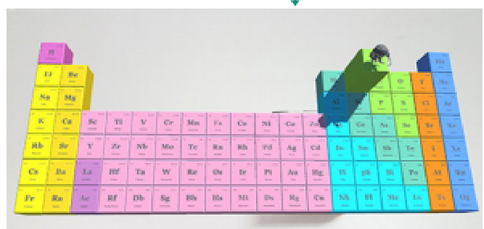
Low-fidelity prototype



After testing the low fidelity prototype, the teachers' feedback was overall very positive; however, they suggested using another type of analogy to display the location of the elements within the Periodic Table. Using a conventional 3D Periodic Table can be easier for students to connect the acquired knowledge in future lessons.

Iteration after teachers' feedback:

changed to



Technology and game-play mechanics

Based on research findings, we set as requirements that the AR visualizations and animations should connect and captivate children in a second-person perspective, addressing them as audiences, engaging them in treasure hunt activities, and encouraging them to achieve specific goals.

Each cube is dedicated to one of the five elements. Each cube face triggers the display of AR digital information dedicated to that element, namely:

Information with the properties of the elements (1);

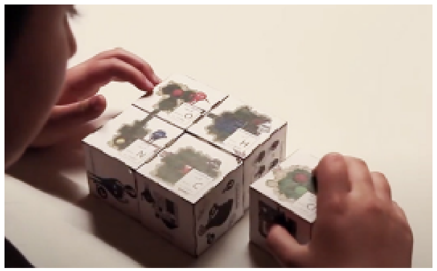
Location within the Periodic Table (2);

Stories (3);

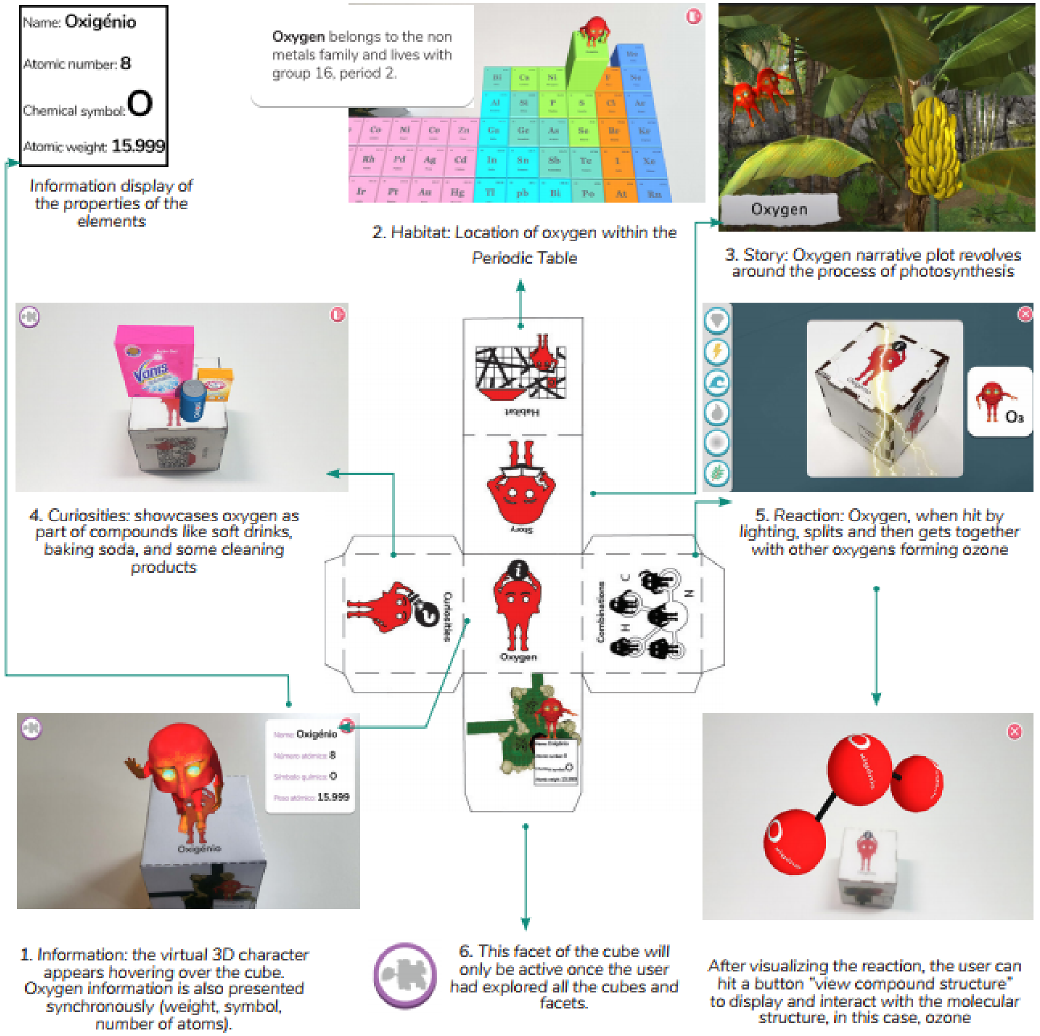
Products that contain such elements (4);

Experiments to create a reaction (5);

Since no content dependencies have been designed, each child can explore one, two or three facets of each cube without a specific order. As a final step, if the child decides to explore all the facets of the five cubes, a prompt message asks them to put together a map (gathering the cube facets containing a piece of a map (see image below) to be captured by the device camera. A pop-up message on the device will showcase how to align the facets of the five cubes together. Once the map is assembled and scanned, this action prompts a screen asking the user to select their favourite character and take a selfie to share with their family or friends.



For the final reward (selfies), the participants must assemble a map using the cubes.



USER STUDY

We designed a study to understand if the multi-level knowledge construction of the game can contribute to facilitating the learning of scientific concepts. Our objective is also to optimize the use of human factors, participatory design, technology esthetics, and game mechanics in engaging young children with scientific content about the Periodic Table.

Young participants (age 11 to 13 years old) were recruited through a local public school. After submitting consent forms, questionnaires, and the study protocol to be assessed by the Regional Secretariat of Education, we obtained ethical approval to conduct the study at the regional school system. We then arranged a meeting with the school teachers to showcase the game, the objectives, and the research process and set up a date and time to conduct the study. Two weeks before the study, a consent form was sent to gather the children's guardians' permission (signature) to participate. The document explained the research protocol (see Figure 2) and information about its confidentiality and image rights. The teachers collected the signed forms and communicated the number of participants to the researchers, who prepared all the resources for the study.

Procedure

Data about the age, gender, previous experience with AR, chemistry, and the topic Periodic Table previous knowledge was collected.

Content knowledge questionnaire:

A questionnaire was developed by the main researcher and validated by the teachers (see Figure 3). Correct answers were attributed a valued "1", incorrect answers "0" - for a total of 10 points. The same questions were used (in a different order to avoid bias) in a post-test conducted after the participants interacted with the game.

Perception of chemistry Pre and Post Questionnaire

We adapted a Pana's scale [18], which consists of several words that describe different feelings and emotions. We used 10 items to measure affects on the domain of chemistry. Five questions reflected a negative perception and five positive perceptions about chemistry.

Question: I think chemistry is ... *(you can select more than one answer): Useful, difficult, fun, boring, interesting, not useful, easy, complex, simple, cumbersome.*

Another two questions were added to the post-test questionnaire about their affects on chemistry,

1. Do you think that chemistry could be your favourite school domain?

2. In the future, would you like to study or have a profession in the domain of chemistry?

Interview

We also conducted an informal interview with each child, with open questions like *"Did you like the game?", "why?", "What would you change?", "What is your opinion about the game?".*

Observational notes were taken by three researchers to capture insights through the expression, comments, and body movements of the participants while interacting with the game.

Recording of the session

After verifying the consent forms as per the guardian's authorization to film, we recorded the interaction of the participants with the game. This provides insights we may have missed while taking the observation notes.

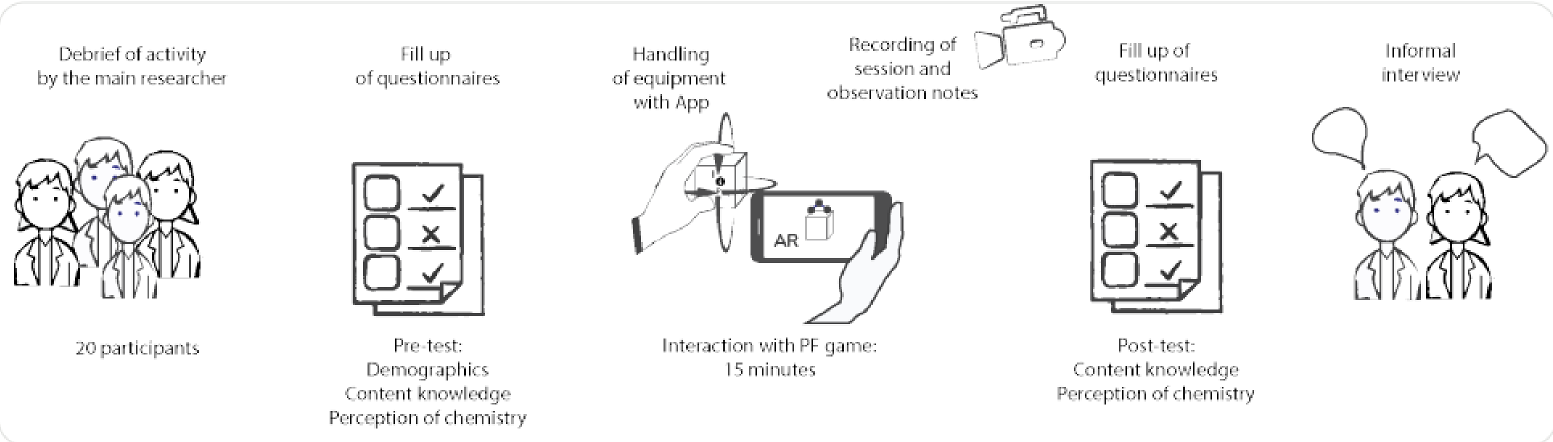
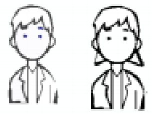


Figure 2. Study protocol

RESULTS

The data was analysed using IBM Statistical Package for the Social Science version 25 (SPSS, Chicago, Illinois) and used 2-tailed testing at α (alpha) of 0.05. The quantitative results were gathered through the comparative data from pre- and post-intervention.

Demographics:



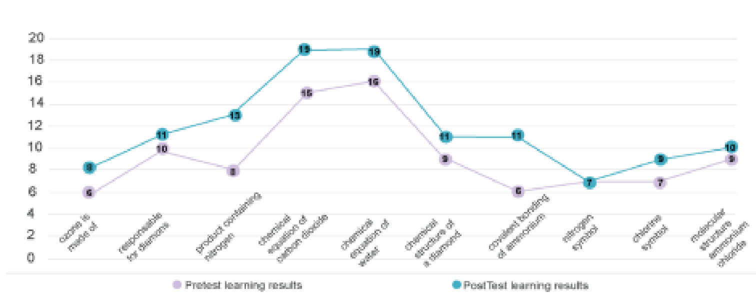
20 participants from 6° grade			
n=	Age		
7 participants	11 year old	10 male	10 female
10	12		
3	13		
Experience with AR technology:		5 "yes"	6 " yes"
Notions about some topics on the chemistry school curriculum		4 "yes"	6 "yes"
Idea or notion about what is the Periodic Table about		4 "yes"	6 "yes"

Learning outcome results: We assessed the normality of the distribution of the learning scores of the participants to find what type of analysis to perform. Our result Sig. p =.593 of the Shapiro-Wilks suggested no violation of the assumption of normality. We used a between-subject parametric independent paired T-test using the post-test and the pre-test results. The results of the learning outcome after using the PF Discovery game are higher (M=5.80, SD=2.46) than before using the game (M=4.65, SD=2.73). This difference was positive, t(19)=2.42, p=.026, and represents a large effect, r= .48 (see Figure 3).

Perception of chemistry: The result of the perception of chemistry after interacting with the game showed a decrease in the negative affects pre-results (M=1.50, SD=0.82) vs post results (M=0.70, SD=0.73) and an increase in the positive affects pre-results (M =1.10, SD=1.02) vs post-results (M=2.20, SD=1.05) (see Figure 4). However, in the answers to the question "Do you think that chemistry could be your favourite domain? only six said "yes", two said "no", and 12 said "maybe". Also, their answer to the possibility of having chemistry as a future profession, only five participants said "yes", four said "no" and 11 "maybe".

Observation notes and records: At the beginning of the game, two participants were sitting, but as the game went along, they started to stand up to move around to get closer (by moving the mobile phone) to the characters. The game incentivizes a cooperative environment, participants smiled and communicated with other colleagues, giving tips on how they gathered some chemical reactions: "I bet that Oxygen is going to create air", "Have you seen this?!. The game shows potential to promote chemistry literacy and symbolic representation by the participants comments when viewing the information: "whoa! I just saw Hydrogen waiving at me", "I'm only missing Chlorine story", "I just made water!"," Now I have to put together Nitrogen, the "N" and Oxygen, the "O" "What am I going to get now?!". The aesthetics and the animations were appealing to the participants: "Hydrogen just burped...laugh", "The characters are so cute!".

Interview answers: The overall feedback was positive. The satisfaction was apparent: "I liked everything", "I like it, can I download it?". The children realized that playing the game could enhance their future chemistry classes: "I like looking at the molecules...this will prepare me for my future classes", "I think this game is going to be useful for my classes". The stories and characters played an important role in engaging the children: "I enjoy viewing the stories", "I will put shoes on the characters" and "Oxygen is cool", "I think that the characters and animations were amazing!". One participant reported a technical issue during the game: "I didn't like when I scanned oxygen, and the information wasn't showing up".



Paired sample test results (compare means post-pre) Mean= 1.15, SD= 2.13 t= 2,410 p = 0.02

Figure 3. Learning outcome results according to questions from pre-and post- intervention

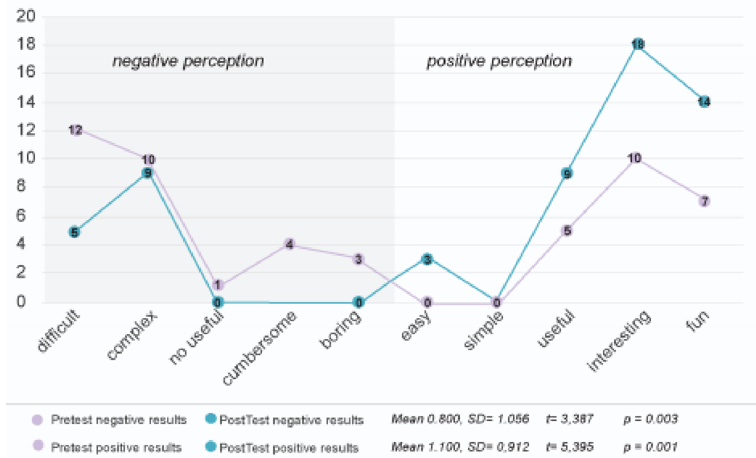


Figure 4. Positive and negative affects results about chemistry

DISCUSSION

In this pictorial, we reflected on the design and development of an AR and TI educational game to support children's understanding of abstract concepts in science. The game introduces the properties of the chemical elements, bonding and chemical reactions, molecular structure and location of the element found in the Periodic Table. Our design choices were guided by a participatory design process including teachers and chemistry specialists, and game experts and evaluated by children. The quantitative results showed significant results in the learning outcome of the participants, increased their positive affects and decreased their negative effects. These results are supported by the qualitative data, which showcase the children's enthusiasm and engagement with the content. Even though these results are from a small sample group, the optimistic results lead us to believe that PF has the potential to promote and facilitate learning content about chemistry for young students.

All in all, we found that the AR technology supports different digital formats providing flexibility when adapting content knowledge to children, allowing the interaction with chemistry content on a symbolic, macro and micro level, and facilitating chemistry understanding. The display of the reactions/substance using AR animations (macro) while simultaneously showcasing representational information of the chemical equation involved in such reactions (symbolic) helps to create a mental connection between both. At a micro-level, the visualization and interaction with a molecular structure allow for displaying spatial relationships between the elements. Children can view all the elements and their covalent bonding, helping to create a more accurate mental process of this phenomenon compared with a more traditional method of learning, as per previous claims by Üce, Musa, and İlknur Ceyhan (2019) [67].

The mechanics of the PF AR system (scanning the markers to get the information) created a feeling of anticipation, promoting the children's curiosity and leading them to gather the information. We believe this is also linked to the aesthetics and animations used to provide the content. The characters/elements and the stories, while providing learning information through the analogies and narrative plot, were designed to be appealing and funny to the children. According to Jessy Schell, balancing these game elements (aesthetics, story, mechanics and technology) can enhance the user experience [59]. The mechanics also incites the participants to explore the content and view information related to their real-world (products that contain such elements), promoting a constructivist learning approach. The use of the physical cubes, besides being intuitive and easy to use (grabbing and rotating), provides the children with a stronger sense of direct stimuli and a realistic feeling of the experience by directly interacting with the virtual world.

The involvement of stakeholders from different areas of knowledge and expertise contributes in different ways. Teachers can help filter the adequate scientific information to showcase according to student's characteristics helping to adapt mechanics, aesthetics and assets towards the learning goals, convey the proper analogies, and provide methods to reinforce the learning content. Game designers can support usability issues, playability and balance of game elements. Finally, children's usability evaluation allows us to see their natural interaction with the game's features validating or not our design decisions.

We believe that the symbiosis between learning content, human factors (teachers, designers and students) and technologies (AR and TI) can affect the rapid development of individual interest in chemistry. AR function appears to be a promising avenue for promoting students' long-term engagement in science. It can also provide a novel interface parallel to the use of tangible physical interaction, that stimulates the senses with benefits to the cognitive process of children, while engaging and motivating towards more abstract domains.

CONCLUSION

Periodic Fable Discovery's objective is to entertain children while engaging them with the basics of chemistry and the Periodic Table. Using an interdisciplinary approach allowed the unfolding of our design choices from content, aesthetics, game mechanics, interaction design, and technology, providing adequate methods for our users. The overall balance between all the game elements to create an entertaining experience while engaging children with STEM subjects worked well. Periodic Fable Discovery aesthetics appeal to our audience by using fun characters and mimicking each element's properties. The display of the characters within the AR tridimensional Periodic Table (columns and rows demonstrating the group and period to which the elements belong) is an innovative framework for allocating the chemical elements within the Periodic Table. The exhibit of compounds containing the game elements created curiosity in our users and instigated them to look for more information.

The AR technology allows game elements to foster children's engagement with the scientific subject. The creative process was not limited by AR technology. AR supports different digital formats providing flexibility when adapting content knowledge to children, e.g., using 2D video clips to display short stories about the bonding of the elements, 3D animations to showcase the properties of the elements, and 3D AR display of molecular structures.

The manipulation of the cube to gather the information is accessible and stimulating, which incentivizes the user to engage with the learning process. The quality of the graphic, organization of the information, and language used in the app proved to be adequate for the target group, facilitating the understanding of the information. An active exploration of the cube facets invites a more exploratory approach and becomes easier to learn as it reduces cognitive load.

Finally, the quantitative and qualitative results from the users study showcase that there is an opportunity for using similar guideposts to develop apps to engage children with STEM domains and facilitate learning content.

LIMITATIONS AND FUTURE WORK

While a tentative was made to include children in the initial design process (10 students), their feedback was mostly directed at the character's colour, with no concise opinion. Another feedback was to add more stories to the app, which we did in the high-fidelity prototype. However, these interactions were limited by logistics, pandemic conditions and time restrictions and we aim to expand these insights in the future.

Some technical challenges could have hampered the participant's experience, like the AR light dependency to scan the AR makers, which can create frustration for the children. Also, AR technology can lead to equipment overheating and battery draining.

Despite the enthusiastic results obtained, we want to replicate the study with a larger number of participants to validate our results. We also believe that a longitudinal study to identify the use of this tools in the students' perseverance in science education and its effect according to spatial skills development will benefit the research and educational community.

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REFERENCES

[1] Adbo, K., & Vidal Carulla, C. (2020). Learning about science in preschool: Play-based activities to support children's understanding of chemistry concepts. International Journal of Early Childhood, 52(1), 17-35.

[2] Amartya Banerjee and Michael S. Horn. 2014. Ghost hunter: parents and children playing together to learn about energy consumption. In Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14). Association for Computing Machinery, New York, NY, USA, 267–274.

[3] Antle, A. N. (2007, February). The CTI framework: informing the design of tangible systems for children. In Proceedings of the 1st international conference on Tangible and embedded interaction (pp. 195-202). (How TI supports cognition)

[4] Arnab, S. (2020). Game science in hybrid learning spaces. Routledge.

[5] Baykal, G. E., Alaca, I. V., Yantaç, A. E., & Göksun, T. (2016, June). Developing Transmedia Puzzle Play to Facilitate Spatial Skills of Preschoolers. In Proceedings of the The 15th International Conference on Interaction Design and Children (pp. 631-636).

[6] Bruner, J. S. (1966). Toward a theory of instruction (Vol. 59). Harvard University Press.

[7] Câmara Olim, S. M., Nisi, V., & Rubegni, E. (2022, June). Periodic Fable Augmenting Chemistry with Technology, Characters and Storytelling. In Interaction Design and Children (pp. 123-136).

[8] Chang, J. S. K., Yeboah, G., Doucette, A., Clifton, P., Nitsche, M., Welsh, T., & Mazalek, A. (2017, June). Tasc: combining virtual reality with tangible and embodied interactions to support spatial cognition. In Proceedings of the 2017 Conference on Designing Interactive Systems (pp. 1239-1251).

[9] Chen, C. A., & Lai, H. I. (2021). Application of augmented reality in museums–Factors influencing the learning motivation and effectiveness. Science Progress, 104(3_suppl), 00368504211059045.

[10] Chen, C. H. (2020). Impacts of augmented reality and a digital game on students' science learning with reflection prompts in multimedia learning. Educational Technology Research and Development, 68(6), 3057-3076. (Motivation on science)Chen, P., Liu, X., Cheng, W., & Huang, R. (2017). A review of using Augmented Reality in Education from 2011 to 2016. Innovations in smart learning, 13-18.

[11] Chen, S., Jamiatul Husnaini, S., & Chen, J. J. (2020). Effects of games on students' emotions of learning science and achievement in chemistry. International Journal of Science Education, 42(13), 2224-2245.

[12] Chi, S., Wang, Z., Liu, X., & Zhu, L. (2017). Associations among attitudes, perceived difficulty of learning science, gender, parents' occupation and students' scientific competencies. International Journal of Science Education, 39(16), 2171-2188

[13] Chiu, W. K. (2021). Pedagogy of Emerging Technologies in Chemical Education during the Era of Digitalization and Artificial Intelligence: A Systematic Review. Education Sciences, 11(11), 709.

[14] Di Serio, Á., Ibáñez, M. B., & Kloos, C. D. (2013). Impact of an augmented reality system on students' motivation for a visual art course. Computers & Education, 68, 586-596

[15] Direção Geral da Educação (DGE), (July 2022), https://www.dge.mec.pt/

[16] Dunleavy, M., & Dede, C. (2014). Augmented reality teaching and learning. Handbook of research on educational communications and technology, 735-745

[17] Ebesutani, C., Okamura, K., Higa-McMillan, C., & Chorpita, B. F. (2011). A psychometric analysis of the Positive and Negative Affect Schedule for Children–Parent Version in a school sample. Psychological assessment, 23(2), 406.

[18] England B. J., Brigati J. R., Schussler E. E. and Chen M. M., (2019), Student Anxiety and Perception of Difficulty Impact Performance and Persistence in Introductory Biology Courses. CBE Life Sci. Educ., 18(2), ar21

[19] Erbas, C., & Demirer, V. (2019). The effects of augmented reality on students' academic achievement and motivation in a biology course. Journal of Computer Assisted Learning, 35(3), 450-458.

[20] Fjeld, M., Juchli, P., & Voegtli, B. M. (2003, September). Chemistry Education: A Tangible Interaction Approach. In INTERACT

[21] Franco-Mariscal, A. J., Oliva-Martínez, J. M., & Almoraima Gil, M. L. (2015). Students' perceptions about the use of educational games as a tool for teaching the periodic table of elements at the high school level. Journal of Chemical Education, 92(2), 278-285.

[22] Frederking, J., Cruz, M., Baskinger, M., & Overbeeke, K. (2008, February). Beyond the screen: Designing immersive collaborative experiences for children through digital and physical interaction. In Proceedings of the 7th ACM conference on Designing interactive systems (pp. 156-163).

[23] Georgiou, Y., & Kyza, E. A. (2021). Bridging narrative and locality in mobile-based augmented reality educational activities: Effects of semantic coupling on students' immersion and learning gains. International Journal of Human-Computer Studies, 145, 102546

[24] Gilad Gome, Julian Waksberg, Andrey Grishko, Iddo Yehoshua Wald, and Oren Zuckerman. 2019. OpenLH: Open Liquid-Handling System for Creative Experimentation with Biology. In Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '19). Association for Computing Machinery, New York, NY, USA, 55–64. https://doi.org/10.1145/3294109.3295619

[25] Gopalan, V., Bakar, J. A. A., Zulkifli, A. N., Alwi, A., & Mat, R. C. (2017, October). A review of the motivation theories in learning. In AIP Conference Proceedings (Vol. 1891, No. 1, p. 020043).AIP Publishing LLC.

[26] Granic, Isabela, Adam Lobel, and Rutger CME Engels. "The benefits of playing video games." American psychologist 69, no. 1 (2014): 66.

[27] Helmenstine, T: Science notes - learn science to science. http://sciencenotes.org/category/chemistry (Aug 2019)

[28] House J. D. and Telese J. A., (2017), Confidence in Science and Achievement Outcomes of Fourth-Grade Students in Korea: Results from the TINTRINSICSS 2011 Assessment. Education, 137(4), 389–392.

[29] https://www.dge.mec.pt/sites/default/files/Curriculo/Aprendizagens_Essenciais/12_quimica.pdf

[30] Jack Shen-Kuen Chang. 2017. 'Tangible and Virtual Interactions for Supporting Spatial Cognition,' in Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems (DIS '17 Companion), 382–383. https://doi.org/10.1145/3064857.3079163

[31] Jean Piaget. 1964. 'Part I: Cognitive Development in Children: Piaget Development and Learning,' Journal of Research in Science Teaching 2, 3: 176–186. https://doi.org/10.1002/tea.3660020306

[32] Jiahao Guo, Yuyu Lin, Hongyu Yang, Junwu Wang, Shuo Li,

Enmao Liu, Cheng Yao, and Fangtian Ying. 2020. 'Comparing the Tangible Tutorial System and the Human Teacher in Intangible Cultural Heritage Education,' in Proceedings of the 2020 ACM Designing Interactive Systems Conference, 895–907

[33] Johnstone, Alex H. "Teaching of chemistry-logical or psychological?." Chemistry Education Research and Practice 1, no. 1 (2000): 9-15.

[34] Khan, T., Johnston, K., & Ophoff, J. (2019). The impact of an augmented reality application on learning motivation of students. Advances in Human-Computer Interaction, 2019.

[35] Lam, M. C., Tee, H. K., Nizam, S. S. M., Hashim, N. C., Suwadi, N. A., Tan, S. Y., ... & Liew, S. Y. (2020). Interactive augmented reality with natural action for chemistry experiment learning. TEM Journal, 9(1), 351

[36] Laurent, J., Catanzaro, S. J., Joiner Jr, T. E., Rudolph, K. D., Potter, K. I., Lambert, S., ... & Gathright, T. (1999). A measure of positive and negative affect for children: scale development and preliminary validation. Psychological assessment, 11(3), 326.

[37] Luraschi, M., Rezzonico, R., & Pellegri, G. (2012). The chemist, that madman! How children perceive science. CHIMIA International Journal for Chemistry, 66(11), 820-825. 73-85).

[38] María Blanca Ibáñez and Carlos Delgado-Kloos. 2018. 'Augmented Reality for STEM Learning: A Systematic Review,' Computers and Education 123: 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

[39] McLeod, S. (2020). Lev Vygotsky's sociocultural theory.

[40] Mahaffy, P. (2004). The future shape of Chemistry education. Chemistry Education Research and Practice, 5(3), 229–245

[41] Maldonado, H., & Zekelman, A. (2019, June). Designing Tangible ABCs: Fröbel's Sticks and Rings for the 21st Century. In Proceedings of the 18th ACM International Conference on Interaction Design and Children (pp. 326-333).

[42] Manzano-León, A., Camacho-Lazarraga, P., Guerrero, M. A., Guerrero-Puerta, L., Aguilar-Parra, J. M., Trigueros, R., & Alias, A. (2021). Between level up and game over: A systematic literature review of gamification in education. Sustainability, 13(4), 2247.

[43] Mellor, K. E., Coish, P., Brooks, B. W., Gallagher, E. P., Mills, M., Kavanagh, T. J., ... & Anastas, P. T. (2018). The safer chemical design game. Gamification of green chemistry and safer chemical design concepts for high school and undergraduate students. Green Chemistry Letters and Reviews, 11(2), 103-110

[44] Palmer T.-A., Burke P. F. and Aubusson P., (2017), Why school students choose and reject science: a study of the factors that students consider when selecting subjects. Int. J. Sci. Educ., 39(6), 645–662.

[45] Patall E. A., Hooper S., Vasquez A. C., Pituch K. A. and Steingut R. R., (2018), Science class is too hard: Perceived difficulty, disengagement, and the role of teacher autonomy support from a daily diary perspective. Learn. Instr., 58, 220–231.

[46] Paul Marshall. 2007. Do Tangible Interfaces Enhance Learning?. In Proceedings of the 1st International Conference on Tangible and Embedded Interaction (Baton Rouge, Louisiana) (TEI '07). Association for Computing Machinery, New York,NY, USA, 163–170. https://doi.org/10.1145/1226969.1227004

[47] Psotka, Joseph. "Immersive training systems: Virtual reality and education and training." Instructional science 23, no. 5 (1995): 405-431.

[48] Qi Lu, Shao-en Ma, Jiayin Li, Haipeng Mi, and Yingqing Xu. 2019. IRelics: Designing a Tangible Interaction Platform for the Popularization of Field Archaeology. In Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '19). Association for Computing Machinery, New York, NY, USA, 45–54.https://doi.org/10.1145/3294109.3295647

[49] Recloak, (2021, Feb 26). Little Alchemy game. https://little-alchemy.com/

[50] Resnyansky, D. (2020, December). Augmented Reality-Supported Tangible Gamification for Debugging Learning. In 2020 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE) (pp. 377-383).

[51] Ronald T Azuma. 1997. A survey of augmented reality. Presence: teleoperators & virtual environments 6, 4(1997), 355–385.

[52] Rubens, C., Braley, S., Torpegaard, J., Lind, N., Vertegaal, R., & Merritt, T. (2020, February). Flying LEGO Bricks: Observations of Children Constructing and Playing with Programmable Matter. In Proceedings of the fourteenth international conference on tangible, embedded, and embodied interaction (pp. 193-205).

[53] Rui Chen, Po-Jui (Ray) Chen, Rui Feng, Yilin (Elaine) Liu, Andy Wu, and Ali Mazalek. 2014. SciSketch: a tabletop collaborative sketching system. In Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14). Association for Computing Machinery, New York, NY, USA, 247–250.

[54] Saadon, N. F. S. M., Ahmad, I., Pee, A. N. C., & Hanapi, C. (2020, May). The implementation of augmented reality in increasing student motivation: systematic literature review. In IOP Conference Series: Materials Science and Engineering (Vol. 854, No. 1, p. 012043).

[55] Sara Price and Carey Jewitt. 2013. A multimodal approach to examining 'embodiment' in tangible learning environments. In Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13). Association for Computing Machinery, New York, NY, USA, 43–50.

[56] Sarah Matthews, Stephen Viller, and Marie A. Boden. 2020. "... And We Are the Creators!" Technologies as Creative Material. In Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (Sydney NSW, Australia) (TEI '20). Association for Computing Machinery, New York,NY, USA, 511–518.

[57] Scavarelli, Anthony, Ali Arya, and Robert J. Teather. "Virtual reality and augmented reality in social learning spaces: a literature review." Virtual Reality 25, no. 1 (2021): 257-277.

[58] Schell, J. (2008). The Art of Game Design: A book of lenses. CRC press.

[59] Sharon Lynn Chu and Brittany M. Garcia. 2017. Toward Wearable App Design for Children's In-the-World Science Inquiry. In Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17). Association for Computing Machinery, New York, NY, USA, 121–130.

[60] Shirazi, S. (2017). Student experience of school science. International Journal of Science Education, 39(14), 1891-1912

[61] Shuxia Yang, B Mei, X Yue (2018). Mobile augmented reality assisted chemical education: insights from elements 4D, 95 (6), 1060-1062. DOI: 10.1021/acs.jchemed.8b00017

[62] Solbes J., (2011), ¿Por que´ disminuye el alumnado de ciencias? [Why is there a decrease in science students?], Alamb.

Did. Cienc. Exp., 67, 53–61

[63] Srisawasdi, N., & Panjaburee, P. (2019). Implementation of game-transformed inquiry-based learning to promote the understanding of and motivation to learn chemistry. Journal of Science Education and Technology, 28(2), 152-164

[64] Stojanovska, M. (2021). Celebrating the International Year of Periodic Table with chemistry educational games and puzzles. Chemistry Teacher International, 3(1).

[65] Teppo, M., Soobard, R., & Rannikmäe, M. (2021). A study comparing intrinsic motivation and opinions on learning science (grades 6) and taking the international PISA test (grade 9). Education Sciences, 11(1), 14.

[66] Üce, M., & Ceyhan, İ. (2019). Misconception in Chemistry Education and Practices to Eliminate Them: Literature Analysis. Journal of Education and Training Studies, 7(3), 202-208.

[67] Ulrich, M., Evans, B., Liu, F. W., Johnson, M., & LiKamWa, R. (2021, September). AR-some Chemistry Models: Interactable 3D Molecules through Augmented Reality. In Adjunct Publication of the 23rd International Conference on Mobile Human-Computer Interaction (pp. 1-4).

[68] Wetzel, R., Blum, L., Broll, W., & Oppermann, L. (2011). Designing mobile augmented reality games. In Handbook of augmented reality (pp. 513-539). Springer, New York, NY.

[69] Wofford, J. (2009). K-16 Computationally rich science education: A Ten-Year review of the journal of science education and technology (1998–2008). Journal of Science Education and Technology, 18(1), 29–36.

[70] Wouters, P., Van Nimwegen, C., Van Oostendorp, H., & Van Der Spek, E. D. (2013). A meta-analysis of the cognitive and motivational effects of serious games. Journal of educational psychology, 105(2), 249.

[71] Yang, S., Mei, B., & Yue, X. (2018). Mobile augmented reality assisted chemical education: insights from elements 4D.

[72] Zhang, X., Chen, C., Yang, T., & Xu, X. (2020). Spatial Skills Associated With Block-Building Complexity in Preschoolers. Frontiers in Psychology, 2265

Periodic Fable Augmenting Chemistry with Technology, Characters and Storytelling

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ABSTRACT

Children often perceive abstract concepts such as chemistry as difficult, and teachers struggle to convey content knowledge in these subjects. In this pictorial, we address the need to promote the interest for chemistry in children by developing a multi-layered Augmented Reality serious game that uses storytelling, character design and game mechanics to connect and engage young audiences with chemistry: the Periodic Fable an Augmented Journey. Our contribution relies on the design and development of the system to convey content knowledge about the Periodic Table while fostering the children's interest and challenging their possible daunting perception of the domain. After designing and implementing the game, we conducted an exploratory study using a mixed-method approach engaging 21 young participants from a public school to assess the learning gains and the role of storytelling through levels of narrative transportation. The results show positive perception and learning outcome of chemistry, narrative transportation showcasing an opportunity for a unique form to approach chemistry using an edutainment format.

Authors Keywords

Serious games; Augmented Reality; Chemistry; Periodic Table.

CSS Concepts

• Human-centered computing, Human computer interaction (HCI), Interaction paradigms, Mixed / augmented reality

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Periodic Fable an Augmented Journey is an adventure serious game developed using the collaboration of educational stakeholders and game designers to encourage young children to invest in Chemistry. The system follows an Elemental Tetrad approach, a term coined by Jesse Schell [38] to convey the importance of four-game categories: aesthetics, gameplay mechanics, storytelling and technology.

INTRODUCTION

Children as young as nine to ten years old perceive chemistry as difficult, complex and dull even before it reaches them within the school curriculum [19, 26, 38]. Educators often struggle to communicate and transfer content knowledge in chemistry, especially when reaching students who negatively perceive this subject [26]. Augmented reality and games affordances can convey educational content in a ludic manner. These edutainment systems are tools used to mitigate the students' lack of motivation and engagement in chemistry [25, 49] and have the potential to reach a younger audience as to foster their interest in chemistry [12, 32]. However, the design and develop process of these systems need to be adapted to the cognitive development and characteristics of this young scientists. This pictorial presents our game's design elements and the participatory design process geared to convey and evaluate accurate scientific information through a ludic and entertaining approach, complemented with the results from a pre and post test assessing learning gains. Moreover, we applied a narrative transportation scale, to better understand the storytelling potential in this domain.

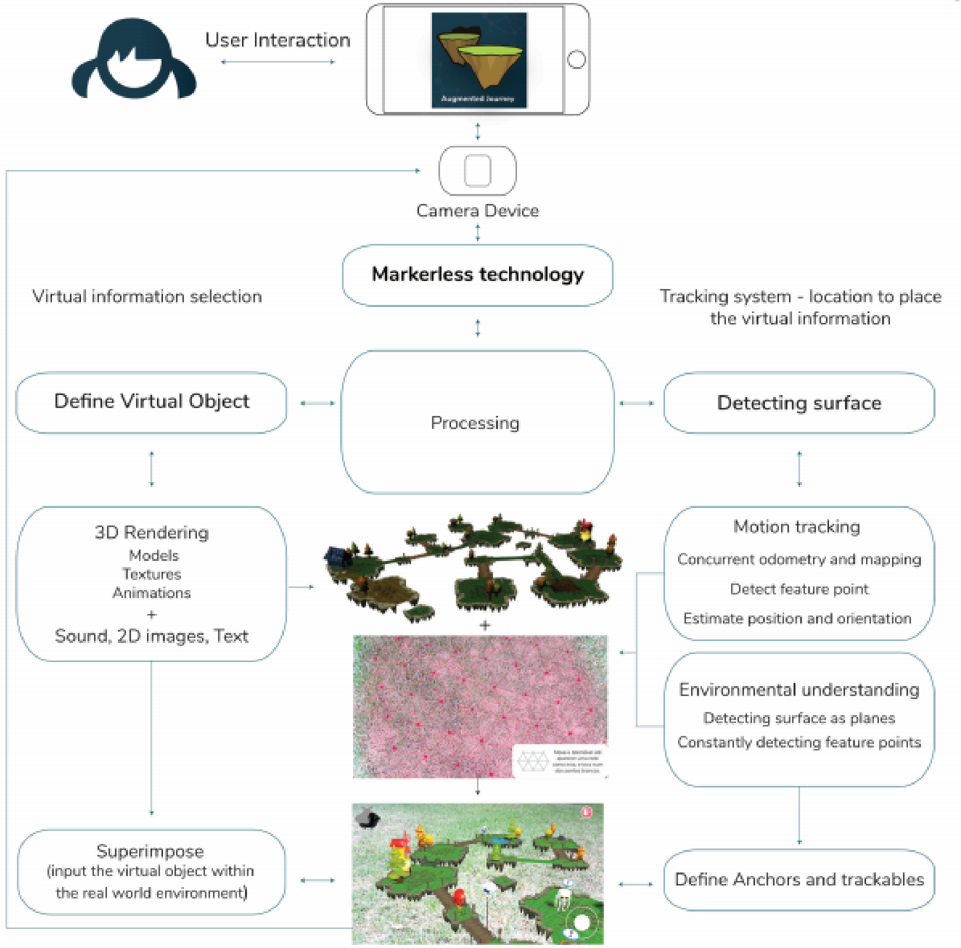
“... AR technology allows the visualization of abstract concepts.”

RELATED WORK

Playful experiences and games have shown positive effects in fostering a broad spectrum of cognitive skills development [16]. Educational games increase concentration levels and stimulate learning in children [4], allowing for the exploration of teaching devices such as metaphors, analogies, and stories. Moreover, progress in the children's uptake and familiarity with digital technologies allows for integrating novel methods in the traditional curricula, including Virtual and Augmented Reality intervention and the spatial manipulation of 3D object [3]. These systems are also effective tools to motivate children towards learning content, providing a solution for many students who feel alienated by the more traditional methods of teaching [37]. Even though many elements are involved in a game, four categories with equal importance can maximize the user experience: technology, story, mechanics, and aesthetics [44].

Augmented reality (AR) is a technology that allows for the coexistence of digital information inputs and real-world within the same space. This unique feature has great potential for several areas, including STEM education [5, 18] [48]. Some of the affordances for the learning framework are the reduction of the cognitive load by the use of visualization of abstract concepts; increases the students' concentration levels; promotes independent learning; helps in the development of spatial skills, and enhances the student's engagement and learning [22, 23, 37]. Furthermore, due to the advancements in mobile technology and students' tech-savvy experiences, AR mobile systems allows for the creation of educational content that can be accessible in formal and informal settings.

Periodic Fable (PF) an Augmented Journey has been developed using ARCore with mobile marker-less technology. The technology identifies patterns in the real world (using the mobile camera) as a reference/point to allocate the virtual information. In the case of PF game mechanics, it allows the required movement of the users within the physical space to explore a tridimensional world.



PF An Augmented Journey system architecture: The ARCore's light estimation and motion tracking technology uses the mobile phone's camera to identify interesting points, called features, tracks how those points move over time, enabling the system to detect any flat surfaces, like a table or floor and allowing the placement of virtual objects and any other type of digital data.

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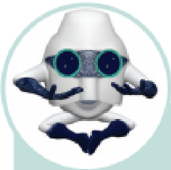
THE POWER OF CHARACTER AND STORYTELLING

Narrative game learning environments that combine stories and pedagogical support strategies to deliver effective, engaging educational experiences have shown to be powerful to teach science and arouse interest and promote positive attitudes toward learning science in the early years [29]. The effectiveness of this method of teaching and learning depends on factors like the contextualization of the learning content within the narrative plot, which implies pedagogical planning, identifying goals according to the students' cognitive development and cultural reality [46]. The character design process needs careful development, which involves choosing the visual characteristics and aspect of the characters, their purpose, and how to create a connection to its audiences, evoking the audience's emotion and investment [31]. Virtual characters can be used to promote discovery and exploration of educational content [44].

Based on this notion, PF An Augmented Journey design and development follow different stages to identify the best approach and solutions towards engaging young students while providing content knowledge about the Periodic Table of Elements. The AR game uses character design and plotting devices grounded on the properties of the elements and their most common chemical reactions.



Hydrogen

The lightest of the elements, depicted a relaxed and meditative character, prone to float due to its chemical characteristics, analogous to the status of a meditative person.

Nitrogen

It is a highly active creature, matching the nature of Nitrogen, which can release vast amounts of energy, creating a shock wave through an explosion.

Oxygen

Oxygen, highly reactive and capable of bonding with other elements, is depicted as a friendly creature. It tries to socialize with the player by waving its hand as a sign of salutation.

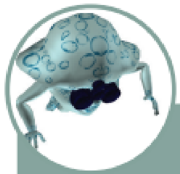
Carbon

A stable bonding element. The character's posture with both hands on the hips shows the character's personality trait as a stable and confident creature.

Chlorine

It is a green gaseous element whose reactivity makes it toxic but valuable to humanity. Its disinfectant capacity makes it a strong character.

The visuals of the virtual characters follow a symbolic style, with exaggerated proportions regarding the arms and legs and a round body, inspired in the ball-and-stick model of the molecular model. The body/face of the character represents the atoms, and the arms and legs are rods that can connect and create bonds with other elements. The way the elements /characters have been visually represented has the purpose of engaging the children as for instance the display of the elements/characters reactions.



Helium

Its depicted as a very light character that needs to be held by a rope because of the Earth's gravity, so it does not escape into space.

Platinum

Sought by its economic value, it is represented by an aristocratic visual image allusive to being considered a noble metal.

Arsenic

Because of its toxicity, it is represented as a spiky character, overused as an insecticide..

Silver

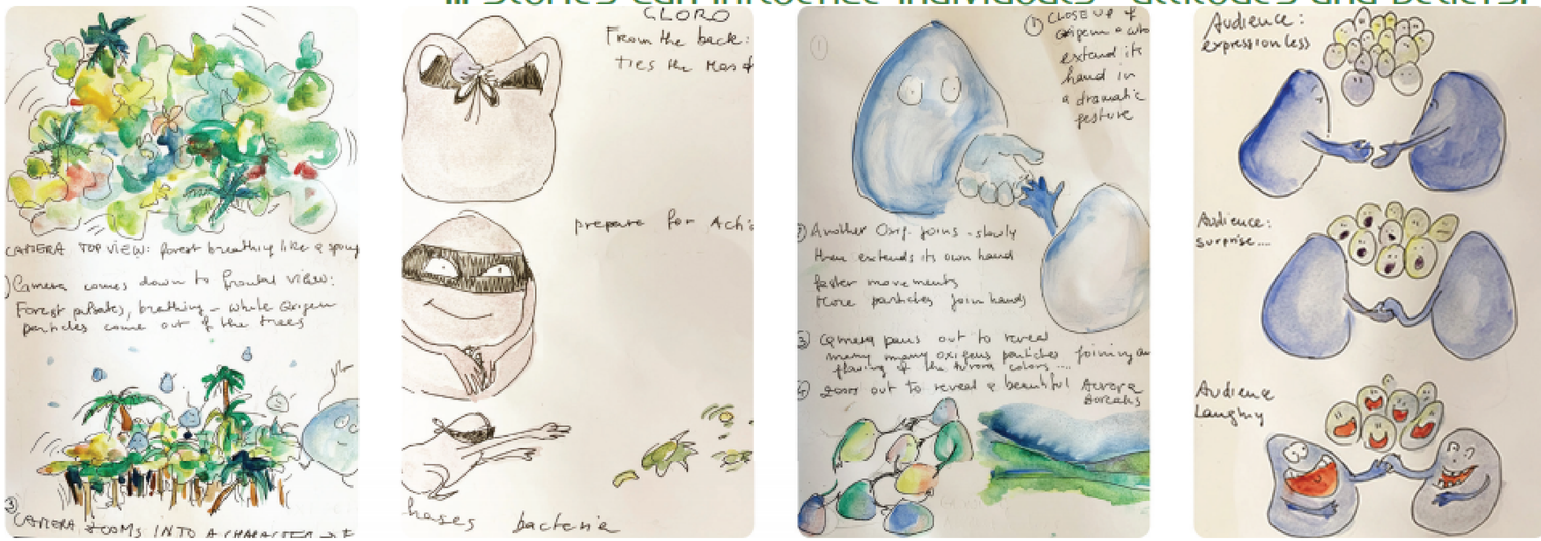
Portrayed as a vain character because of its value as a decorative and lustrous metal. Its scarcity is showcased by its overuse in ornaments and jewels. .

Zinc

It is depicted as a worrisome character allusive to its demand-induce scarcity to protect other metals (iron and steel) against corrosion.

In developing the PF an Augmented Journey, we took the opportunity to reflect on the limited supplies of some chemical elements and the extended use of others by industries contributing to environmental change [41]. The *PF an Augmented Journey* game brings forward the sustainability of chemical elements and presents the children with elements at risk of extinction as part of the gameplay, such as arsenic, helium, silver, platinum and zinc. PF narration incorporates characters and dialogues to showcase and create awareness about this issue. These elements were chosen because of their economic value, importance, supply, risk and availability.

"... Stories can influence individuals' attitudes and beliefs."



The story development process follows a script of the plot, storyboards, development of 3D environments (assets, characters, textures) and finally animation and rendering.

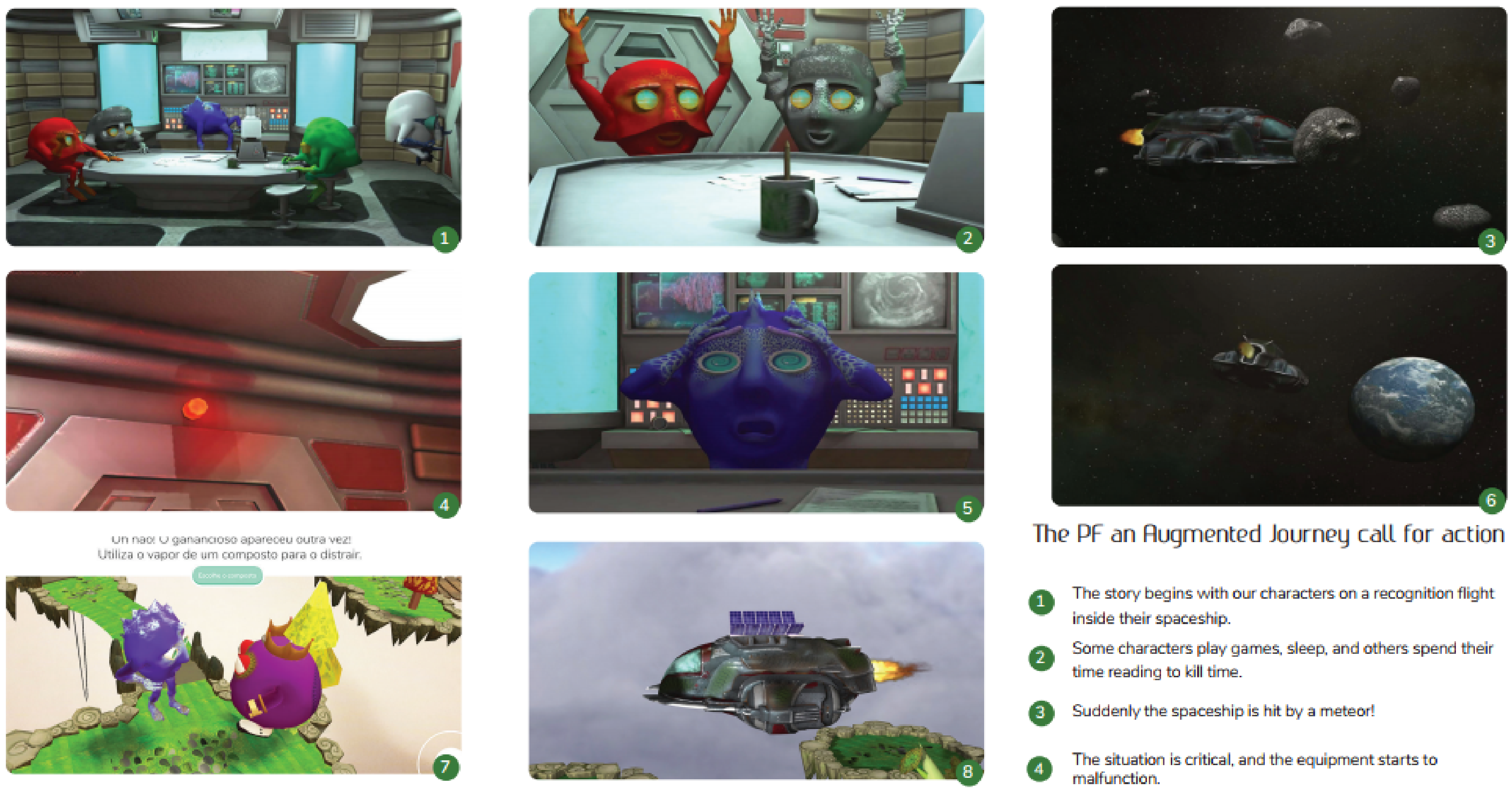
Chemistry is all around us, and despite its importance, many students do not associate how it relates to their everyday lives and its role in environmental change. The need to maintain a sustainable future and keep up with innovations in technology and discoveries highlights the need to promote the interest for sciences in young scientists at a much earlier age than the approach by the school curricula [10].

Children's attitudes towards STEM, particularly chemistry, are known to manifest increasing disinterest [19, 38]. and lack of motivation due to the perception of being complex and difficult domains. Previous findings show how immersive medias experiences can promote content learning as well as critical thinking [8][50]. A gamified storytelling approach can immerse children in the narrative, positively affect their attitudes and raise their interest in learning science in the early years [24, 27]. According to Ermi and Mäyrä, immersion is attributed to sensory factors, challenge-based experiences and imagination – which they call imaginative immersion. Imaginative immersion is a particular kind of immersion when players become absorbed in the world and stories or begin to empathize or identify with game characters [14]. At the same time, Harviainen Harviainen, T.J. (2003) distinguishes imaginative immersion between "character immersion" and "narrative immersion", depending on if the story or the character is absorbing the player [13]. Readers experience emotions in response to stories and entertainment in general; education can exploit this mechanism to foster learning.

Transportation into a story world makes narrative events seem closer to a personal experience and the impact of the lesson to learn can be strengthened [30]. Moreover, attitudes based on cognitive and emotional foundations are more persistent over time ([39]. Emotionally rich stories are more likely to be remembered [24]. Digital games can give life to incredibly engaging fictional worlds, in which learning takes place as part of the mechanics of the game itself in addition to the incidental content learning [5].

PF An Augmented Journey is designed with an edutainment approach in mind, based on interactive gaming and storytelling to engage children in concepts about the Periodic Table of chemical elements and their sustainability. The plot is built on a tightly structured beginning, introducing the characters and the problem -development use of gamer's action to solve the problem while gathering the learning material and finally -the end, solving the problem and leaving a positive message and sense of accomplishment.

In the development of the plot, we used several incidents (hit of the spacecraft and dialogs with different characters) which forces the character to take an action. Such a format is called a beat, a script analysis unit representing the smallest defined action in a play script. A beat is an event, decision, or discovery that alters the way the protagonist pursues his or her goal. It usually takes the form of action-reaction [28].



The PF an Augmented Journey call for action

1. The story begins with our characters on a recognition flight inside their spaceship.
2. Some characters play games, sleep, and others spend their time reading to kill time.
3. Suddenly the spaceship is hit by a meteor!
4. The situation is critical, and the equipment starts to malfunction.
5. The alarm goes on!
6. The spaceship loses control and is taken out of orbit towards planet Earth.
7. The player explores the 3D world, dialogues with the characters and overcomes obstacles.
8. The spaceship is fixed and the journey continues.

In the PF an Augmented Journey, storytelling is used to create the backstory for the game. The plot unravels as the protagonists run into an accident that changes their status quo. This storytelling device is known as the inciting incident. In the PF Augmented Journey, the inciting incident is used to build the motivation for the game's "call for action," where protagonists call the players to action to restore the altered status quo. While the inciting incident is a storytelling device, the call for action is typical of games and integrated within the game mechanics. In the game, the child is called by one of the protagonists of the PF story to help solve the problem by fixing the broken spaceship and getting back on their journey. The players also while dialoguing with the different characters are asked to overcome some obstacles by using the chemical reactions.

As players take on the challenge, they will be engaged in exploring a 3D AR world, encountering new reactions and more elements in the form of new characters.

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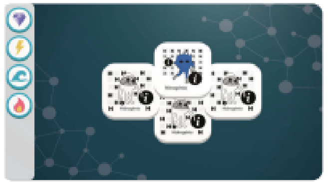
GAMEPLAY MECHANICS

"Game mechanics are the different actions, behaviors and control mechanisms afforded to the player within a game context" [17]. The design of the mechanics of PF is an iterative process taking into account the balance between several factors: learning objectives, target audience, story, scenarios, characters. The PF an Augmented Journey is designed as an exploration of a AR 3D world. Players have to find and collect parts of a spaceship in the 3D world by moving within the real environment, to help the protagonists fix their vehicle and continue their journey. The use of 3D AR technology affords participants' immersions simultaneously in both the real world and the virtual information [15]. The gameplay allows communicating with characters through textual input and output to gather the information that helps them to complete the task while learning about the sustainability of the elements. Players have to select and use the appropriate chemical reactions and compounds to unlock parts of the world where spaceship pieces have to be found. The game finishes after the player have reached the last module of the AR 3D world and has enabled characters to fix their spaceship by joining all of the found pieces. A congratulation screen acknowledges that the player has concluded his/her mission. The player can then take a selfie with their favorite character.

"... Mechanics allow the users' actions and control."

After the intro, a screen will upload asking the player to select a character to start a journey.



Animation of elements bonding creating compounds is displayed

The new compounds are displayed in the left corner of the screen and identified with icons.

The game finishes when parts of the spaceship assemble and the main characters return to their planet.

Example of the game-play interaction in the next page

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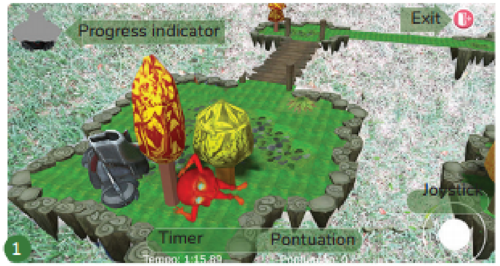
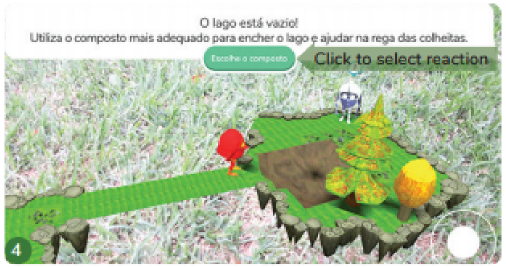


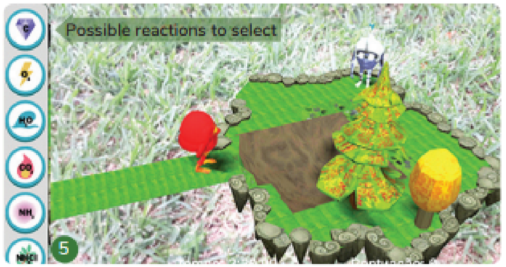
The chosen character wakes up and realizes that the spaceship has crashed into a different world.

A message asks the player to help find all the spaceship pieces to fix it.

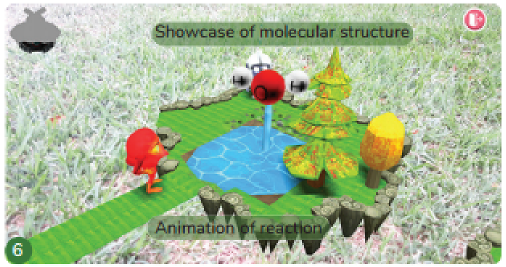
Using the joystick, the player guides the character around the 3D world.



The first obstacle in the game is an empty lake. Zinc gives a hint by complaining about not having enough water for agriculture.



The icons with the reactions pop up and the player has to select the appropriate reaction to keep going. If the player selects the wrong reaction, a message and a sound feedback will ask to try again.



Once the player selects the appropriate reaction an animation displays the molecule structure and substance created.

Zinc talks about its overuse from being used for metallics alloys for so many years.

As a reward, Zinc gives a piece of the spaceship for helping and the adventure continues.

Next part of the game is unlocked.

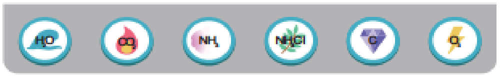
PF An Augmented Journey Learning Scaffolding

The learning of the basic concepts of the periodic table are scaffolded at different moments of the game. The overall learning goals are:

-introduction to the notions of chemical bondings and molecular structure

-introduction to the sustainability of the chemical elements

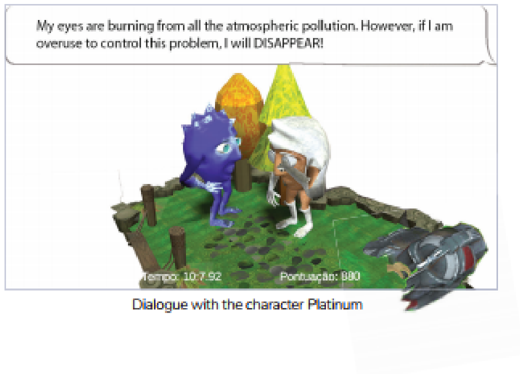
The displaying of chemical formulas in the icons representing reactions/compounds accustomed children to the symbology used in the domain.



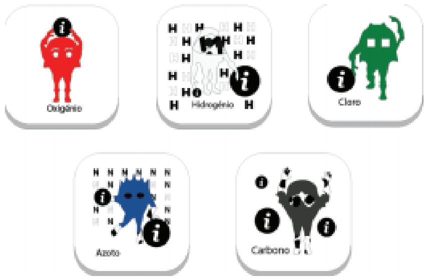
Represented reactions and substances: water, fire, ammonia, fertilizer, diamond and ozone.

The sustainability of the chemical elements is administered throughout dialogues while interacting with different characters throughout the game. These dialogues reflect the causes of the scarcity of the elements like their economic value, overuse and availability (Silver, Platinum, Zinc, Arsenic, Helium). The interactions are accompanied by cute animations and funny sounds (characters' dialects) to create empathy with the characters. The format of this interaction changed from an AR 3D animation to a screen 3D animation base, after some comments by children (5) that couldn´t observe the detail of the face expression and movement.

As positive reinforcement, the player receives a piece of the spacecraft from these characters. The process is repeated until the end of the game: overcoming obstacles, dialogue to gather information, reward.

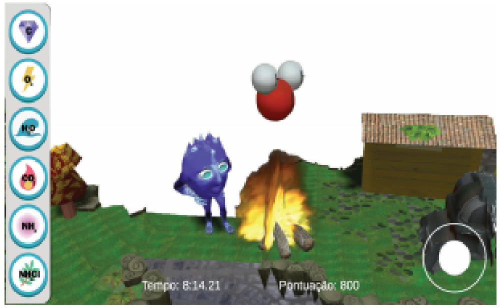


Dialogue with the character Platinum



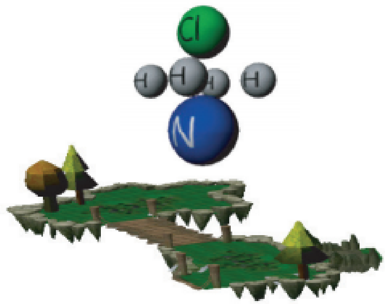
Analogies of the elements.

Analogies are used several times in the game to convey the bonding properties of the elements. The bonding of the chemical elements is first introduced to the player at the beginning of the game using an animation



Visualization of molecular structure and reaction created

The chemical bonding follows a repetitive learning process: problem-solving task (find the adequate chemical reactions/ compound for the obstacle)—visualization of molecular structure (with correspondent atoms) from different perspectives. - visualization of animation of the compound/reaction created with the selected molecular structure (used of compound/reaction that the child can relate to like water, diamonds, etc.). Positive reinforcement: the resolution of the problem (clear the passage), rewards (a piece of spacecraft) and upload of a new module with a new challenge.

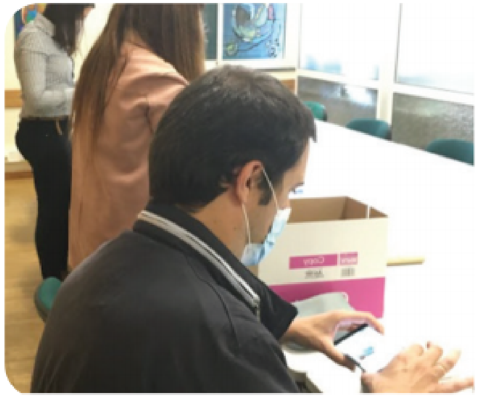


3D representation of compounds ammonium chloride.

The visualization of the spatial relation of the elements is supported in the display of the 3D AR molecular structure. Anchoring the 3D game map to a point in the real world, the participants can move in relation to the digital information (e.g. visualize the molecular structures after the reactions) supporting embodies and spatialized meaning-making.

Postcard from PF an Augemented Journey

At the end of the game, the player receives a final positive reinforcement by acquiring a selfie postcard of the game to share with friends and family.



School coordinators/ teachers interacting with the game.

Our 21 participants were primarily 11-year-old students (52.4%), then 12-year-old (38.1 %) and finally 13-year-old (9.5%), all from 6th-grade level. For most of these participants, the technology was not a novelty since they had engaged or knew about AR from previous experiences.

METHODOLOGY

Design process

The initial concept and character design were based on a participatory design (PD) process, bringing together an interdisciplinary team that included: a chemical biologist, two chemist teachers, a science teacher and three interaction design researchers. The teacher's participation was secured after the leading researcher presented the project at their institutions, e.g. at the "Ciência Viva" national science centre, and at the Madeiran Regional office for education. Time and pandemic constraints challenged the process. We had around five in-person interactions, two online discussions (zoom) and a couple of emails to debate about the content and showcase the work progress. The two school teachers proposed the type of information to include in the game according to the cognitive development and students' lack of experience with the topic Periodic Table (according to the school curriculum only happens later when children are 14-year-old). The information was also complemented by the chemical biologist. After discussing the content needed, we ended up with the elements/characters Oxygen, Hydrogen, Chlorine, Nitrogen and Carbon selected based on the covalent bond combinations responsible for most of the biological molecules on Earth. Zinc, Helium, Platinum, Silver and Arsenic were selected because are considered critical or in danger of being depleted.

The three interaction design researchers were selected among HCI and game design experts, at our research institution (ITI-LARSyS). They were involved in the validation and preliminary evaluation of the design concepts and prototypes, which were conducted at the institution's premises. The validation regarded the gameplay and mechanics as well as the interactions and usability (intuitive, easy, fun). The HCI and game researchers were also consulted on the appropriate aesthetics for the target users' age, the playability of the game, game-play engagement and its level of usability.

Study with students

On the day of the study, the main researcher presented a small debrief about the activity and study process. The 21 young participants, five females and 16 males were divided into two groups (10 and then 11 participants) for ease of logistics. Half of the students stayed in the classroom with their school teacher, while the other half moved to the school library, where the other two researchers had previously prepared the mobile devices for the game and the equipment for the study (recording cameras). A mobile phone (Samsung S7 Edge) with the game installed was provided to each participant, who was asked to follow the game instructions. The participants were given 15 minutes to interact with the game (time necessary to beat the game), while all the researchers took observations notes and the session was recorded. After all the participants finished the game, they were guided to the classroom and asked to fill out several questionnaires. The remaining participants were asked to move to the library and follow the same procedure. These questionnaires gather data again about the participants' perception of chemistry as a subject and content knowledge about the Periodic Table.

The children were also asked to compile a narrative transportation scale measurement, to investigate the potential and effects of storytelling in this context. While previous research has been conducted using the narrative transportation scale by Green and Brock, 2000 [11] to analyze the effect of stories as a medium to influence attitudes, beliefs [1] and behavior [47], it is mostly applied to films or in the written context of a book; however, it is a novel approach when applied to a serious game narrative. We believe that it is important to quantify the participants' immersion, cognitive and emotional empathy with the characters as a part of the game elements that contribute to the overall engagement of the users. For this reason, we conducted qualitative and exploratory research to identify the dimensions of narrative transportation (loss of the notion of reality and time, projection in the narrative universe or development of mental imagery and identification with the character).

STUDY RESULTS

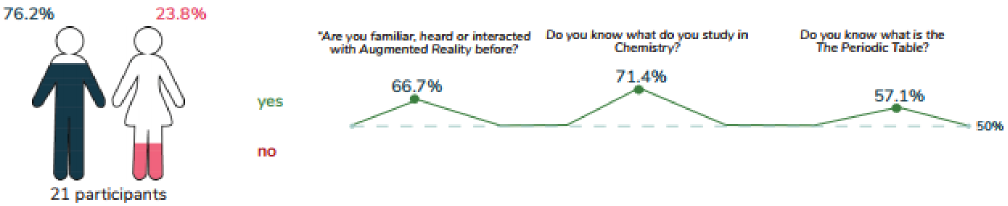
We created the following research question as to guide our research:

RQ1: Can AR serious games change the student's perception of Chemistry?

RQ2: How to design AR serious games balancing mechanics, technology, story, and aesthetics to provide content knowledge to children about the Periodic Table effectively?

RQ3: Can character and storytelling engage students with Chemistry while facilitating the learning process?

Demographics



Participants were familiar with Chemistry as a domain. Quantitative and open questions answers reflected that even though Chemistry is a subject only introduced in the 7th grade, students already have an overall perception of this area. However, regarding the Periodic Table topic, only 12 of the participants had some knowledge about it. Some of the participant's answers were: "I learn about chemical equations", "We do lab experiences", "We learn how to mix two or more elements", "Learn about substances, energy and other things", "We learn about the Periodic Table".

Participants perception of Chemistry

Pre-intervention | Post-intervention

Decrease in the negative perception (items 1, 3, 4, 6, 9)

(M = 1.400, SD= 0,753) → (M = 0.950, SD= 0.944)

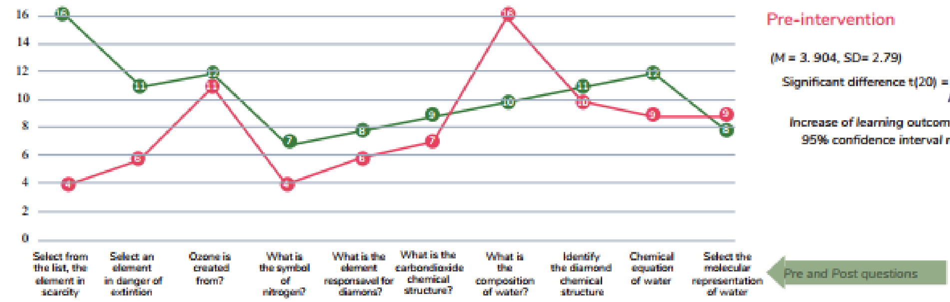
(M = 0.952, SD= 0.973) → (M = 1.428, SD= 1.121)

Increase in the positive perception (items 2, 5, 7, 8, 10)

Instruments: Multiple choice pre-intervention (before using PF an Augmented Journey) and post-intervention (after using PF an Augmented Journey) questionnaire with a negative and positive perception of chemistry.

Results: Compared results from Pre-intervention and Post-intervention about the participants' perception of Chemistry exposed a decrease in the negative perception and an increase in the positive perceptions of the participants.

Learning Outcome



Pre-intervention | Post-intervention

(M = 3. 904, SD= 2.79) → (M = 4.952, SD= 2.37)

Significant difference t(20) = 2.4, p < .000t (two-tailed)

Increase of learning outcome Mean scores of 1.04, with 95% confidence interval ranging from 0.45 to 2.04.

Instruments: Multiple choice pre-intervention and post-intervention questionnaire about the content knowledge. The researchers created the questionnaire with the teachers' collaboration. Comparative analysis of Post-intervention and Pre-intervention results.

Results: The assessment of the normality of the distribution from learning outcomes, Shapiro-Wilk test Sig. p <.093 suggested a non-violation of the assumption of normality. A Paired-samples t-test revealed a statistically significant difference from the Post-intervention scores compared to the Pre-intervention scores, with mean scores of 1.04 and 95% confidence interval ranging from .045 to 2.04. The eta squared (η2p) statistic (.19) indicated a large effect size. These optimistic results showcased the game's potential to facilitate the learning process in the context of chemistry.

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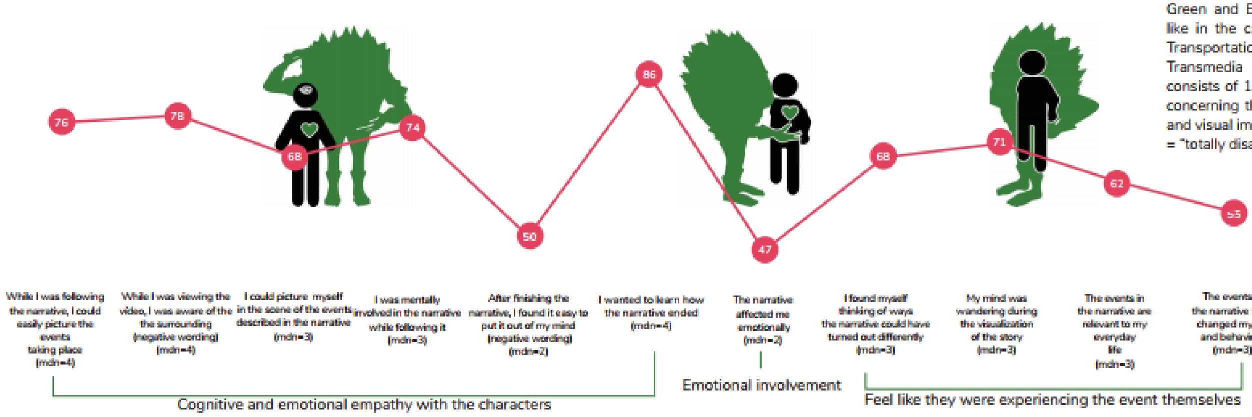
Character and Story Engagement



Instruments: Narrative transportation scale (TS) by Green and Brock 2000 [11] questions were adapted, like in the case of Elodie Jarrier et al. [20]. Narrative Transportation Scale. Measure Development for Transmedia experience). The Transportation Scale consists of 11 items that address the users' experience concerning the character, cognitive, emotional-affective and visual imagery factors. We used a Likert scale with 1 = "totally disagree" and 5 = "totally agree"

The Narrative Transportation Scale had good internal consistency, with a Cronbach alpha coefficient reported of η =0.93. According to Elodie Jarrier et al. [17], the transportation scale [9] identify various factors. The first factor reflects the participant's experience of becoming the character and having an emotional empathic reaction (first six questions). The second factor (question 7) is the emotional involvement in the story. Finally, the third factor is the imaginative facet which covers the imagination produced by the story (4 last questions). In our results, the highest scores were obtained in the first factor (mdn= 4), then the mental imagery (mdn=3), and finally emotion with the lowest score (mdn=2).

DISCUSSION

The PF An Augmented Journey is designed to facilitate better learning acquisition through gaming and storytelling. The results of our study showcased the potential of PF as a tool that can engage and help understand concepts in the context of Chemistry. Regarding our RQ2, there were significant learning outcomes, indicating that the interaction with the game elements facilitated the acquisition of knowledge about the Periodic Table. We believe that these results positively reflected some of our design and development goals and design choices, which can be summarized in:

PD approach with educational stakeholders allows identifying suitable pedagogics to administer content targeting the user's characteristics. Supporting, Barendregt, W, et al, 2016 and Manches A. Price 2011. identifying learning goals and aligning activities with these goals is a challenging but critical process [2][27]. We suggest considering the cognitive development, social and environmental connections of the children, towards the complexity of the content. PF content is about abstract phenomena - the bonding of chemical elements a topic that is intended for older children, however using concrete referents that the child has prior experience with like water, diamonds, fertilizer, and ammonia can help to create a mental connection aiding the understanding process. The selection of the reaction/compounds to explore in PF is also based on the possibility of being the most interesting and engaging for the children.

Designing the game mechanics to implement specific pedagogical approaches can optimize the learning experience. The gameplay mechanic must be designed according to the method that is most suitable to the learning goal. PF by allowing virtual objects' superimposition on the real world, AR facilitates children's understanding of complex and abstract concepts through spatial reasoning by making them visible and allowing for multidimensional perspectives. The participants were able to visualize 3D AR atoms bonding in different perspectives by moving around the physical space, contributing to their notion of molecular structure. The use of AR also allowed for the movement of the participants in a real-world, making the space part of the gameplay, increasing the children's immersion support [21]. However, AR was not the best technology to showcase dialogue with endangers elements because of its scalability. The participants wanted a close up of characters expressions and movements while acquiring the information.

The cognitive and emotional empathy with characters incites problem-solving skills while acquiring scientific content knowledge. Experiencing emotions through characters engages the child and maintains his/her desire to reach the final goal of the game. PF supports the players' identity transfer into the game world to form a bond with the virtual identity, promoting the desire to explore (3D environment and other characters) to discover a solution (gathering pieces of the spaceship) and reach the final goal (help the character reach their planet). This supports Schloss, I. et al. (2021) claims about the potential of character embodiment as a tool to promote exploration and discovery in science learning [45].

AR playful experiences also positively affected the student's motivation and attitudes towards the sciences. After interacting with the game, the participants' positive perception of chemistry increased, while the negative decreased, showcasing that PF can help improve students' attitudes towards scientific domains (answer to RQ1). When developing an educational game, the design of visual storytelling, plot development and characters is critical. PF exploits visual storytelling and gaming balance elements to foster players' immersion (full involvement in the activity and the sense of being part of the narrative).

The Narrative Transportation scale can provide insights toward identifying the user's immersion with an interactive AR story. As per our results, Periodic Fable ignites both narrative-induced imaginative immersion, "character immersion" and "narrative immersion" (RQ3). PF calls for a strong connection with the learning content by immersing the player with the character and the story. It is also possible that the fantasy world created by the narrative offered a more friendly learning environment and a mechanism for learner-character bonding which aligns with prior work by Sherry Ruan et al. [40]. These results are also supported by Steen, F., & Owens, S., who stated that the more immersed children are in a game, the more they invest and the more educational potential the game can harness [9].

CONCLUSION

Our paper introduces Periodic Fable An Augmented Journey, an AR based narrative game to support and engage children with concepts about the Periodic Table. PF was developed through an iterative co-design process involving educational stakeholders. The evaluation of the system helps to understand how technology, game mechanics, aesthetics and story (character and narrative) and pedagogics, can provide interactive ways to foster children's interest in chemistry an potential their career path. Our findings suggest children's engagement with the system had positive effects in the learning process of the content knowledge, however despite our positive results, our study was limited by our small sample group, this research will benefit from future studies with a larger number of participants to validate our findings in formal and non-formal settings.

The design of educational serious games is a complex process that includes designers, game developers and pedagogical experts that must be able to efficiently communicate to produce a product that is both educationally efficient and fun to play.

ACKNOWLEDGMENTS

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SELECTION AND PARTICIPATION OF CHILDREN

The recruitment was done through a local public school. We arranged a meeting with the school teachers to showcase the game, the objectives, and the research process and set up a date and time to conduct the study. Two weeks prior to the study, a document (consent form) was given to one of the school coordinators to gather the children's guardian permission (signature) for their children to participate. The document contained a brief explanation of the proposed research, nature of the participation, information about its confidentiality and image rights. It also informed the guardians that the participants could at any point abandon the study if they wished so. Afterwards, the coordinators collected the signed forms and communicated the number of participants to the researchers who prepared all the resources, equipment and material.

A day before the study, the participants that had signed consent form were asked to fill out individual questionnaires during one of their classes (prepared by the researcher). These questionnaires were created to gather demographics, perceptions and feelings toward the chemistry domain and preliminary data about their current content knowledge of the subject. On the day of the study, the main researcher presented a small debrief about the activity and study process. Afterwards all the participant interacted with the games and finally, fill out a post-questionnaire.

REFERENCES

[1] Appel, M., & Mara, M. (2013). The persuasive influence of a fictional character's trustworthiness. Journal of Communication, 63(5), 912-932.

[2] Barendregt, W., Bekker, T. M., Börjesson, P., Eriksson, E., & Torgersson, O. (2016, June). Legitimate participation in the classroom context: Adding learning goals to participatory design. In Proceedings of the The 15th International Conference on Interaction Design and Children (pp. 167-174).

[3] B. Shelton and N. Hedley, "Exploring a cognitive basis for learning spatial relationships with augmented reality" Technol. Instr. Cogn. Learn., vol. 1, no. June 2014, pp. 323–357, 2004.

[4] C. Arcos et al., "Playful and Interactive Environment-Based Augmented Reality to Stimulate Learning of Children," no. April, pp. 18–20, 2016.

[5] Cerqueira, J., Cleto, B., Moura, J. M., & Sylla, C. (2018, June). Visualizing platonic solids with augmented reality. In Proceedings of the 17th ACM Conference on Interaction Design and Children (pp. 489-492).

[6] Dobal, F., & Lalioti, V. (2021, June). Circular Species: Designing critical thinking into children's science education through biomaterials and augmented reality. In Interaction Design and Children (pp. 8-17).

[7] F. F. Steen and S. A. Owens, "Evolution's pedagogy: An adaptationist model of pretense and entertainment," J. Cogn. Cult., vol. 1, no. 4, pp. 289–321, 2001.

[8] Fried, D. B., Tinio, P. P., Hughes, A., & Paneque, D. (2019). Elementary student achievement and teacher perception of an advanced chemistry curriculum. European Journal of Science and Mathematics Education, 7(4), 137-148.

[9] Green, M. C., & Brock, T. C. (2000). The role of transportation in the persuasiveness of public narratives. Journal of personality and social psychology, 79(5), 701.

[10] Haeusler, Carole, and Jennifer Donovan. "Challenging the science curriculum paradigm: Teaching primary children atomic-molecular theory." Research in Science Education 50, no. 1 (2020): 23-52.

[11] Harviainen, T. J. (2003). The multi-tier game immersion theory. In As Larp Grows Up--Theory and Methods in Larp (pp. electronic-version).

[12] HL. Ermi and F. Mäyrä, "Fundamental components of the gameplay experience: Analysing immersion," Proc. DiGRA 2005 Conf. Chang. Views - Worlds Play, no. January 2011,

[13] Holmes, Corinne A., Nora S. Newcombe, and Thomas F. Shipley. "Move to learn: Integrating spatial information from multiple viewpoints." Cognition 178 (2018): 7-25.

[14] Host'ovecký, M., Salgovic, I., & Virágh, R. (2018, November). Serious game in science education: How we can develop mathematical education. In 2018 16th International Conference on Emerging eLearning Technologies and Applications (ICETA) (pp. 191-196). IEEE.

[15] Hunicke, R., LeBlanc, M., & Zubek, R. (2004, July). MDA: A formal approach to game design and game research. In Proceedings of the AAAI Workshop on Challenges in Game AI (Vol. 4, No. 1, p. 1722).

[16] Im, H., & Rogers, C. (2021, June). Draw2Code: Low-Cost Tangible Programming for Creating AR Animations. In Interaction Design and Children (pp. 427-432).

[17] J. Osborne and J. Dillon, "Science education in Europe: Critical reflections," London Nuff. Found., no. January, p. 8, 2008.

[18] Jarrier, E., Bourgeon-Renault, D., Derbaix, M., & Petr, C. (2017, June). Narrative transportation scale: Measure development for transmedia experience. In International Conference on Arts and Culture Management.

[19] Jensen, L. J., Valentine, K. D., & Case, J. P. (2019). Accessing the pokélayer: Augmented reality and fantastical play in Pokémon Go. In Educational media and technology yearbook (pp. 87-103). Springer, Cham.

[20] Jiang, S., Huang, X., Xie, C., Sung, S., & Yalcinkaya, R. (2020, June). Augmented scientific investigation: support the exploration of invisible" fine details" in science via augmented reality. In Proceedings of the Interaction Design and Children Conference (pp. 349-354).

[21] Kim, J., Agarwal, S., Marotta, K., Li, S., Leo, J., & Chau, D. H. (2019, June). Mixed reality for learning programming. In Proceedings of the 18th ACM International Conference on Interaction Design and Children (pp. 574-579).

[22] Loderer, K., Pekrun, R., & Plass, J. L. (2020). Emotional foundations of game-based learning. In J. L. Plass, R. E. Mayer, & B. D. Homer (Eds.), Handbook of game-based learning (pp. 111–151). The MIT Press.

[23] Lu, A., Wong, C. S., Cheung, R. Y., & Im, T. S. (2021, April). Supporting Flipped and Gamified Learning With Augmented Reality in Higher Education. In Frontiers in Education (Vol. 6, p. 110). Frontiers.

[24] Luraschi, M., Rezzonico, R., & Pellegri, G. (2012). The chemist, that madman! How children perceive science. CHIMIA International Journal for Chemistry, 66(11), 820-825.

[25] Manches, A., & Price, S. (2011, June). Designing learning representations around physical manipulation: Hands and objects. In Proceedings of the 10th International Conference on Interaction Design and Children (pp. 81-89).

[26] McKee, R. (1997). Story: style, structure, substance, and the principles of screenwriting. Harper Collins.

[27] Morais, C., & Araújo, J. L. (2019). Awakening to chemistry through storytelling and practical activities: middle school students interacting with pre-school children. Chemistry Education Research and Practice, 20(1), 302-315.

[28] Naul, E., & Liu, M. (2020). Why story matters: A review of narrative in serious games. Journal of Educational Computing Research, 58(3), 687-707.

[29] Nieminen, M. (2017). Psychology in character design: Creation of a Character Design Tool.

[30] Olim, S. C., & Nisi, V. (2020, November). Augmented Reality Towards Facilitating Abstract Concepts Learning. In International Conference on Entertainment Computing (pp. 188-204). Springer, Cham.

[31] Radu, I., & MacIntyre, B. (2009, June). Augmented-reality scratch: a children's authoring environment for augmented-reality experiences. In Proceedings of the 8th International Conference on Interaction Design and Children (pp. 210-213).

[32] Ross, J., Guerra, E., & Gonzalez-Ramos, S. (2020). Linking a hierarchy of attitude effect to student engagement and chemistry achievement. Chemistry Education Research and Practice, 21(1), 357-370.

[33] Rosselli, F., Skelly, J. J., & Mackie, D. M. (1995). Processing rational and emotional messages: The cognitive and affective mediation of persuasion. Journal of experimental social psychology, 31(2), 163-190.

[34] Ruan, S., He, J., Ying, R., Burkle, J., Hakim, D., Wang, A., ... & Landay, J. A. (2020, June). Supporting children's math learning with feedback-augmented narrative technology. In Proceedings of the Interaction Design and Children Conference (pp. 567-580).

[35] S. A. Matlin, G. Mehta, H. Hopf, and A. Krief, "The Periodic Table of the Chemical Elements and Sustainable Development," European Journal of Inorganic Chemistry, vol. 2019, no. 39–40. pp.4170–4173, 2019.

[36] Schell, J. "The Art of Game Design: A book of lenses". CRC Press, pp 51-54, 2008.

[37] Schloss, I., O. Bailey, J., & Tripathi, S. (2021, June). "I'm in his belly!": Children's Responses to Different Types of Characters in Virtual Reality. In Interaction Design and Children (pp. 43-48).

[38] Silva, M. A. R., Dias, A. L., & Anacleto, J. C. (2010). Using Contextualized Narrative Game to Improve Students and Teachers Communication. In CSEDU (2) (pp. 232-237).

[39] Umanath, S., Butler, A. C., & Marsh, E. J. (2012). Positive and negative effects of monitoring popular films for historical inaccuracies. Applied Cognitive Psychology, 26(4), 556-567.

[40] Villanueva, A., Kotak, H., Liu, Z., Mehta, R., Li, K., Zhu, Z., ... & Ramani, K. (2020, June). ARbits: Towards a DIY, AR-compatible electrical circuitry toolkit for children. In Proceedings of the 2020 ACM Interaction Design and Children Conference: Extended Abstracts (pp. 205-210).

[41] Wong, C. H., Tsang, K. C., & Chiu, W. K. (2021). Using Augmented Reality as a Powerful and Innovative Technology to Increase Enthusiasm and Enhance Student Learning in Higher Education Chemistry Courses. Journal of Chemical Education, 98(11), 3476-3485.

[42] Zohar, A. R., & Levy, S. T. (2020, June). What do atoms feel? understanding forces and energy in chemical bonding through the ELI-Chem environment. In Proceedings of the Interaction Design and Children Conference (pp. 355-360).

Enhancing Children Spatial Skills with Augmented Reality Serious Games

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ABSTRACT

Augmented reality (AR) applications have shown to be extremely valuable for entertainment and educational purposes. AR experiences support the learning performance of scientific subjects by providing visualization of phenomena and abstract concepts. This process facilitates the transfer of 2D information into 3D mental models, a cognitive process essential in the Chemistry domain. In the pages that follow, we contribute to the design and development of two AR serious games that combine participatory design with human-computer interaction principles to introduce Periodic Table concepts to 9-13-year old children. We present initial findings regarding the children's acceptance and satisfaction of the games, usability, engagement and overall feedback from our target audience. Although the overall assessment showed positive results in AR's entertainment value and usability, a preliminary pilot test (N=7) using a mix-method approach identified the need for minor game-play interventions. We aim to optimize our games by continuing our research with our target audience, analyzing their feedback, making refinements and assessing the game's learning effectiveness. Our purpose is to research and create guidelines for designing AR serious games to facilitate the learning of abstract concepts while supporting spatial skills. We also aim to change student perception of Chemistry as challenging and dull, and to motivate children to invest in this area.

CCS CONCEPTS

• **Human-centered computing → Interaction design**; **Participatory design**; **User centered design**; • **Human Center Computing**; • **Mixed /Augmented Reality**;

KEYWORDS

augmented reality; serious games; spatial skills; storytelling and chemistry

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1 INTRODUCTION

The motivation of children towards a domain can lead to their success and future career choices. Many entities acknowledge the need to prepare citizens in the areas of Science, Technology, Engineering and Math. These areas, however, are sometimes perceived as complex and difficult, discouraging students from following these paths [15]. In some cases, the use of textbooks and 2D information to provide abstract content in Chemistry is not the most reliable method to create cognitive connections and to facilitate the learning process. There is a clear need for innovative tools that enhance learning through meaningful connections with the students' context, engaging them towards the subject being taught.

Along these lines, we developed Periodic Fable, a couple of AR serious game, instrumental to conduct design-based research about AR as a tool that, while facilitating the learning of abstract concepts in Chemistry, supports visual-spatial skills. While using similar assets, both parts of the game have different pedagogical approaches, using play mechanics to provide content knowledge in a ludic manner. This paper discusses preliminary feedback gathered from our target audience's first pilot test, to identify technology, game design, motivation and usability issues. Our aim is to continue the optimization of our game by conducting future studies with larger sample groups to answer our research questions and to create design guidelines that contribute to the production of efficient and engaging AR serious games.

2 LITERATURE REVIEW

Chemistry demands student imagination to comprehend concepts like atoms, molecules, chemical bonds, and other concepts which, without visible or physical referents, can be a challenging process. The understanding of abstract concepts is specially demanding when the cognitive capacity of children to create mental images, rotate and envisage elements in space is low. These abilities, referred to as spatial skills, visual-spatial or spatial abilities, allow students to translate external representations like 2D visualization into internal 3D models [10]. In this context, it is important to note that, when children are overwhelmed by information that they cannot assimilate, the result is often tantamount to cognitive overload, frustration and lack of interest [20] towards the content.

Like other STEM subjects, Chemistry is perceived by young children as challenging, difficult, unattractive, and less relevant to everyday life [11, 15, 17]. As a result, educational stakeholders have acknowledged the need to incorporate tools that can improve students' engagement, arising interest and enjoyment, in order to enhance their behavior towards this domain [13]. Education professionals also advocate for the introduction of more "student-friendly" activities that integrate real-life context with learning content into school curricula. The development of positive attitudes towards these subjects, together with earlier contact with scientific phenomena, will significantly impact STEM literacy. This will also promote the understanding and development of scientific thinking, thus influencing children's perception of these domains [11].

Previous studies showed that Augmented Reality (AR) helps to learn scientific subjects such as Chemistry by materializing visualizations of abstract and complex concepts through animations, 3D modeling, and other digital information [4, 8, 9]. AR characteristics of superimposing digital information within the real environment provides children with the opportunity to engage with educational content in digital format [18] while relating them to the actual physical world [1–3] . Furthermore, activities using 3D objects, either virtual or physical, develop broader spatial skills by providing an effective context for teaching [7], and can lead to growth in spatial reasoning ability [7].

3 SYSTEM DESIGN

Periodic Fable's games interaction design, aesthetics, mechanics, storytelling, technology and content are the results from ideation rounds and participatory design methods with educational stakeholders (chemistry school's teachers, chemistry researchers and students) and heuristic evaluation with game designers. The implementation of the participatory design feedback are incorporated in the characters analogies, storyline, showcase of 3D models of molecular/compound structures, creation of meaningful connections between the learning content with the real world, use of appealing aesthetics and offering the player an active role and fun game-play mechanics. We also envision the use of tasks within the games-play to train spatial skills like the understanding of space (thinking about the location of objects/containers needed for the activity), visualisation of three-dimensional (3D) molecular structure and map exploration (to gather chemical elements) [14].

To begin, we selected only ten chemical elements to explore. The criteria was their abundance in the environment (oxygen, hydrogen, nitrogen, carbon, chlorine), and the urgent need to tackle elements considered critical because of their overuse and exploitation (helium, platinum, silver, zinc and arsenic). The games were developed for android mobile devices using ARCore SDK for Unity 3D.

3.1 Periodic Fable An Augmented Journey

Periodic Fable (PF) An Augmented Journey is an adventure game where the user has to apply the knowledge of chemical reactions displayed through animations at the beginning of the game, to be able to overcome obstacles while navigating an AR 3D world. The game stresses the narrative, in different game components:

(1) Displaying the story plot through entry screen animation. The animation shows a group of characters, Oxygen, Hydrogen, Chlorine, Nitrogen or Carbon, together in a space trip. After being hit by a comet, their spacecraft is taken out of orbit and crashes into our world. The player can help the characters go back to their planet by collecting parts of the spacecraft scattered on the 3D world (Fig.1 - no. 1);
(2) Character selection. It is up to the player to select the main character for the game by clicking in one of the creatures displayed on the screen (Fig.1 - no. 2);
(3) Visualization of compound elements. Before the player can start to navigate the 3D world, a short animation shows what elements are in the compound/reactions needed for the obstacles. The compound/reactions are represented by icons displayed at the left side of the screen (Fig.1 - no. 3);
(4) Anchoring the AR visualization of the game 3D world in the real world. The player has to use the device camera to scan and recognize patterns in the real- world player surroundings. The AR application will build the AR experience around that location and allow the visualization of the tri-dimensional AR world;
(5) Explore the 3D world by guiding the character with a digital joystick. Once the 3D world has been anchored, a message asking for help is displayed. A 3D character standing on one of the 3D world modules can be guided through the 3D environment with the joystick (Fig.1 - no. 4);
(6) Overcoming obstacles by selecting the appropriate compound/reaction (identified by an icon on the left side of the screen). While exploring the 3D world, some passages are blocked because of circumstances like climate change (high ultraviolet rays, dry lakes, etc.) that can be overturned by selecting a proper reaction/compound like water, ozone, etc. (Fig.1 - no. 5).
(7) Visualization of compound/reaction and unblocking of obstacle. If the player selection of the appropriate compound/reaction is correct, an animation of atoms joining together is revealed and the obstacle is vanquished, allowing him/her to collect a part of the spacecraft. If the player selects the wrong compound/reaction , a message and sound feedback asks him/her to try again (Fig.1 - no. 6);
(8) Dialog with elements at risk of being depleted (Helium, Zinc, Arsenic, Platinum and Silver). At each passage of an obstacle, the main character meets with other chemical elements and receives information regarding why they are almost depleted or in critical danger because of overuse (Fig.1 - no. 7);
(9) Gathering parts of the spacecraft. As the player interacts with the elements at risk of being depleted, or overcomes an obstacle, he/she gathers a part of the spacecraft displayed at the top left corner of the screen (Figure 1- no. 4). Once all the parts are gathered, an animation of the spacecraft assembling and flying away is revealed (Fig.1 - no. 8);
(10) Conclusion of the game experience. A message of congratulations is displayed;
(11) Game Reward. A Reward-Selfie screen is displayed at the end of the experience, inviting the player to take a picture with one, two or as many characters the participant chooses to share (Fig.1- number 9).

3.2 Periodic Fable in the Wild

The second game, *Periodic Fable (PF) in the Wild*, uses a situated learning pedagogical approach by integrating everyday routine

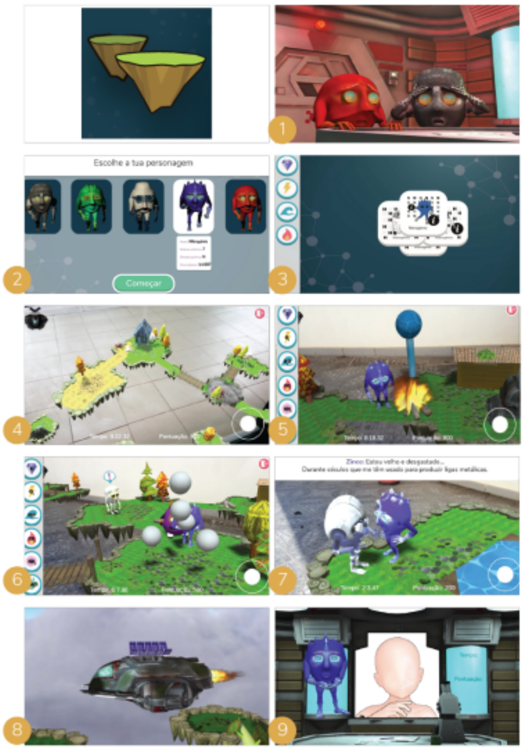

Figure 1: Periodic Fable An Augmented Journey game flow

products (e.g., a water bottle, bleach, batteries, balloons) as part of the game-play mechanics. The game starts with a tutorial that guides the user towards the different game components:

(1) Gathering of chemical atoms composing the product in question. The atoms are gathered by scanning markers allocated in the products displayed on shelves. All the collected atoms are displayed afterwards on a 2D grid. The application indicates when it has collected enough atoms by blocking the capture button. An animation of a character that represents an element with such atoms will also be showcased (Fig.2 - no. 1);
(2) Reconstruction of chemical composition of the selected product by combining the atoms identified in the screens chemical structures through a mini word puzzle kind of game. The collected atom' icons are aligned on a simple grid, and need to be connected by the participant's fingertip, one atom at a time. The player is guided in the sliding action by the chemical formula, which shows the order of the atoms, and is displayed on the right side of the screen (Fig.2 - no. 2);
(3) Anchoring the AR visualization in the real world. The player again has to use the camera device to scan and recognize a pattern for the visualization of the tridimensional AR compound/molecular structure that he/she has created (Fig.2 - no. 3);
(4) Conclusion of the game experience. Message of congratulations and player score display appear after the AR experience. The player's score is calculated by the time he/she spent on each activity (Fig.2 - no. 4);

(5) Game reward. A Reward- Selfie screen is displayed at the end of the experience, inviting the player to take a picture with all the game characters to share with family and friends (Fig.2 - no. 5).

4 METHODS

Our seven participants, three females and four males aged 11 to 13 were recruited through opportunistic sampling. Children were asked about their interest in participating, and their parents/guardians were contacted and informed of the study. Then the children and their parents were informed of the protocol and purpose of the research.

The participants attended different public schools, and since in Portugal the Periodic Table is not introduced until the 8th grade (13 to 14-years old), only three students had some previous knowledge of the content. The study took place at ITI - Interactive Technology Institute installations and it took about one hour for each children to evaluate both games. The study began with a short explanation of the purpose and the same protocol was followed for both games: 1. A demographic survey with questions regarding age, gender and grade level. We also included questions about previous knowledge of the Periodic Table and AR technology; 2. Each participant received a mobile device (Samsung S7 edge smartphone) with installed games; 3. The first game was Periodic Fable and Augmented Journey. While the participants played, two researchers observed and took notes regarding struggles, doubts, expressions and comments; 4. Finally, we applied post-test questionnaires and interviewed the participants.

We used a PANAS C test [19], a shortened version of the PANAS (Positive and Negative Affects Scale) adapted for children (20 items), to evaluate the entertainment value and the affects of the Apps on the participants. According to Watson et al., Positive Affects (PA) represent the extent to which an individual experiences pleasurable engagement with the environment. A high PA score is indicative of emotion, such as enthusiasm and alertness. In contrast, a low PA score characterizes emotions such as lethargy or sadness. The Post-test questionnaires included a usability and satisfaction assessment using likert scale with smileyometer [16] of five levels - "1" for totally disagree and "5" for totally agree (Table 1). The interview questionnaire evaluated participant satisfaction as well, and gave us the opportunity to gather suggestions from our target users. Questions like: *What did you like the most? What didn't you like? If you had to change anything, what would it be? Did you find the game useful? Why? What did you learn?* This information was also crucial for the continuing evaluation and iteration of our games.

5 EVALUATION, RESULTS AND REFLECTIONS

Regarding the technology, five of the seven users had previous knowledge or had used augmented reality applications before. Three participant, the oldest of our sample group, had knowledge of the Periodic Table content.

5.1 PF An Augmented Journey Results

While experiencing PF an Augmented Journey, our users had higher Positive affect scores with Mean Scores (M=18,57; SD= 3.04) than Negative affect Mean Scores (M=6.28; SD= 0.95). These results show that the participants were engaged with the game. The results obtained in Q1, Q2 and Q4 (Table 1), where the players reported high means of engagement, also confirm this. In addition, the participants reported during the interview that the most enjoyable part of the game was exploring the 3D world environment through the knowledge acquired about the use of chemical reactions/compounds to overcome obstacles. Children's lamented lack of interaction with some characters representing the "almost depleted chemical elements". Participants said "I want to interact more with these characters", and "I did not feel they were doing anything in the game". When we asked our participants how to improve the game, their answers reflected previous statements: "make the endangered elements/characters more interactive and more expressive". Upon these comments the researchers noticed that since the characters were displayed on top of the large virtual world, their facial expressions and movements were almost unnoticeable. While this reveals a design flaw that can be corrected, on the other hand these comments highlight the engagement and empathy of the children's with the characters and their struggles, pointing at the potential of characters persuasion and narrative immersion in delivering important messages through such games. While this is something that has been investigate in media and communication studies [5, 12], further investigations could target the specifics of serious games and AR games.

The players considered the game easy to play and useful (Q3 and Q6) and it allowed them to learn about chemical reactions/compounds: "I think this is good for learning and I need to use the right compound to keep going"; "I like learning like this, it is not boring". Moreover, the children recalled specific scientific information "I learned that ammonia at room temperature is a gas"; "Water is created with oxygen and hydrogen"; "Carbon is on a diamond"; "I learned the symbols of the chemical elements". Although we need to undertake additional studies to test the learning effectiveness of the app, these answers confirm the potential of the technology for learning.

From the observations notes, it emerged that several participant struggled to start the game. It was noted that the digital graphic joystick implemented to move characters through the 3D environment was not intuitive or easy to use. Improvements in terms of simplification of usability and instructions are needed.

5.2 PF in the Wild Results

PF in the Wild users reported higher Positive affect scores (M=18.00; SD= 2.12) than Negative (M= 6.00; SD= 0.70). The players enjoyed the exploration task of looking around the space and finding the products that displayed the game specific markers (see Fig.3 - first image). Scanning markers located on the products boxes and containers to collect the atoms of the chemical elements was also reported as a fun activity. Nevertheless, we also observed that, once the players got familiar with the game-play, they scanned the products markers to gather the proper atoms without reflecting in the products composition. This was not intended to happen, and

Figure 2: Periodic Fable in the Wild game flow

Figure 3: Pilot study

Table 1: Usability results from PF an Augmented Journey

Q#	Questions	Mean	SD
Q1	I would like to play PF an Augmented Journey again	5.00	0.000
Q2	I would recommend the game to friends and family	4.86	0.378
Q3	I thought that PF an Augmented Journey was easy to use	0.486	0.378
Q4	I think that the game is fun to play	5.00	0.000
Q5	I found that the various functions in the game, were well integrated	3.71	0.756
Q6	I found the game useful	5.00	0.000
Q7	I would image that most people would learn to use this game very quickly	4.57	0.757
Q8	I felt very confident using PF an Augmented Journey	4.29	0.756

Table 2: Usability results from PF in the Wild

Q#	Question	Mean	SD
Q1	I would like to play PF in the Wild again	4.14	0.900
Q2	I would recommend the game to friends and family	4.00	0.690
Q3	I thought that PF in the Wild was easy to use	0.471	0.488
Q4	I think that the game is fun to play	4.14	0.690
Q5	I found that the various functions in the game, were well integrated	3.29	0.756
Q6	I found the game useful	4.71	0.488
Q7	I would image that most people would learn to use this game very quickly	4.29	0.756
Q8	I felt very confident using PF in the Wild	4.00	0.816

a second iteration of the prototype should ensure the design of a reflective activity after such task. Childrens' found the animation of the characters representing the elements entertaining. They considered the game easy and useful since it allowed them to learn the composition of some products and to visualize the 3D molecular/compound structures. This was the feature they enjoyed the most, since they had to move around and collect atoms. However, they also highlighted some drawbacks of the game mechanics identified mainly in the repetition of some tasks. The players observed: "The mini game of joining the atoms was repetitive"; "I thought it was too repetitive to put the atoms together"; "I would change the part of putting atoms together, and put something different every time". Regardless, when asked if they would like to play both games again, all of them answered affirmatively.

In sum, this pilot evaluation confirms the value of PF in the learning of Chemistry and fostering of spatial reasoning, while pointing at some flaws and improvements. All users engaged and enjoyed both games, with PF An Augmented Journey being more exciting compared to PF in the Wild. We can infer that refinements on the repetitive tasks could improve the positive engagement with the PF in the wild game, while fixing the graphic Joystick of PF Augmented journey can improve its usability.

6 CONCLUSION AND FUTURE WORK

We have described the design and results of a pilot evaluation of Periodic Fable, a couple of serious game designed to support spatial reasoning and chemistry in 9-13-year old children. Although we identified game-play elements that need refinement, the overall players' assessment was very positive. The PANAS-C results with positive affect higher than negative means value affects indicate pleasure and engagement with the games. The fact that the participants regarded the game as easy, useful, and expressed the desire to play it again also indicates that the players were thoroughly engaged. Due to reduced number of participants in the study, however, the game prototypes could not be fully validated. Our next step is to act on the feedback and to conduct a broader study and usability testing of the AR serious games with larger sample groups in formal and non-formal settings. Protocol refinements will also be implemented, so as to recruit participants from schools, summer camps and children associations. Participants will be randomly divided into control (to play PF an Augmented Journey) and experimental (PF in the Wild) groups. We intend to assess and compare both games as the effectiveness of learning outcomes (Pre and Post-questionnaires), motivation (Instructional Materials Motivation Survey), and engagement. We also aim to evaluate the games as to its benefits towards spatial skill development, by conducting Pre and Post game interactions test using as instrument the Purdue Spatial Visualization Test Rotation (PSVT:R) [6].

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REFERENCES

[1] Vanessa Cesário, Rui Trindade, Sandra Olim, and Valentina Nisi. 2019. Memories of carvalhal's palace: Haunted encounters, a museum experience to engage teenagers. In *IFIP Conference on Human-Computer Interaction*. Springer, 554–557.
[2] John Dewey. 1998. *The essential Dewey: Pragmatism, education, democracy*. Vol. 1. Indiana University Press.
[3] Matt Dunleavy. 2014. Design principles for augmented reality learning. *TechTrends* 58, 1 (2014), 28–34.
[4] Ingo Eilks and Avi Hofstein. 2015. *Relevant chemistry education: From theory to practice*. Springer.
[5] Melanie C. Green, Kaitlin Fitzgerald, and Melissa M. Moore. 2019. Archetypes and Narrative Processes. *Psychological Inquiry* 30, 2 (2019), 99–102. https://doi.org/10.1080/1047840X.2019.1614808 arXiv:https://doi.org/10.1080/1047840X.2019.1614808
[6] RB Guay. 1977. The Purdue Visualization of Rotations Test Purdue Research Foundation. *West Lafayette, IN* (1977).
[7] Jorge Martin Gutiérrez, Melchor Garcia Dominguez, and Cristina Roca González. 2015. Using 3D virtual technologies to train spatia skills in engineering. *The International journal of engineering education* 31, 1 (2015), 323–334.
[8] Ferli Septi Irwansyah, YM Yusuf, Ida Farida, and Muhammad Ali Ramdhani. 2018. Augmented reality (AR) technology on the android operating system in chemistry learning. In *IOP conference series: Materials science and engineering*, Vol. 288. IOP Publishing, 012068.
[9] Jorge Martin-Gutiérrez, Peña Fabiani, Wanda Benesova, Maria Dolores Meneses, and Carlos E Mora. 2015. Augmented reality to promote collaborative and autonomous learning in higher education. *Computers in human behavior* 51 (2015), 752–761.
[10] Sandra K Metoyer, Sarah Witham Bednarz, and Robert S Bednarz. 2015. Spatial thinking in education: Concepts, development, and assessment. In *Geospatial Technologies and Geography Education in a Changing World*. Springer, 21–33.
[11] Carla Morais. 2015. Storytelling with chemistry and related hands-on activities: Informal learning experiences to prevent "chemophobia" and promote young children's scientific literacy. *Journal of Chemical Education* 92, 1 (2015), 58–65.
[12] Emily Moyer-Gusé. 2008. Toward a theory of entertainment persuasion: Explaining the persuasive effects of entertainment-education messages. *Communication Theory* 18, 3 (2008), 407–425. https://doi.org/10.1111/j.1468-2885.2008.00328.x
[13] Farooq Mughal and Aneesa Zafar. 2011. Experiential learning from a constructivist perspective: Reconceptualizing the Kolbian cycle. *International Journal of Learning and Development* 1, 2 (2011), 27–37.
[14] Nora S Newcombe. 2013. Seeing Relationships: Using Spatial Thinking to Teach Science, Mathematics, and Social Studies. *American Educator* 37, 1 (2013), 26.
[15] Jonathan Osborne, Shirley Simon, and Sue Collins. 2003. Attitudes towards science: A review of the literature and its implications. *International journal of science education* 25, 9 (2003), 1049–1079.

[16] Janet C Read, Stuart MacFarlane, and Chris Casey. 2002. Endurability, engagement and expectations: Measuring children's fun. In *Interaction design and children*, Vol. 2. Shaker Publishing Eindhoven, 1–23.

[17] Ghassan Sirhan. 2007. Learning difficulties in chemistry: An overview. (2007).

[18] Pornpon Thamrongrat and Effie Lai-Chong Law. 2019. Design and Evaluation of an Augmented Reality App for Learning Geometric Shapes in 3D. In *IFIP Conference on Human-Computer Interaction*. Springer, 364–385.

[19] David Watson, Lee Anna Clark, and Auke Tellegen. 1988. Development and validation of brief measures of positive and negative affect: the PANAS scales. *Journal of personality and social psychology* 54, 6 (1988), 1063.

[20] Hsin-Kai Wu and Priti Shah. 2004. Exploring visuospatial thinking in chemistry learning. *Science education* 88, 3 (2004), 465–492.

Towards Identifying Augmented Reality Unique Attributes to Facilitate Chemistry Learning

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Abstract. Augmented Reality (AR) applications have the potential to improve students' Chemistry learning performance. By identifying the unique features and affordances of this technology, we can design more effective tools to facilitate the learning process of abstract concepts. We developed Periodic Fable in the Wild, an AR serious game as an instrument to conduct design-based research. The game aims to facilitate the learning of abstract concepts related to the Periodic Table by children (9 to 13 years old). We intend to optimize our game by continuing our research with our target audience, analysing their feedback, making refinements and continuing testing.

Keywords: Augmented Reality · Serious games · Spatial skills · Chemistry.

1 Introduction

Children, as young as nine years old, have already a perception of Chemistry as complex, not so attractive, less relevant to everyday life and a challenging domain [1, 2]. Some of the factors that contribute to a negative perception of Chemistry are that it demands imagination, since there is no visible or physical referent; translating 2D information into 3D mental models can lead to cognitive overload and students with low spatial skills struggle with mental models [2].

Augmented Reality (AR) uniqueness of superimposing digital information within the real environment provides children's opportunities to:

1. Engage with educational content in digital format [3] while relating them to the actual physical world [4].
2. Provide visualization of abstract and complex concepts through animations, 3D modeling and other digital information.
3. Develop broader spatial skills by using activities with 3D objects (virtual or physical), providing an effective context for teaching [5].

By developing an AR serious game to conduct design-based research, we intend to identify AR features and affordances towards facilitating the learning of abstract concepts in Chemistry. We also intend to change the negative perspective of this domain by using game design elements to engage children toward the learning content.

2 Periodic Fable in the Wild Systems Designs

Periodic Fable (PF) in the Wild is an AR serious game targeting 9 to 13-year-old children, designed to teach them basic chemistry concepts of the Periodic Table of Elements in formal and non-formal educational settings. The game's subtheme evolves around the chemical composition of some products and substances (verified and validated by a chemistry teacher and a chemistry researcher). The AR game uses a marker-based system that operates with images/patterns (scan by the mobile device) to trigger the upload of virtual information (in our case, tridimensional models, animations, text, sound and a 2D minigame). The app was developed for android mobile devices using ARCore SDK for Unity 3D.

PF in the Wild was also developed with the aim to integrate every day routine products, that children are accustomed to (water bottle, bleach, batteries, balloons), as part of the game-play mechanics. The game´s situated learning approach allows our target group to gain scientific knowledge about the chemical compounds that form the products. The goal is to achieve this by interacting with physical objects, AR technology and collaborating with other colleagues. PF in the Wild contributes to the learning process by creating meaningful connections between the content and the context.

The game starts with a tutorial that guides the user through the different game components:

1. The gathering of chemical atoms composing the product in question. The atoms are collected by scanning markers allocated in the products displayed on shelves (see Fig.1 - number 1). All the collected atoms are displayed afterward on a 2D grid (see Fig.1 - number 2). The application indicates the player when it has collected enough atoms by blocking the capture button. An animation of a character that represents an element with such atoms will also be showcase (see Fig.1 - number 1).
2. Reconstruction of chemical composition of the selected product by combining the atoms identified in the screen´s chemical structures (using a mini word puzzle kind of game). The collected atoms' icons are aligned on a simple grid and need to be connected by the participant's tip of the finger from one atom to the next. The player is guided in the sliding action by the chemical formula, which shows the order of the atoms, and it is displayed on the right side of the screen (see Fig.1 - number 2).
3. Anchoring the AR visualization in the real world. The player has to use the device camera to scan and recognize a pattern in the real-world player surrounding. The AR application will build the AR experience around that loca-

tion and allow the visualization of the tridimensional AR compound/molecular structure created by the player (see Fig.1 - number 3).

4. Conclusion of the game experience. Congratulation message and player score display appear after the AR experience. The player's score is calculated by the time they spend on each activity within the game (see Fig.1 - number 4).
5. Game reward. A Reward- Selfie screen is displayed at the end of the experience inviting the player to take a picture with all the game characters to share with family and friends (see Fig.1 - number 5).

Fig. 1. PF in the Wild game flow

To get an overall understanding of the game, we conducted a pilot study with five participants (three female and two male). Children with ages ranging from

11 to 13 played the game for about 10 minutes. Some of the comments that we gather from post-game experience interviews point to the learning potential of the game "I think this is good for learning since I need to use the right compound to keep going"; usability "it is easy and good for learning"; the repetitiveness of the game mechanics "mini-game is too repetitive." We also asked the players to think aloud and took observation notes. In this note, we observed one of the players seems lost in collecting the elements and manifested frustration by saying, "I forgot which compound I was trying to form." Nevertheless, when asked: Will you play again? all of the participants answered "yes".

3 Conclusion and Future Work

We developed an AR serious game to evaluate the features and affordance of the technology towards facilitating the learning of abstract concepts of the Periodic Table. After a preliminary pilot study with the five children, we identify game-play elements that need refinements, such as the game's repetitiveness, which we plan to address by incorporating new elements, like animations and visual feedback between each task. Also as to better guide the user towards the compound that needs to be created at the different stages of the game, we will implement the display of UI with an images of the compounds structure until the tasks are accomplished (see Fig.1, number 2 - right corner). Nevertheless, the overall players' assessment was positive and the comments oversee the app's potential as a tool to engage children with the content knowledge, in order to validate the game, further research is needed. This research's next step is concept and usability testing of the AR serious game with larger sample groups in formal and non-formal settings.

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References

1. Luraschi, Michela, Riccardo Rezzonico, and Giovanni Pellegri. "The chemist, that madman! How children perceive science." CHIMIA International Journal for Chemistry 66, no. 11 (2012): 820-825.
2. Osborne, J., Simon, S., & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. International journal of science education, 25(9), 1049-1079.
3. Thamrongrat, P., & Law, E. L. C. (2019, September). Design and Evaluation of an Augmented Reality App for Learning Geometric Shapes in 3D. In IFIP Conference on Human-Computer Interaction (pp. 364-385). Springer, Cham.
4. Cesário, V., Trindade, R., Olim, S., & Nisi, V. (2019, September). Memories of Carvalhal's Palace: Haunted Encounters, a Museum Experience to Engage Teenagers. In IFIP Conference on Human-Computer Interaction (pp. 554-557). Springer, Cham.
5. Fowler, S., Cutting, C., Kennedy, J., Leonard, S. N., Gabriel, F., & Jaeschke, W. (2021). Technology enhanced learning environments and the potential for enhancing spatial reasoning: a mixed methods study. Mathematics Education Research Journal, 1-24.

Towards Identifying Augmented Reality Unique Attributes to Facilitate Chemistry Learning

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Introduction

We developed **Periodic Fable in the Wild**, an Augmented Reality (AR) serious game as an instrument to conduct design-based research. The game aims to facilitate the learning of abstract concept of the Periodic Table by children (9 to 13 years old).

Factors that contributes to negative perception of Chemistry are:

-Demands imagination since there is not visible or physical referents [1].
-Translating 2D information into 3D mental models can lead to cognitive overload.
-Students with low spatial skills struggle with mental models [2].

Augmented Reality . (AR) uniqueness of superimposing digital information within the real environment provides children's opportunities to:
-Engage with educational content in digital format [3] while relating them to the actual physical world [4].
-Provide visualization of abstract and complex concepts through animations, 3D modeling and other digital information.
-Develops broader spatial skills by using activities with 3D objects (virtual or physical), providing an effective context for teaching [5].

Results

Pilot test (N=5), (3 female and 2 male), grade level 6 to 8th (11 to 13 year old).

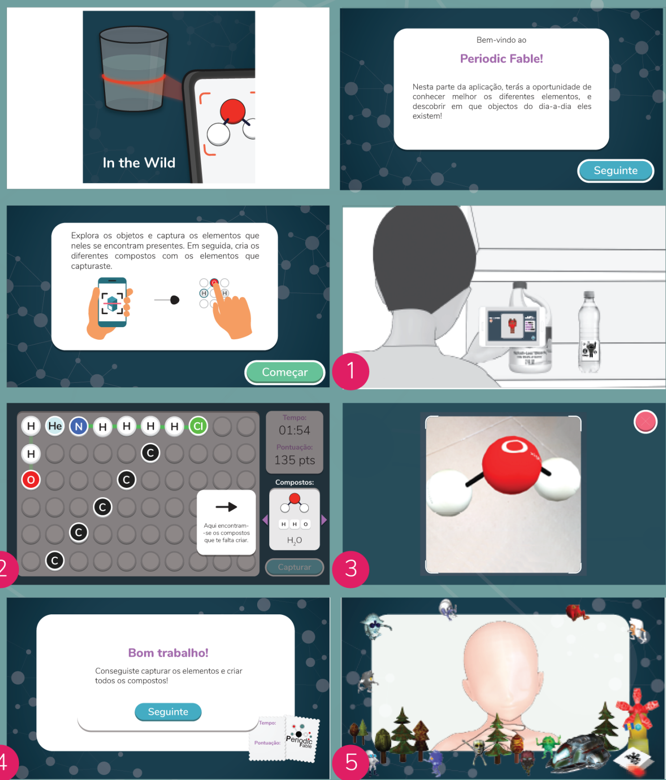
Players comments :

"I think this is good for learning since I need to use the right compound to keep going"
"it is easy and good for learning"
"minigame is too repetitive"
When asked: Will you play again? all the players answer "yes"

Conclusion

Preliminary pilot study with the 5 children, we identify gameplay elements that need refinement; nevertheless, the overall players' assessment was positive, however, due to few participants in the user study, the game prototype could not be fully validated. This research's next step is concept and usability testing of the AR serious games with larger sample groups in formal and non-formal settings.

Periodic Fable In the Wild System Design



Periodic Fable in the Wild is also a game developed with the aim to integrated every day routine products that children are accustomed to (water bottle, bleach, batteries, balloons, computer motherboard) as part of the game-play mechanics. The game´s situated learning approach allows our target group to gain scientific knowledge about the chemical compounds that form the products by interacting with physical objects, AR technology and collaborating with other colleagues.

1. The **gathering of chemical atoms** composing a certain product;
2. **Reconstruction of chemical composition** of the selected product by combining atoms;
3. Anchoring and **visualization of the tridimensional AR compound/molecular structure** created by the player (using a pattern in the real world surrounding);
4. Conclusion of the game experience. **Congratulation message and score display** ;
5. **Reward- Selfie screen** to take a picture with all the game characters to share with family and friends.

References

[1] Luraschi, M., Rezzonico, R., Pellegri, G.: The chemist, that madman!how children perceive science. CHIMIA International Journal for Chem-istry66(11), 820–825 (2012)
[2] Osborne, J., Simon, S., & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. International journal of science education, 25(9), 1049-1079.
[3] Yuen, S. C. Y., Yaoyuneyong, G., & Johnson, E. (2011). Augmented reality: An overview and five directions for AR in education. Journal of Educational Technology Development and Exchange (JETDE), 4(1), 11.
[4] Cesário, V., Trindade, R., Olim, S., & Nisi, V. (2019, September). Memories of Carvalhal's Palace: Haunted Encounters, a Museum Experience to Engage Teenagers. In IFIP Conference on Human-Computer Interaction (pp. 554-557). Springer, Cham.Fowler, S., Cutting, C., Kennedy, J., Leonard, S. N., Gabriel, F., & Jaeschke, W. (2021). Technology enhanced learning environments and the potential for enhancing spatial reasoning: a mixed methods study. Mathematics Education Research Journal, 1-24.
[5] Fowler, S., Cutting, C., Kennedy, J., Leonard, S. N., Gabriel, F., Jaeschke,W. (2021). Technology enhanced learning environments and the potential forenhancing spatial reasoning: a mixed methods study. Mathematics EducationResearch Journal, 1-24.Abdinejad, M., Talaie, B., Qorbani, H. S., Dalili, S. (2021). Student Percep-tions Using Augmented Reality and 3D Visualization Technologies in ChemistryEducation. Journal of Science Education and Technology, 30(1), 87-96

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Augmented Reality towards facilitating abstract concepts learning

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Abstract. Chemistry is often regarded as a complex and demanding subject for youth to learn, partly because of abstract concepts that are challenging to depict. These areas require spatial reasoning, defined as the ability to retain, generate and manipulate abstract visual images in space, either physically or mentally. By allowing the superimposition of virtual objects in the real world, Augmented Reality (AR) facilitates students' understanding of difficult concepts through spatial reasoning by making them visible and allowing for multidimensional perspectives. "Periodic Fable" is an AR serious game targeting 8 to 11-year-old children, designed to teach them basic chemistry concepts of the Periodic Table of Elements in non-formal settings. After designing and implementing the game, we conducted an exploratory study with 36 young participants, using a mixed-method approach. A comparative study between pre- and post-intervention questionnaires and observation results shows a positive learning outcome, demonstrating the potential of this tool in a non-formal context.

Keywords: Augmented Reality · Edutainment· Non-formal learning · Periodic Table.

1 Introduction

The acquisition and development of abstract reasoning is extremely important in children's. Great part of abstract reasoning acquisition happens during the learning process of school subjects. These subjects, involve inquiry, experimentation, evidence, the evaluation and analysis of ideas, problem-solving, creative thinking, and overall understanding of information by making connections with the real world [44]. Children's understanding of abstract concepts in STEM disciplines has been shown to increment by means of spatial reasoning [34] enabling them to reason about the space around while manipulating real or imaginary object configurations in space [7].

Playful educational experiences and games have shown positive effects in a wide spectrum of the development of cognitive skills [25, 19]. Educational games increase concentration levels and stimulate learning in children [1], allowing for

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the exploration of teaching tools such as metaphors, analogies, and the spatial manipulation of 3D objects through technologies like Virtual and Augmented Reality [42]. Virtual and Augmented Reality serious games create compelling, collaborative and participatory experiences to enhance the user's engagement and learning. These experiences can provide alternatives to a real-world environment for situated learning, allowing the user to experience a sense of "being there" while applying acquired knowledge [11]. Immersive games hold great potential for cognitive and motor development, and represent a powerful tool to facilitate the teaching of school curriculum and an effective way of acquiring knowledge within a non-formal context. Playing games is also considered a crucial activity for human development of socialization, expression, and communication skills [35]. Given these conditions, knowledge is acquired through a participatory process whereby the learner is "transformed through his actions and relations with the world"[6]. As argued by John Dewey, teaching involves "engaging children in a fun and playful environment, imparting educational content, and instigating interest in learning more"[12].

Given the possibility of transporting knowledge to other settings, Augmented Reality enables the connection between content knowledge and user context, thus making the learning more effective. Many Augmented Reality games have proved especially effective for STEM subjects. AR enables users to visualize otherwise inaccessible representations and to experiment in a low-risk and low-cost platform[3]. Augmented Reality has also been shown to be a powerful tool in the development of spatial skills, such as student understanding of structures that can be either invisible to the naked eye or spatially complex [50, 15, 47].

The Periodic Table is one of the biggest achievements in the modern sciences, not only for chemistry, but also in physics, medicine, earth sciences and biology. In 2019, the United Nations celebrated the 150th international anniversary of the discovery of the Periodic System by Dmitri Mendeleev. As a result, numerous competitions, events and museum exhibitions have been dedicated to this topic. We took this opportunity to reflect on the Periodic Table and its elements and introduce them to young children, who might have not experienced them yet in their school curricula.

In this article, we present our research based on the design and preliminary testing results of Periodic Fable, a game intended to promote non-formal learning of the concepts of the Periodic Table for 11 years old and younger children, that have not tackled "chemistry" as a school subject yet. Periodic Fable incorporates image recognition, tangible objects, 3D virtual reconstruction of models, animations, and is part of a growing number of initiatives that seek to utilize this type of technology to create awareness and engage children in non-formal science learning. The project was designed and produced to complement the celebrations of the anniversary of the Periodic Table.

2 Related Work

2.1 Learning Framework

Situated learning builds upon social learning and development theories, according to which the quality of learning depends on social interaction with the learning context[41][27][49]. Many virtual games and immersive simulations have been designed for training and education, to motivate students by providing a more immersive and engaging learning environment to support situated learning. The seamless integration of virtual content with the real environment can evoke in the users a perceptual state of non-mediation, a sense of presence reinforcing immersion [40]. AR design strategies create virtual immersive experiences and games, which are based on action and symbolic and sensory factors. Research has shown that immersion in virtual environments can enhance education by allowing for multiple perspectives of the learning content, applying situated pedagogy and transfer of knowledge [11]. Even exceptional students in formal educational settings often find it difficult to apply what they learn in class to similar real-world contexts [11]. AR allows users to discern and interact with the real environment while simultaneously receiving additional digital information into their field of perception [5]. The simulation of real-world problems and contexts can be obtained by near transfer. This assimilation of knowledge can then be transferred to other situations, allowing for the construction of more knowledge. Examples of this process can be found in game simulations for flight and surgical training, whereby the user can practice and train certain skills, making mistakes and getting positive feedback when the task is performed in a low-risk environment before transferring this knowledge to real-world situations.

Children learn by using their senses, playing and performing activities, assimilating concepts in an intuitive manner [29]. Constructivism theory argues that children learn by interacting with the physical environment, socially, and by responding to external stimuli consciously. A constructivist environment allows children to build on previously acquired knowledge, in a reflexive process directed by a teacher, parent, or colleague [52]. Likewise, learning by doing is a fundamental activity in children. It is successful when the information is comprehended and used, and this, in turn, contributes to a change, hence transformation in cognitive structure [21]. The potential of Augmented Reality and educational games is supported by constructivism theories. Learning can also benefit from novelty effects due to new technologies [38], since the excitement and curiosity of the students cause them to be more engaged and motivated.

Research shows that students' performance is affected in different variables of the learning process, while engaging in an activity individually or in a collaborative process. [2]. Some effects are related to the intrinsic motivation (enjoying the activity itself), self-efficacy (believe in the capacity to solve a task) and self-determination (decision to do something). These results have been shown in many AR experiences where the activity is performed individually, but also studies shown that there is a tendency for active exchange of knowledge while students performed an AR activity [26]. However limited of research is known about the learning efficacy when comparing both methods[32].

2.2 Augmented Reality

Augmented Reality (AR) is defined as the perception of reality that has been enhanced through computer-generated inputs and other digital information [3]. AR falls in the realms between a physical and a virtual reality spectrum, meaning that AR supplements reality, rather than completely replacing it. AR is demonstrating to hold great potential in the area of Edutainment (education and entertainment) [37]. As a pedagogical tool, AR enables critical thinking and develops creativity [51]. The continuous investment in Augmented Reality has led to a proliferation of apps in the educational realm, with an increase in off-the-shelf wearable devices, like Curioscope [9], a marker-based t-shirt that allows children to visualize 3D models of human anatomy. Elements 4D, by DAQRI, created an app for chemistry designed to simulate how elements of the periodic table react in real life [10]. Animal Alphabet uses AR Flashcards to learn letters. ZooKazam [30] and Bugs 3D [46] aim to teach about animal species. Arloon Plants [45] allows children to learn about the flora. Star Walk [48] AR app suppor ts learning about the stars, the solar system and the planets. MerchEdu allows students to explore and interact with STEM concepts using a tangible cube [33]. Despite their usefulness, however, many of the commercial AR applications targeted at children have not been evaluated for their effectiveness in learning outcomes. In addition, Augmented Reality's ability to render objects that are hard to visualize using 3D Models (simulation), makes the understanding of abstract concepts more manageable. AR can enhance learning environments, engage, stimulate and motivate students [13, 14]. In scientific subjects, complex approaches are required for the students to envision concepts like micro and macro-worlds, and its assimilation remains a difficult and challenging process. Students make observations, collaborate with others, inquire, ask questions, investigate and interpret data when engaging with the AR system [11]. Chemistry in public schools with large size classes suffers from limited resources and time available, and, as a result, some students do not have the opportunity to conduct experiments. AR simulation helps to bridge this gap, contributing to the observation of some reactions on a one- to-one basis[16]. In Switzerland, an AR virtual chemistry laboratory was created for students to view and acquire atoms through a virtual drag-and drop technique. This platform allowed students to construct their own complex molecules, developing active learning skills [20]. Besides the allowance of inquiry-based learning, using this system also helped students to be active in the learning process [8]. Low- achieving students benefit considerably by interacting with 3D models of micro-particles, better understanding the composition of substances [8]. The teaching of molecule formation, covalent bond and molecule structure using AR vs traditional methods such as a textbook, proved to be more effective in improving student performance [36]. StereoChem is a mobile Augmented Reality application used to help students understand stereochemistry, focusing on the study of stereoisomers (molecular formulas that differ in spatial orientation) to help in the perception of the 3D molecules[28]. Augmented Chemistry allows students to obtain and understand information about the spatial relations between molecules by using the input of keyboards and tangible interaction. Augmented Chemistry represents the molecules in a 3D environment, providing multiple viewpoints and control of the interactions [43].

2.3 Tangible Interfaces

The combination of tangible, physical interfaces with tridimensional virtual imagery allows children to play, engage, and have fun as they learn, facilitating the cognitive load [4] in a natural and genuine way [8].

Tangible interfaces can ease the communication of abstract concepts. This is the case of Digital MiMs, computer enhanced building blocks that support learning in mathematics, probabilistic behavior and more. Another example is ProBoNo, a software and tangible hardware prototype developed for children from four to six years of age. PrBoNo allows children to navigate virtual worlds more playfully and engagingly. A study of this system concluded that the tangible interface facilitated the transfer of knowledge acquired in a digital environment to a situation in the real world [22].

However, regarding the benefits of tangible interactions for children, Horn et Al.[24], advocate for a hybrid approach (a single interactive system that consists of two or more equivalent interfaces). Teachers and learners can select the most appropriate interaction according to the task and needs of a specific situation [24]. Moreover, Ambient Wood, a large-scale learning activity targeting 11-12-year-old children, aims to teach children about the nature of scientific inquiry by means of tangible discovery, reflection, and experimentation. A study of the system highlighted that, while tangibility per se is not enough to engage children in a task, it is crucial to have the appropriate tangible system [31].

3 Methods

3.1 System Design

Periodic Fable is a serious AR game for android mobile devices (with gyroscope, accelerometer and compass sensor), designed and produced to target 8 to 11-year-old children that come into contact with chemistry for the first time. The game developed using ARCore, Autodesk Maya, Mudbox and Adobe Photoshop, provides basic concepts about chemical elements like their symbols, atomic numbers, atomic weight, reactions with other elements, and products that contain the element. It also allows users to obtain information by scanning markers, and joining elements(depicted as creatures) to create reactions. Thus, the learning process becomes fun, engaging the students[11].

Content The content of the game was selected with the help of a Ph.D. student (in a Chemical biology related area) and two Chemistry teachers. It takes into account the knowledge of chemistry that our target audience already acquired in science classes. Children from 8 to 11 learned some basic chemistry notions while learning about topics like pollution (carbon monoxide), blood components, the atmosphere, photosynthesis (carbon, oxygen), and the cycle of water (hydrogen, oxygen), to name some. It is not until later that chemistry becomes a curricular subject. The elements selected to feature in the Periodic Fable game are the most abundant in the environment, and have compelling reactions, which makes the students more curious, inspiring them to speculate about possible combinations. The Periodic Fable design relies upon constructivism as a learning method, allowing the children to explore and interact freely with the content, thus complementing their knowledge about the chemical elements. Moreover, to create a connection between the content and the real-world, we decided to include information that could be transferred to the everyday routine of the children.

Technology/Game Mechanics The AR game uses a marker-based system and tangible cubes as part of the mechanics. The camera of the mobile phone scans a pattern/image, recognizes it, and superimposes a digital image on the screen of the device (in our case, 3D models and animations, 2D images, video, text and audio). The criteria for the selection of the equipment is based on the children's ease of access to mobile devices, their portability, and affordability. Autodesk Maya, Adobe Photoshop, Adobe AfterEffects and Unity 3D were used for the development of the game.

We designed a tangible cube as a starting point. The child has to explore each facet of the cube to gain access to different information, which allows the user physical manipulation and exploration of spatial arrangement. The decision is the result of several iterations, heuristic evaluation and small sample testing to make playing the game easy, without need for supervision (almost intuitive). Few instructions are necessary, thus avoiding cognitive overload. The game features a cube per element, and each face of the cube expresses qualities and scientific facts about that element. At the moment we have developed five cubes, corresponding to oxygen, hydrogen, carbon and nitrogen, because they are the most important elements; their covalent bond combinations are responsible for most of the biological molecules on earth. We added chlorine to the list because, like the other elements, its properties and reactions can be the most interesting and engaging for the children. In the future, we hope to develop the experience for all the elements of the Periodic Table, allowing users to position each cube in the proper location, and to construct their own physical Periodic Table.

Aesthetics Each tangible cube is dedicated to one chemical element. All the facets of each cube (used as markers) are identified with text and a 2D image of the character holding an icon indicating the type of information that will be prompted (story/book, curiosities/ question mark, combination /silhouette of a group of characters, code name, habitat/building, information / letter "i").

The 3D characters were designed taking into consideration the properties of the elements that they represent. For example, oxygen is a highly reactive element, and capable of combining with other elements. Because of this, oxygen is depicted as a friendly creature, illustrated with the code name of the symbol it represents: "O". The atomic number reflects the creature's age, and the atomic mass is indicated as its weight (see Fig. 2 number 1). We created these analogies for each element as a way to facilitate retention of the information. The creature's aesthetics, from color to animation, are also keyed to properties of the element and provided with several iterations to create more empathy with the user. The colors assigned to each character reflect the Robert Corey, Linus Pauline and Walter Koltun coloring standard convention known as CPK color, used to distinguish the atoms of chemical elements in molecular models [23] . The color scheme is associated with some properties of the elements. For example, hydrogen, a colorless gas, is white; chlorine is green; carbon is either charcoal or graphite; nitrogen is blue, since it makes up most of the atmosphere and oxygen is associated with combustion; blood is red. The inspiration for the base shape of our 3D character is the ball-and-stick model of the molecular models, whereas the body of the characters is rounded like the spheres that represented the atoms, and the arms and legs are rods that can connect and create bonds with other elements. We designed glasses for each of the individual characters, and feet, hands, and other human features to animate and give each element a different personality, so that children can associate the creatures to the element's properties, empathize and engage with them. For example, the animation for hydrogen is a calm Zen creature that floats while meditating, thus portraying its low density the fact that it is essential for life (see Fig. 1).

Fig. 1. Left to right -hydrogen, nitrogen, oxygen, chlorine and carbon

Story The concept of content-infused story games (CIS Games) builds on the fusion between games and stories to educate children [17]. Building upon this concept, a facet of the tangible cube is designed to identify with the element it represents holding a book. These animations feature in short, funny animation clips, turning into stories the outcome of joining two or more elements, and the reactions that this might trigger. For example, one of the stories dedicated to hydrogen presents the characters having fun in a water-park. Two hydrogens slide down a water toboggan and get stuck at the end of the ride. The oxygen that slides next is unable to stop hitting the two hydrogen creatures, and all turn into water. Chlorine is depicted as a superhero that saves his friend from a huge bacterium in a lab. Our aim is to make children learn and remember some of the chemical combination's outcomes and properties while having fun.

Game-play The game starts with a short tutorial that guides the children in understanding the mechanics of the game: how to explore the faces of a tangible cube, gather the elements/characters, and use them to create reactions. The participant selects one of the cubes (this selection can be random) and scans one of the markers/images on each facet, generating/uploading the information linked to that particular pattern.

Facet 1 (Information) Triggers an animation of a 3D character representing a chemical element. It also provides information about the chemical symbol, including atomic mass, chemical name and atomic number(see Fig. 2 number 1).

Facet 2 (Habitat) Uploads an image of an apartment building divided according to the blocks of Periodic Table (atomic weight and arranged in horizontal rows/periods and vertical columns /groups). We decided to showcase the different characters in this blocks/apartment location creating an analogy (apartment building vs location of the element in the periodic table), so children will assimilate the lodging of the element in the Periodic Table (see Fig. 2 number 2).

Facet 3 (Curiosities) In this facet corresponding AR scenes, 3D models of products that have that element within their composition are visualised (see Fig. 2 left-number 3).For example, we depict oxygen as being a compound that can be found on a Pepsi drink, a cleaning product like Vanish (see Fig. 2 right - number 3). Our design took a situated learning approach, whereby children can create connections with the products in their surroundings and chemical elements.

Facet 4 (Stories) Capturing facet triggers short clip (less than one minute) dedicated to that particular element reaction with another elements (see Fig. 2 number 4)

Facet 5 (Combinations) Capturing facet 5 allows the children to select and explore the reactions of different elements. We placed icons on the left side of the screen for the user to select and then explore several reactions (water, fertilizer, ammonia, fire, ozone, or to create a diamond) (see Fig. 2 number 5). Once the user clicks on the button, the application will indicate what type of creatures/elements are needed, and the user will be prompted to scan the corresponding cube with the camera of the mobile device (see Fig. 2 number 6).

If this activity is performed correctly, the interface notifies the child with a message congratulating him or her for the reaction just created (see Fig. 3 number 2) and showing the elements that were part of the reaction (Fig. 3 number 3). Then an animation of the reaction just created plays out (see Fig. 2 number 6).

Each element experience ends when the user has explored all the facets of the cube dedicated to that element, and captured its reactions. The experience can be repeated for the other cubes, until all cubes have been explored. Since no dependencies of content have been designed, each child can explore one, two, three, or all the cubes, always achieving full closure with each experience.

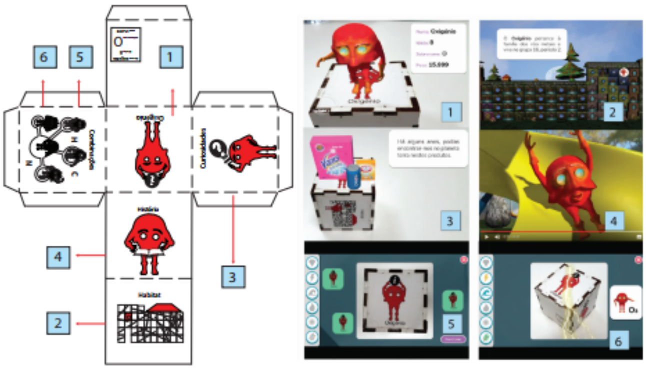

Fig. 2. Left: 2D representation of tangible cube; Right - Interaction with the faces. 1. information/animation; 2. Habitat- location of the characters/elements within the Periodic Table; 3. Products that contain the elements; 4. Stories; 5. Combination of the elements; 6. Reactions

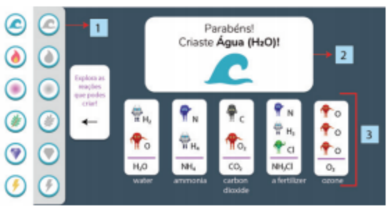

Fig. 3. 1. Icons reactions; 2. Congratulation messages; 3. Elements that participated in the reaction

3.2 Participants Demographic and Data Collection

According to school curricula in Portugal, Chemistry becomes available as a subject only during the 7th grade, where students are 12 years old. To experiment if the AR based game facilitated the learning of abstract concepts in early childhood we decided to evaluate our game with children before they had engaged with abstract concept of chemistry as a school curricular activity. We based our study at a Computer Science Club at a public school in Madeira. We engaged 36 participants, 20 females (55.6%) and 16 males (44.4%) ranging from 8 to 11 years old. The study was designed as in between study, where 18 participants experienced the Periodic Fable in pairs (50%)-Experimental Condition or Group 2, while 18 individually (50%) - Control Condition – or Group 1. The study was designed to explore if the AR game would support the learning of abstract concepts such as chemistry basic, in children with no previous exposure to the subject and to explore which interaction conditions (single or pairs) would yield the best learning outcome. The study took place during one day, on November 27, 2019.

3.3 User Technology Access

Most of the students (32; 88.9%) had access to a mobile device prior to the study, but four (11.1%) did not. 15 participants (41.7%) had access to a mobile device less than a year ago. 11 participants (30.6%) had had access to a mobile device for more than a year, 7 (19.4%) had had access to a mobile device for over 2 years, and only four (8.3%) had no access to a mobile device. 12 participants (33.3%) knew or had heard about AR technologies, while five (13.9%) had already used AR. Only four students (11.1%) had previous knowledge of the Periodic Table.

3.4 User Study Protocol

Recruitment was done through a local school at Santa Cruz, Madeira. The experimenter contacted a teacher from the school Computer Science club, explained the project's objectives and demonstrated the study procedures. Parents signed Parental Consent before the intervention, which included information about the date and time of the study. On the intervention day, we briefed the participants and asked them to answer a pre-test questionnaire, which included questions like: What happens when you combine one oxygen and two hydrogen? What is the symbol for nitrogen? What formed the ozone? What products have chlorine in them? What are the elements found in diamonds? After having answered the questionnaire, the participants were assigned randomly to one of the two groups, to avoid any bias.

Each group of participants experienced one condition. Group 1 (Control Condition) performed the intervention individually while, Group 2 (Experimental Condition) performed the intervention in pairs (see Fig. 4) While in the control condition, individual students were seated at their desks and given a set of 5 cubes and a mobile phone to explore the cubes by themselves; in the experimental condition, students sat in pairs and shared the 5 cubes and the mobile phone. Both groups of participants had to answer individually a post- intervention questionnaire with the same questions as in the pre-intervention questionnaire, but posed in different order, so as to assess the learning more accurately. The participants were monitored by three researchers during the interactions. Observation notes were taken regarding struggles with the application, the points students seemed to enjoy most, confusion with any of the tasks, and emotional reactions. The whole experience, including pre- and post questionnaires, took 30 minutes. The experiment material consisted of an android smartphone and the five tangible cubes. Data regarding usability and satisfaction on part of the students were collected using a questionnaire with a Smileyometer [39] Likert scale (it uses pictorial representation) of 5 levels - “1” for totally disagree and “5” for totally agree (see Table 1).

Table 1. Usability and engagement data results

Q#	Question	Percentage	Mean / SD
Q1	I enjoy using Periodic Fable	88.9%	4,89/0.319
Q2	It was easy to use the application	55.6%	4,39/0.803
Q3	I knew what to do during the game	75%	4,72/ 0.513
Q4	The instructions were easy to follow	61.1%	4,53/0.696
Q5	I always knew what to do during the game	52.8%	4,11/1.214
Q6	The capture of the information with the markers always worked	44.4 %	4,25/ 0.770
Q7	The camera never lost the information of the marker	55.6%	4,29/0.926
Q8	The application always read the correct marker	77.8 %	4,67/0.717
Q9	It was a great experience to play the game	88.9%	4,83/0.561
Q10	I was always performing the same action during the game	58.3%	4,36/0.961
Q11	The amount of information was enough	69.4%	4,58/0.692
Q12	The 3D objects always appeared on my mobile screen	66.7%	4,56/0.695
Q13	There was a tutorial	75%	4,67/ 0.676

Table 2. Again and Again / Engagement scale

Q#	Question	Percentage	Mean / SD
Q1	Do you want to see the animations of the elements/creatures again?	94.4%	1.06/0.232
Q2	Would you like to watch the stories again?	72.2%	1.25/0.500
Q3	Would you like to make more combinations of elements?	86.1%	0.66/ 0.398
Q4	Would you like to see the habitat of the elements again?	86.1.1%	1.08/0.439
Q5	Would you like to see more information about the elements?	80.6%	1.19/0.401
Q6	Did you learn any information from this experience?	88.9 %	1.11/ 0.319

The second measurement, related to enjoyment, was gathered through an Again-Again table. This measure is based on the knowledge that people like to do fun things again [39]. We also analyzed which part of the experience was most enjoyable for the participants by answering “Yes” as code 1, “No” code as 0, and “Maybe” as code 2 questions related to each side of the tangible cube (see Table2). To estimate gains in learning outcomes regarding the concepts of the Periodic Table, we used the multiple-choice pre-intervention and post-intervention questionnaire data. We also conducted two comparative analyses using a non-parametric test within and between groups

4 Results

The study aimed to assess whether the use of the AR Serious Game facilitates the learning of concepts related the Periodic Table. We also wanted to analyze whether interventions in pairs had higher gains than individual interventions.

The normality of the sample in terms of results was evaluated, and since the values of Skewness and Kurtosis ($p= 0.002$) showed that the assumption of normality was violated, we used a non-parametric test. For analysis within each group, we used the Wilcoxon signed rank test, with the game played individually (Control Condition or Group 1) and in pairs (Experimental Condition or Group 2). The results show that the post-intervention learning outcome is significantly higher for participants in the Control condition ($Mdn = 2$), $T= 78$, $p=0.001$, $r=0{,}54$ (large effect) as well as in the Experimental Condition ($Mdn=1$), $T=36$, $p=0.010$, $r=0.43$ (large effect). In sum, the application had a strong, positive effect in the learning of concepts about the Periodic Table in both groups (see Fig. 4).

We conducted a between group analysis – using the Mann-Whitney test – with the same conditions as above. When measuring the children’s knowledge before playing the game ($Mdn=.00$) $U= 110.00$, $p= 0.10$, $r=-0.31$(medium effect), the results show that the difference in learning outcomes between groups was not significant. However, in the post- intervention test, the children that played individually had significantly higher results than those that did the intervention in pairs ($Mdn= 1$), $U= 98.50$, $p=0.04$, $r=-2.09$ (medium effect). Contrary to the findings of Martín-SanJosé [32] individual intervention had higher learning gains that in a collaborative setting. We attribute these results to the fact that the participants that did not share the mobile device had more freedom to explore the tangible cube, controlling the areas that they wanted to visualize, the time dedicated to each area, and could repeat the tasks ad libitum (see Fig. 4).

We also performed a Whitney U analysis to evaluate if there were any gender differences in the learning outcomes. From the data, we can conclude that gender differences were not statistically significant ($U=139$, $p=.519$). The users were pleased with factors about the usability and engagement of the game (see Table 1). Question 6 (Q6) had the lowest score ($Mean=4{,}25$). Few children had difficulties when scanning the cubes images/ markers(see Fig. 4).

Related-Samples Wilcoxon Signed Rank Test Summary

		Individual intervention	Pair intervention
Within Groups Learning Outcome	Total N	18	18
	Test Statistic	78.000	36.000
	Standard Error	12.124	6.955
	Standardized Test Statistic	3.217	2.588
	Asymptotic Sig. (2-sided test)	.001	.010

Independent-Samples Mann-Whitney U Test summaries

		Pre test	Pos test
Between Groups Learning Outcome	Total N	36	36
	Man - Whitney U	110.000	98.500
	Wilcoxcon W	281.00	269.500
	Test Statistic	110.000	98.500
	Standard Error	27.842	30.415
	Standardized Test Statistic	-1.881	-2.088c
	Asymptotic Sig. (2-sided test)	.060	.037
	Exact Sig. (2 -sided test)	.104	0.44

Fig. 4. Top: Results within subject learning outcome - Bottom: Results between subjects learning outcome

The Kruskal-Wallis test results do not demonstrate any difference in the usability and engagement of the activity between the groups conditions, $\chi^2(1) = 0.22$, $p = 0.15$.

5 Discussion, Limitations and Future Work

Our results reinforce the positive effects of gaming techniques and AR technologies in the engagement and motivation of the students [4]. According to the questionnaire, the AR visualization of the animated characters/elements introducing themselves to the players was the most enjoyable part of the experience, hence we can infer that the creatures/elements captivating characterizations as funny looking, intriguingly futuristic characters was a successful factor in engaging the children(see Table 2). The participants' reactions show that they enjoy combining the elements through the cube facets that triggered the AR scenes. One of the students commented aloud "I just made water!" and another responded, "I just created a diamond!" According to the data, the 2D animated short stories about the elements were the least captivating part of the experience. Overall, the participants acknowledged that they had learned something new about the Periodic Table. The data also show that the application increased the curiosity of the children regarding other chemical elements.

The results of the preliminary study reported that our game, has positive learning outcomes regarding basic Periodic Table concepts in non-formal settings. Our results also show that there is potential in combining smart phones and Augmented Reality in non-formal spaces to facilitate the learning of content that is not available through the school curriculum, and that this helps to create intrinsic motivation towards future STEM subjects. Young students who came in contact with chemistry through the Periodic Fable game for the first time were able to learn while engaging in the activity.

Exploring all the faces of the tangible cube to gather/visualize information was an intuitive and rewarding process. Nevertheless, some technical challenges were identified regarding the ease of use of the Augmented Reality application. Technical problems such as tracking loss made the interaction difficult for some. Since our application depended on image-based tracking, the experience stopped when moving away from the marker. This was frustrating to some children who wanted to view the animations without being interrupted. Other technical limitations when using AR marker-based technology are dependency on light quality to read the images/markers; delays in the rendering of data; over-heating of the equipment; battery consumption; the need for robust equipment with the required sensors (gyroscope, accelerometer, and compass).

The results of the study enabled us to distill insights that could be beneficial when designing an AR serious game for a young audience: 1) find the appropriate pedagogical framework for the content to be delivered [18], AR benefits situated and constructive methods; 2) pay attention to the adequacy of aesthetics to the age range; 3) design analogies and metaphors carefully, ensuring that they support the mental images and the construction of ideas needed to facilitate the understanding of the concept; 5) balance the amount of information delivered with the usability load to avoid cognitive overload.

6 Conclusion

In this paper we have reported on the design and preliminary study of a Periodic Fable AR serious game designed to support children's understanding of abstract concepts such as those found in chemistry. Our study demonstrated that the AR game facilitated the understanding of chemistry and the learning of abstract concepts in non-formal settings. Further research is needed to categorize its benefits and limitations more clearly, and to develop clear guidelines and appropriate tools to address these challenges.

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References

1. Arcos, C.G., Fuertes, W., Villacis, C., Zambrano, M., Noboa, T., Tacuri, A., Aules, H., Toulkeridis, T.: Playful and interactive environment-based augmented reality to stimulate learning of children. 2016 18th Mediterranean Electrotechnical Conference (MELECON) pp. 1–6 (2016)
2. Arvanitis, T.N., Williams, D.D., Knight, J.F., Baber, C., Gargalakos, M., Sotiriou, S., Bogner, F.X.: A human factors study of technology acceptance of a prototype mobile augmented reality system for science education. Advanced Science Letters **4**(11-12), 3342–3352 (2011)
3. Azuma, R.T.: A survey of augmented reality. Presence: Teleoperators & Virtual Environments **6**(4), 355–385 (1997)
4. Billinghurst, M., Clark, A., Lee, G., et al.: A survey of augmented reality. Foundations and Trends® in Human–Computer Interaction **8**(2-3), 73–272 (2015)
5. Bower, M., Howe, C., McCredie, N., Robinson, A., Grover, D.: Augmented reality in education–cases, places and potentials. Educational Media International **51**(1), 1–15 (2014)
6. Britton, J.: Vygotsky's contribution to pedagogical theory. English in Education **21**(3), 22–26 (1987)
7. Buckley, J., Seery, N., Canty, D.: A heuristic framework of spatial ability: A review and synthesis of spatial factor literature to support its translation into stem education. Educational Psychology Review **30**(3), 947–972 (2018)
8. Cai, S., Wang, X., Chiang, F.K.: A case study of augmented reality simulation system application in a chemistry course. Computers in human behavior **37**, 31–40 (2014)
9. Curiscope: Bring learning to life. https://www.curiscope.com/. (May 2020)
10. DAQRI: Elements 4d interactive blocks. https://https://www.kickstarter.com/projects/daqri/elements-4d-interactive-blocks/. (Jan 2014)
11. Dede, C.: Immersive interfaces for engagement and learning. science **323**(5910), 66–69 (2009)
12. Dewey, J.: Liberalism and social action, vol. 74. Capricorn books New York (1963)
13. Di Serio, Á., Ibáñez, M.B., Kloos, C.D.: Impact of an augmented reality system on students' motivation for a visual art course. Computers & Education **68**, 586–596 (2013)
14. Duh, H.B., Klopfer, E.: Augmented reality learning: New learning paradigm in co-space. Computers and Education **68**(1), 534–535 (2013)
15. Dunleavy, M., Dede, C.: Augmented reality teaching and learning. In: Handbook of research on educational communications and technology, pp. 735–745. Springer (2014)
16. Edomwonyi-Otu, L., Avaa, A.: The challenge of effective teaching of chemistry: A case study. Leonardo Electronic Journal of Practices and Technologies **10**(18), 1–8 (2011)
17. Fails, J.A., Druin, A., Guha, M.L., Chipman, G., Simms, S., Churaman, W.: Child's play: a comparison of desktop and physical interactive environments. In: Proceedings of the 2005 conference on Interaction design and children. pp. 48–55 (2005)
18. Fisch, S.M.: Cross-platform learning: On the nature of children's learning from multiple media platforms. New directions for child and adolescent development **2013**(139), 59–70 (2013)
19. Fissler, P., Kolassa, I.T., Schrader, C.: Educational games for brain health: revealing their unexplored potential through a neurocognitive approach. Frontiers in psychology **6**, 1056 (2015)

20. Fjeld, M., Schar, S.G., Signorello, D., Krueger, H.: Alternative tools for tangible interaction: A usability evaluation. In: Proceedings. International Symposium on Mixed and Augmented Reality. pp. 157–318. IEEE (2002)
21. Gardner, H.: Using multiple intelligences to improve negotiation theory and practice. Negotiation journal **16**(4), 321–324 (2000)
22. Göttel, T.: Probono: transferring knowledge of virtual environments to real world situations. In: Proceedings of the 6th international conference on Interaction design and children. pp. 81–88 (2007)
23. Helmenstine, T.: Science notes – learn science do science. http://sciencenotes.org/category/chemistry/periodic-table-chemistry/page/2/ (Aug 2019)
24. Horn, M.S., Crouser, R.J., Bers, M.U.: Tangible interaction and learning: the case for a hybrid approach. Personal and Ubiquitous Computing **16**(4), 379–389 (2012)
25. Host'oveckỳ, M., Salgovic, I., Viragh, R.: Serious game in science education: How we can develop mathematical education. In: 2018 16th International Conference on Emerging eLearning Technologies and Applications (ICETA). pp. 191–196. IEEE (2018)
26. Hung, Y.H., Chen, C.H., Huang, S.W.: Applying augmented reality to enhance learning: a study of different teaching materials. Journal of Computer Assisted Learning **33**(3), 252–266 (2017)
27. Johnson, D.W., Johnson, R., Holubec, E.: Cooperation in the college classroom. Edina, MN: Interaction Book Company (1991)
28. KL, N.S., Chavan, P.S., Murthy, S.: Stereochem: Augmented reality 3d molecular model visualization app for teaching and learning stereochemistry. In: 2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT). pp. 252–256. IEEE (2018)
29. Kritzenberger, H., Winkler, T., Herczeg, M.: Collaborative and constructive learning of elementary school children in experiental learning spaces along the virtuality continuum. In: Mensch & Computer 2002, pp. 115–124. Springer (2002)
30. LLC, A.A.: Zookazam magical animals. http://www.zookazam.com/ (Jan 2020)
31. Marshall, P., Price, S., Rogers, Y.: Conceptualising tangibles to support learning. In: Proceedings of the 2003 conference on Interaction design and children. pp. 101–109 (2003)
32. Martín-SanJosé, J.F., Juan, M., Torres, E., Vicent, M.J., et al.: Playful interaction for learning collaboratively and individually. Journal of Ambient Intelligence and Smart Environments **6**(3), 295–311 (2014)
33. MergeLabs, I.: Merge edu. https://mergeedu.com/l/engage/ (2020)
34. Newcombe, N.S., Frick, A.: Early education for spatial intelligence: Why, what, and how. Mind, Brain, and Education **4**(3), 102–111 (2010)
35. Paredes, J.: Juego, luego soy. Teoría de la actividad lúdica. Sevilla: Wanceulen (2003)
36. Pasaréti, O., Hajdin, H., Matusaka, T., Jámbori, A., Molnár, I., Tucsányi-Szabó, M.: Augmented reality in education. INFODIDACT 2011 Informatika Szakmódszertani Konferencia (2011)
37. Pérez-Sanagustín, M., Hernández-Leo, D., Santos, P., Kloos, C.D., Blat, J.: Augmenting reality and formality of informal and non-formal settings to enhance blended learning. IEEE Transactions on Learning Technologies **7**(2), 118–131 (2014)
38. Radu, I.: Augmented reality in education: a meta-review and cross-media analysis. Personal and Ubiquitous Computing **18**(6), 1533–1543 (2014)

39. Read, J.C., MacFarlane, S., Casey, C.: Endurability, engagement and expectations: Measuring children's fun. In: Interaction design and children. vol. 2, pp. 1–23. Shaker Publishing Eindhoven (2002)
40. Riva, G., Waterworth, J., Murray, D.: Interacting with Presence: HCI and the Sense of Presence in Computer-mediated Environments. Walter de Gruyter GmbH & Co KG (2014)
41. Roth, W.M.: Authentic school science: Knowing and learning in open-inquiry science laboratories, vol. 1. Springer Science & Business Media (2012)
42. Shelton, B.E., Hedley, N.R.: Exploring a cognitive basis for learning spatial relationships with augmented reality. Technology, Instruction, Cognition and Learning **1**(4), 323 (2004)
43. Singhal, S., Bagga, S., Goyal, P., Saxena, V.: Augmented chemistry: Interactive education system. International Journal of Computer Applications **49**(15) (2012)
44. Squire, K.D., Jan, M.: Mad city mystery: Developing scientific argumentation skills with a place-based augmented reality game on handheld computers. Journal of science education and technology **16**(1), 5–29 (2007)
45. TM, A.: Arloon plants. http://www.arloon.com/apps/plants/ (Jan 2019)
46. TTPM, P.T.: Bugs 3d interactive boom. https://ttpm.com/p/9759/popar-toys/bugs-3d-interactive-book/ (Jan 2020)
47. Valimont, R.B., Gangadharan, S.N., Vincenzi, D.A., Majoros, A.E.: The effectiveness of augmented reality as a facilitator of information acquisition in aviation maintenance applications. Journal of Aviation/Aerospace Education & Research **16**(2), 9 (2007)
48. Vito Technology, I.: Star walk – the sky at your fingertips. https://starwalk.space/en/. (Jan 2020)
49. Vygotsky, L.S.: Thought and language (e. hanfmann & g. vakar, trans.) (1962)
50. Wijdenes, P., Borkenhagen, D., Babione, J., Ma, I., Hallihan, G.: Leveraging augmented reality training tool for medical education: A case study in central venous catheterization. In: Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems. pp. 1–7 (2018)
51. Zünd, F., Ryffel, M., Magnenat, S., Marra, A., Nitti, M., Kapadia, M., Noris, G., Mitchell, K., Gross, M., Sumner, R.W.: Augmented creativity: Bridging the real and virtual worlds to enhance creative play. In: SIGGRAPH Asia 2015 Mobile Graphics and Interactive Applications, pp. 1–7 (2015)
52. Zurita, G., Nussbaum, M.: A constructivist mobile learning environment supported by a wireless handheld network. Journal of computer assisted learning **20**(4), 235–243 (2004)

Periodic Fable Discovery: an Augmented Reality Serious Game to Introduce and Motivate Young Children Towards Chemistry

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Abstract

Children's interest in new technologies and games creates opportunities to use these tools to facilitate their thinking processes for scientific content and education, especially to support abstract reasoning in the areas of Science, Technology, Engineering, Maths (STEM). Chemistry concepts, in particular, can benefit from being presented through hybrid physical/digital interfaces. However, the actual impact of immersive gaming technologies on learning and teaching chemistry to young children can benefit from further evaluations. We developed the "Periodic Fable Discovery" AR game to fill this gap. "Periodic Fable Discovery" is an AR serious game that uses a tangible interface and storytelling to introduce and teach basic chemistry concepts to young children from 9 to 13 years old. After designing and implementing the game, we conducted a study with 30 children, using a mixed-method approach, comparing the AR game versus a traditional method of teaching activity. The results show a significant positive learning outcome, higher motivation and engagement in the AR experience.

Keywords: Augmented Reality, Serious Games, Chemistry, Periodic Table, Children

1 Introduction

Learners of Digital Era (LoDE) is a term coined by Rapetti and Cantoni to address 21st-century citizens that are used to digital technologies [77]. 21st-century children use technologies as part of their everyday routine to communicate, visualize videos, share ideas, browse different information, and play. As a result, many institutions advocate a need for a radical change in education, since many schools do not meet the needs of a new generation of 'tech-savvy' learners. These arguments are supported by several authors, declaring that the continued exposure to modern technology changes the way children behave, think and learn [3, 38, 47, 49]. Education systems and institutions are not averse to change, but these adjustments need the cooperation of other actors and stakeholders [68].

On the other hand, commercial, corporate interest has produced off the shelve educational games, although mostly lacking integrating teaching models or pedagogy assessment. Consequently, it is necessary to promote the idea of innovating learning and teaching practices, not simply introducing new technological mediums in education, but rather to educate through these tools. Furthermore, previous research identifies motivation and interest as factors that can affect the student's performance and future career choices [81]. STEM domains are viewed by students as complex and difficult subjects, leading to continued disinterest and lack of investment [21, 71, 91, 93]. Meanwhile, immersive technologies have shown positive effects in motivating children with abstract learning content in chemistry [15]. Augmented Reality's uniqueness of allowing the display of digital information within the real world facilitates the understanding of concepts without a physical referent that may be hard to depict. AR technology has been used in chemistry for the 3D visualization of structures of atoms and molecules [48] and chemical bonds [67], since these topics are essential for understanding the chemical behaviours and properties of matter [56]. Positive results reinforce the perception that AR facilitates the understanding of the spatial processes and structures of the molecules, which by conventional teaching methods, is more difficult for students to grasp [31]. However, while previous research showcases the potential of using Augmented Reality (AR) in the chemistry domain, most of this research is geared towards high school and college students. Further research is needed to understand how these systems can facilitate and engage young children in learning abstract scientific content.

Based on this notion, this paper presents the design and development process of Periodic Fable Discovery (PFD), a Tangible Augmented Reality serious game platform for mobile devices, targeting 9-13-year old children coming in contact with chemistry for the first time. The PFD follows an interdisciplinary system approach by integrating the affordances of AR and Tangible Interaction (TI) technologies, game elements (aesthetics, mechanics, story) and using a participatory design approach towards identifying the best pedagogics and methods to facilitate and engage young children with content related to the Periodic Table of chemical elements.

We reflect in accordance with the theoretical framework, the design process, and its iterations with various stakeholders. Finally, we describe our research method and analyse the system's effectiveness compared to a more traditional method of teaching/learning and children's engagement.

We contribute by:

- Providing the research community with our guidepost in the design and development of Periodic Fable Discovery (PFD).
- Reflecting upon the contributions of teachers and game designers towards facilitating and engaging young children in learning abstract scientific content about the Periodic Table of chemical elements.
- Reporting the affordances of Tangible Interaction (TI) and Augmented Reality (AR) based games to administer scientific content to young children.
- Finally, showcasing our findings from a user study with 30 participants (9 to 13 years old children) using a mix-method approach, showcasing positive significant results in the learning outcome and motivation of the app when compared to a more traditional method of teaching.

2 Related Work

Playful experiences have a positive effect on student motivation and attitudes towards the Sciences, and this can help to remedy the decreasing interest of students in scientific domains [18, 106, 107].

Edutainment, educational games (EG), game-based learning (BGL) and serious games are defined as experiences that focus on learning and educational deliverance in an enjoyable and fun manner,i.e., entertainment that embodies and facilitates a learning outcome [4, 54, 75, 85]. These experiences engage users through entertainment while intending to convey an idea, content, or even to persuade, by influencing their thoughts and actions in a real-life context, thus exceeding the self-contained scope of the game.

Besides being recreational, game-based experiences are fundamental to the psychological, physiological, and social development of a child [14, 37]. By engaging in this type of activity, children learn about themselves and others, acquire problem-solving and social skills, and enrich their creativity. "Playing is a leading source of child development, since it is a voluntary act, enjoyable in itself, and intrinsically self-motivating, making the child engage actively" [105].

Nevertheless, for a game to be successful, many elements need to be considered in the design process. Jessy Schell coined the term "Elemental Tetrad" to categorize four basic elements: technology, story, aesthetics and mechanics [86]. These items create a specific experiential flow; however, the elements cannot be independently developed since they all interrelate and need to connect. The technology is any medium that permits the game's construction, allowing or restricting certain activities. The story is a sequence of events or situations that unfolds within the game. The aesthetics have the most direct relationship with the user since it provides the visuals and tone of the game. Finally, the mechanics are the process and rules needed to achieve the game goals. Like Kalmpourtzis [40], we support the inclusion of pedagogy as another element to this equation when designing games as tools for learning (see Figure 1).

Fig. 1 Adaptation of the elemental Tetrad (Jessy Schell and Kalmpourtzis)

Balancing all these elements is a challenging process that requires an interdisciplinary approach and several collaborators like teachers, game designers, programmers, and students.

2.1 Playful Immersive Experiences In Chemistry Context

In the domain of chemistry, serious games have been explored to facilitate scientific knowledge acquisition, problem-solving skills and engagement. However, Chemistry continues to be one of the least explored fields within the STEM domains [50, 96]. As reported by Rastegarpour, H.& Marashi, P. (2012)[78], "Playing a chemistry-themed game is a relaxing experience that can motivate students to explore and use chemical concepts in a stimulating and fun way, making studying a more enjoyable task." Games developed to explore different affordances towards Chemistry already exist [19, 20, 27, 66, 67]. In particular, exploratory Augmented Reality (AR) games generate interest in discovering scientific concepts. Augmented Reality (AR) is a technology that allows the superimposition of digital information within the real-world [8].

For example, *ModelAR Organic Chemistry* allows the user to explore chemical structures (3D models) and interact with virtual objects in real space [2]. The Mix Reality (MR) *Chemistry Lab* and *HoloLAB Champions* aim to familiarize students with experimental procedures, safety and protocol knowledge while conducting experiments [27, 33]. *StereoChem* is a mobile Augmented Reality application used to understand Stereochemistry to help in the perception of 3D molecules [44]. *Arloon Chemistry* teaches students how to write inorganic formulae and chemical compounds, thus facilitating learning nomenclature [97]. *Atomicfrenzy* is a combination of AR, tangible cards, and online resources that use the mnemonic techniques to help users to learn about chemical elements [66].

Printed material to trigger the AR information is also used to aid the learning process, like in *360ed Elements AR* [101], *ANSTO XR* [69], *Aumentifylt AR Elements - The Periodic Table of Me* [7], *AR VR Molecules Editor* AR [1], *Popar Periodic Table of elements 4D smart chart* [74], *Dáskalos Chemistry* [24], *Chemistry AR+* [99], and *Immersive Chemistry AR* [61].

Some of the positive effects of the games are the better comprehension, performance and motivation of the students towards chemistry subjects. These results are linked to the technology affordance like the multimodal representation of chemical structures and phenomena, the possibility of virtual chemical experimental procedures and interaction with 3D information [44, 95].

Some serious games use visual and audible feedback, augmented by tactile (touch) feedback to increment the learning experience. Combining tangible user interfaces and AR systems can produce objects that hold natural affordances to support interactions and enable the user to acquire concrete learning experiences through active experimentation [19]. *Happy Atoms* combine a physical set of atom models with digital information, allowing the users to manually join the tangible molecules and generate more digital information through scanning [87]. Elements 4D uses tangible cubes to demonstrate a 360 view of individual chemical elements, including their respective symbol, state, color, atomic number, and mass through the mobile device's screen [20]. *ARChemEX* is a card-based or box-based marker design that reflects the users' mimic physical action (shaking and pouring) in chemistry experiments [48]. *Professor Maxwell's 4D Augmented Reality* Science Kit allows users to follow a manual in order to create new chemical compounds [62]. *Element Capsule* created small interactive toys to represent each of the 118 elements. The toys/characters are sold in capsules and provide basic information about the properties of the elements [17]. The continuous investment in AR by some of the most prominent industry players (Apple, Google, Microsoft) and children's increased access to mobile devices have contributed to the popularity and development of AR off-the-shelf science kits and products for chemistry context. However, a lack of assessment of these artifacts' effectiveness as pedagogical tools in this domain persists. AR's edutainment approach to learning and education is still relatively new and challenging, and even though we start to see more investment in this area, most of these immersive games and simulations have been carried on in a high school educational context neglecting the younger users. Also, despite a great amount of research on AR technologies and education during the last decades, a common criticism is that while educational games improve the learning interest of youth, there is little scientific design in the games, insufficient application of educational and pedagogical methods and lack of assessment tools to analyze its efficacy and impact on students [11, 49].

2.2 Pedagogical Benefits of Augmented Reality

Situated learning builds upon social and development theories according to which the quality of learning depends on social interaction with the learning context [5, 25, 82]. Constructivism theory argues that children learn by interacting with the physical environment, by connecting socially, and by responding to external stimuli consciously [108]. Experiential learning also builds upon constructivism and active learning, whereby students learn from their own experiences in a cyclical manner and without the help of an adult, constructing their knowledge [64]. The success of the learning qualities of any AR gaming experience depends on the adequacy of the interaction between all the elements (mainly cultural, physical and social)[28].

One of the benefits of AR, from a pedagogical point of view, is to provide users an opportunity to be within the context and the content at the same time [12]. This characteristic is beneficial to learners; as Dunleavy et al. demonstrated, even high achieving students in formal educational settings often find it challenging to apply what they learn in class to the real-world contexts [30]. Dunleavy et al. [30] posit that immersion in virtual environments can enhance education by allowing for multiple perspectives of the learning content, applying situated pedagogy and transfer of knowledge, leading to improved performance [41]. Many Augmented Reality and immersive simulations have been designed for training and education, to motivate users by providing a more immersive and engaging learning environment to support situated learning [29, 32, 104]. AR allows users to discern and interact with the real environment while simultaneously receiving additional digital information into their field of perception [12].

The simulation of real-world problems and contexts can be obtained by near transfer. This assimilation of knowledge can then be transferred to other situations, allowing for the construction of more knowledge. Examples of this process can be found in game simulations for flight and surgical training, whereby the user can practice and develop specific skills, making mistakes and getting positive feedback when the task is performed in a low-risk environment before transferring this knowledge to real-world situations.

AR supports many types of communication cues, immediate feedback by colleagues, and stimulates better behavior and smoother interaction among children, encouraging them to achieve higher levels of learning efficiency, engagement and enjoyment [16].

Learners receive the stimulus through the processing continuum, which contains the broad diversity of learning styles [46]. Most studies identify AR as being aligned with situated and constructivist learning theories by placing the learner within a real-world and social environment while facilitating metacognitive learning process (inquiry, active observation, reciprocal teaching and peripheral participation with multiple modes of representation) [29, 45, 94]. However, it is essential to identify different theoretical approaches when designing pedagogical tools like games and Augmented Reality experiences to facilitate children's learning process.

Extended comparative studies indicate that students learn better by using AR than printed media or desktop software, specially in visual thinking domains such as engineering graph [59], geometric shapes [80], chemical structures [56], or electromagnetism [76].

2.3 AR Technology in the context of Chemistry

M. Luraschi et al. [53] suggest that children as early as 9 or 10 year old have already established their viewpoint regarding sciences and that it remains stable until they reach secondary school. This perception will resonate in their career choices [53, 63]. Empirical evidence states that children have a negative perception of STEM domains and chemistry in particular [83, 92]. This attitude is troublesome, for it is necessary to prepare young people for a future that will require a good average of scientific and technological literacy [39, 63, 70].

Chemistry is a subject that demands student imagination to comprehend abstract concepts without visible or physical referents in the real world (atoms, molecules, chemical bonds, biochemical processes). This process is highly challenging; translating external representations like 2D visualization into 3D mental models can lead to cognitive overload, especially if the content itself is highly complex [103]. Hsin-Kai Wu and Priti Shah [103] study shows that students with low spatial skills (ability to generate and manipulate mental visual images in space) often fail at translating external representations into internal models. Furthermore, teachers and chemists struggle to communicate and transfer knowledge about chemical equations, symbolic representation, and the description of chemical changes, thus creating a barrier in the learning process [51, 98]. On the other hand, large lab-based Chemistry classes in public schools have limited resources, including time, space, equipment, and safety hazards. As a result, some students do not have the opportunity to conduct the experiments needed to develop the practical ability, creative thinking, innovation and problem-solving [102]. Previous studies showed that Augmented Reality helps to teach Chemistry by providing visualization of abstract and complex concepts through animations, 3D modeling and other digital information and data (text, audio-visual or haptics) [6, 15, 65, 88, 100]. Moreover, AR can support higher learning outcomes by providing learners with the opportunity to select and organize relevant spatial information [35]. AR technology provides the opportunity for hands-on experiments and inquiry-based action by being able to deliver " virtual" chemistry experiments in formal and informal contexts [27, 73].

3 Periodic Fable Discovery System Design

Periodic Fable Discovery is a mobile AR tangible serious game designed to teach concepts of the Periodic Table of Elements in formal and non-formal settings to 9-13 year old children. The system has been developed using a marker-based AR technology for android mobile devices using Unity ARCore SDK. The marker-base trigger works with the mobile device's camera and renders the corresponding digital information on the device's screen (see Figure 2).

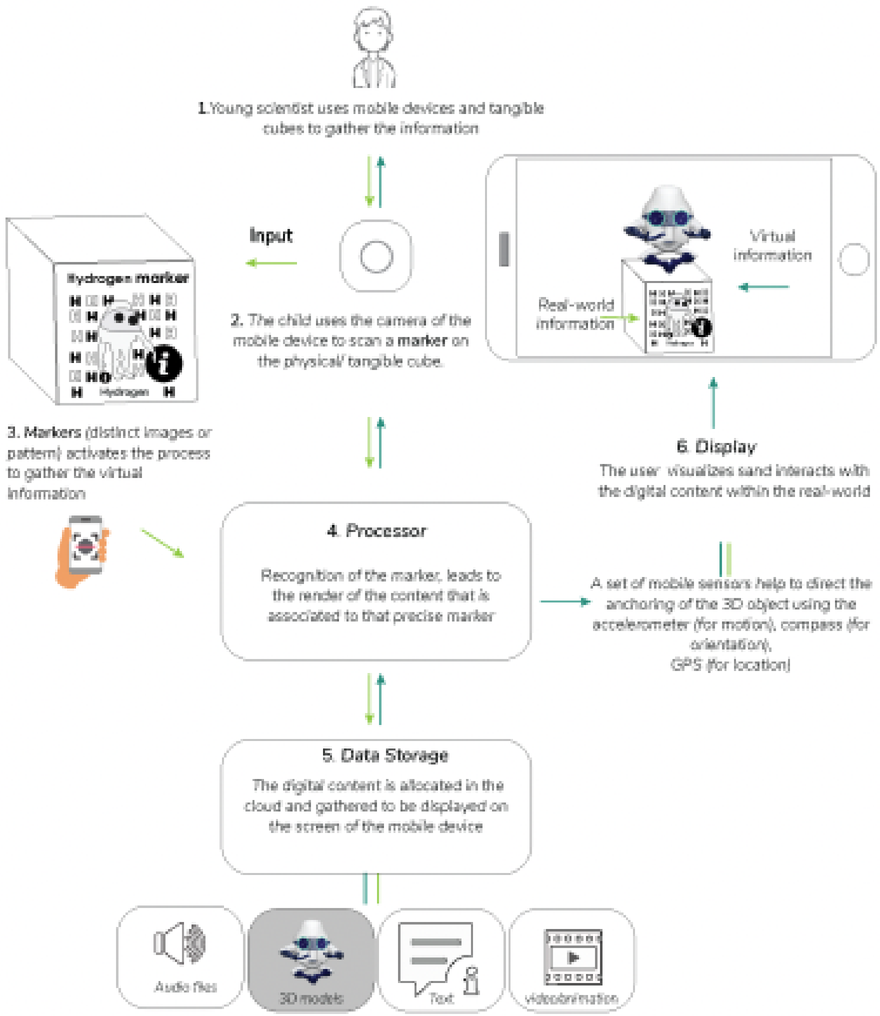

Fig. 2 Periodic Fable System Overview

The experience starts with a short introduction and tutorial that guides the children to understand the mechanics of the game: exploring the faces of five tangible physical cubes, each one identifying a chemical element represented by a distinct character with the same name as the element it represents (oxygen, hydrogen, nitrogen, carbon and chlorine) (see Figure 3).

Each cube face triggers the display of AR scientific digital information about a character embodying a chemical element's properties, location within the Periodic Table, products that contain such element, 3D animation clips about character/element reaction and reaction experiments (see Figure 6).

The information is delivered in 3D models, 2D images, animations, text and audio. The tangible cube allows physical manipulation and freedom to control the areas to explore. Since no content dependencies have been designed, each child can explore one, two, or three facets of each cube without a specific order. The design principle was to make the interaction easy to avoid cognitive overload. The game's high fidelity prototype results from several iterations with educational stakeholders, game designers and evaluation with children (see Appendix A).

3.1 Periodic Fable Discovery Learning Content

The content of this game was delineated and verified with a chemistry researcher (Ph.D. student in the area of Chemical Biology), one science and two chemistry teachers. This collaboration is crucial not only to validate the information but also to understand the characteristics of the users. The content is designed specifically for young students (ages 9 to 13 years old) who, along with the sciences classes in primary and middle school, are introduced to the designation of oxygen, carbon elements in the topics of photosynthesis, pollution, water cycle (hydrogen). In Portugal, Chemistry is introduced to students in the 7th grade (when students are approximately 12 to 13 years old), but it is only in the 8th grade (when students are approximately 13 to 14 years old) that the Periodic Table is taught as a subject.

The criteria for the five elements selected to feature in the PFD depend on their abundance in the environment and their compelling reactions. Four of these elements (oxygen, hydrogen, carbon and nitrogen) are considered most important because their covalent bond combinations are responsible for most of the biological molecules on earth. We added chlorine to the list because of its properties and varied reactions, which can be exciting and engaging for young users, encouraging them to speculate about possible combinations. The designed areas of exploration are developed in pro of these elements. A facet of the cube designated as "habitat" is used to accustom children to visualize the location of the chemical elements within the Periodic Table, also introducing the notion of the existence of other elements organized within a tabular arrangement (see Figure 6, number 5). The facet of the cube identified as "curiosities" showcases products or substances that contain such elements within their composition to create a connection between the content and the participant's environments (see Figure 6, number 2).

3.2 Storytelling development

Narrative is one of the most prominent ways of promoting effective science education [72]. Chemistry, like other STEM domains, uses narrative as a tool to motivate students in the development of inquiry-based learning approaches [72]. In the Periodic Fable Discovery, the narrative consists of five distinct stories and their chemical element protagonists, each one showcasing distinct properties and combination of the featuring chemical elements. The stories were designed to be fun, combined with an accurate depiction of the educational content. Attention was paid to time constraints; each story was condensed to less than 1 minute to optimise the children's attention span. The Oxygen's story is inspired by the photosynthesis process when oxygen molecules join carbon. The animated clip shows two oxygen molecules and a carbon molecule trying to grab a banana when they lose stability and fall on a banana tree leaf, being absorbed by it (photosynthesis process). The result is the oxygen release when the sunlight finally shines on the leaf. The Hydrogen story takes place in a water park, showing two hydrogen characters on the edge of a swimming pool. They are suddenly hit by an Oxygen character, which loses control while coming down from the toboggan. The resulting reaction and the end of the story are the hydrogen and the oxygen molecules joining together and creating water. The Nitrogen story is inspired by the Nitrous oxide, also called dinitrogen monoxide (nitrogen and oxygen), which creates laughing gas. Oxygen is showcased as boring and alone while performing on a stand-up comedy scenario, but the performance becomes funny once two Nitrogens join it. The story of Carbon shows a Hydrogen character opening and drinking a fizzy drink, leading to the release of two happy carbons. The story of Chlorine is based on its power as a cleaning agent, and it is portrayed as a superhero that smashes viruses (see Figure 3).

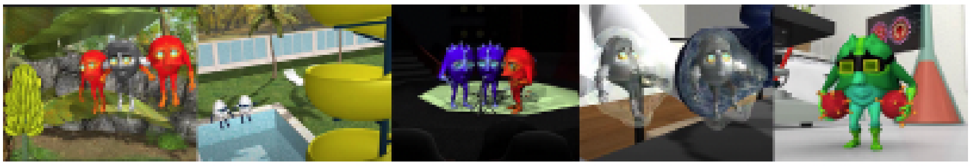

Fig. 3 Left to right: oxygen, hydrogen, nitrogen, carbon and chlorine

3.3 Aesthetics

The aesthetics of the Periodic Fable's characters are the result of several ideations cycles to create empathy with the young users (see Figure 4). The concept design process was initiated with a mood board with character sketches to gather feedback from educational stakeholders. The aesthetics of the tri-dimensional creatures are inspired by the properties of the chemical elements and the form and colour of the physical molecular model (ball-and-stick). Additional accessories were designed to highlight the anthropomorphic personification of the characters. The characters convey some of the properties of the elements within their behavior, which are designed around their chemical properties; for example, Oxygen, being highly reactive and capable of bonding with other elements, is depicted as a friendly creature. Being lighter than air, Hydrogen has a zen and relaxed attitude towards its surroundings. These analogies are used for all five elements (oxygen, hydrogen, carbon, chlorine and nitrogen). The educators' suggestions were related to appreciating the anthropomorphic features and the use of colors for the characters representing the elements. The colour of each creature follows the color code of standard convention known as CPK color (Corey, Pauline and Koltun), used to distinguish the atoms of chemical elements in molecular models [36].

Fig. 4 Character Design

3.4 Game Mechanics

The structure of the information distributed on the six different facets of the cubes is intended to make the interactions more dynamic, splitting the content into distinct and manageable learning chunks, hence easier to remember. Each facet of the cubes displays a 2D image of the character(s), icon(s) and text to identify the element represented and the area of exploration. The decision of using tangible cubes as part of the user interface on our design is because of the opportunity it offers for the development of children's spatial skills [89]. According to Paul Clifton et al.(2016), the use of tangible embodied interfaces can leverage the relationship between the body and spatial cognition to engage, support and improve spatial skills [22]. We also believe that manipulating a cube to gather information (repetitive action of rotation) is an easy task for children to perform, avoiding a long set of instructions and giving freedom and control to the participants over the information (see Figure 5).

AR also allows children to move around the space to explore and visualize different perspectives of the information, e.g., the anchoring in the real world of an AR molecular structure. The novelty of the technology of superimposing the information over the cubes can incite the children's curiosity towards finding more information and engaging them in the learning process. Druin et al. (1999) recommend to consider factors such as: curiosity, repetitive actions and need for control, when designing technological tools for children[26]. These mechanics also allow the children to explore the information at their own pace, space and time, supporting constructivism (construct the understanding of the topic by experiencing and reflecting), experiential and situated learning approach (by interacting with digital agents, artifacts and contexts).

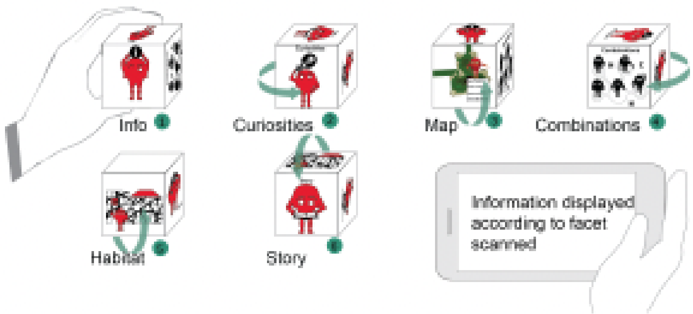

Fig. 5 Interaction with the cubes

3.5 Game Play

The player starts the game with a welcome screen, followed by a short tutorial that instructs him/her to scan the faces of each cube to explore different types of information. The player then has to click on the start button, which will activate the camera to start scanning the markers. The cubes to be explored and scanned can be selected randomly since there are no dependencies. According to the marker selected, which is identified with an icon and text indicating the type of information, the player will visualize the properties of the element (see Figure 6, number 1), products or substance with that element within their composition (see Figure 6, number 2), their location within the Periodic Table (see Figure 6, number 5), and story showcasing such element bonding (see Figure 6, number 6). The cubes share two common activities. One of the activities allows the user to select a compound or substance (by clicking on one of six icons, located on the left of the screen) and look for the appropriate element combination to create such substance (see Figure 6, number 4). Once this is accomplished, an animation and the chemical formula of the created substance is showcased. The user can also visualize and interact with the AR molecular structure by clicking on a button and anchoring the object in the real world. The other activity is unlocked once all the facets of the cubes and combinations are explored. The user needs to assemble a map using the facets that contain a piece of that map to be assembled according to the instructions and gather a reward (see Figure 6, number 3).

4 Methodology

In this study, we use design-based research (DBR), a research design method created explicitly for systematically testing theoretical interventions in the active context of educational environments [90]. The aim is to ensure that the resulting theory will have application in practice by "simultaneously and iteratively [addressing] the scientific processes of discovery, exploration, confirmation, and dissemination" [43]. The research questions (RQs) and methods are grounded in the relevant literature and practical experience with Periodic Fable Discovery.

Fig. 6 Periodic Fable Discovery Game Play

RQ1: Can mobile Augmented Reality serious games significantly affect students' learning outcomes and motivation compared to traditional teaching methods while exploring concepts about the Periodic Table?

RQ2: How can Augmented Reality serious games design elements (technology, aesthetics, story and mechanics) contribute to facilitating the learning process of scientific concepts?

Previous studies with children have been conducted comparing a more traditional method of teaching with digital games in the learning context; however, we believe that it is important to address this study in the context of younger children (9-13 years old), where textbooks continue to be the primary tools used to convey the information.

4.1 Study

A pilot study was conducted, a couple of days before the main study with five participants to identify resources, technological and time constraints. This information guided us through the different steps and helped us refine our final protocol. Even though the pilot study worked well, we anticipated the need to have more than one researcher in our main study. We were also able to estimate the time of the study for each condition (approximately 40 minutes).

Our main study gathered 30 participants (15 females and 15 males) from three different institutions and clubs: Doutorecos (summer camp), Associação Olhar (occupational social association for children) and CAB Junior Basketball (sports club). The study was carried out on the premises of the children's institutions and followed the same process at the different locations: 1) initial contact and scheduling with the institutions; 2) signed consent forms from the guardians of each participant; 3) and data gathering.

4.1.1 Data Gathering Pre-test

Both of the groups had to fill out a pre-test questionnaire to collect demographics, technology usage and knowledge of the topic. The test for the knowledge of the topic was designed by the researchers involved in the experiment and examined for content validity by a chemistry teacher. Participants were presented with five questions, each offering five answer options with only one being correct: 1. What is the symbol for oxygen? 2. What type of compound results when you mix hydrogen and oxygen? 3. What is the chemical formula for ozone? 4. What product contains chlorine? 5. Which element is responsible for diamonds? Participants were awarded five points for each correct answer, and "0" for each wrong answer. The "5" point reward provided the researcher with greater discrimination to reflect on the variation in performance among participants.

The same questionnaire (questions randomly ordered) was applied after the intervention in a post-test to assess the effectiveness of the interventions. We also conducted a final post-test, using the same questionnaire to evaluate the student's retention and recall of the information (sometimes referred as week-after test or evaluation of knowledge of the topic-retrieval/recall test). However, since the study took place at a summer holiday club, attendance was not required and as a result, many participants of the study did not came back on the week that we conducted the week-after test. As a result, our sample group was too small and we decided not to analyse or report the the week-after test results.

4.1.2 Intervention

The participants were randomly separated into two groups (one for each condition); one group used AR (experimental condition) and the other a textbook (control condition)(see Figure 7). The participants using the AR applications sat at a table where the tangible cubes were displayed (five cubes for each participant). The researchers handed each participant a smartphone (Samsung Edge S7) with a previously installed application. They were instructed to click on the app, follow the tutorial and freely explore the content. The participants were also informed to raise their hand in case of any doubt or upon finishing the game. Once the game was finalized, the researcher used the same smartphone to conduct the post-test questionnaire, created using Google Forms. A similar process was followed for the experimental condition, with the difference of the resource used, which was a textbook. The textbook provided the same information as the game, like the narrative of each story in written format using some images (clips gather from animations in the app), displaying the actions about the covalent bonding of water, ozone, diamonds, ammonia and carbon dioxide. Furthermore, it also showed images (once again gather from the app) of the molecular structures of the combined elements, products and substances that contain such chemical elements, replicating the same information as in the cubes (see Figure 8).

4.1.3 Data Gathering Post-test

In education, motivation can be defined as the desire that the individual has to engage in a learning process [23]. To identify the weaknesses and strengths of our design in motivating the children to learn, we conducted an *Instructional Materials Motivation Survey (IMMS)* [52], which is based on the Attention, Relevance, Confidence, and Satisfaction (ARCS) motivation model [42]. This particular instrument has been validated by several research studies using technology as a motivational factor in learning [9, 34, 58]. Since our users were not English speakers, we adapted a translated version [84]. Data were collected using a questionnaire with a Smileyometer [79] Likert scale (it uses pictorial representation) of 5 levels: "1" for totally disagree and "5" for totally agree.

We aimed to assess if the design of the learning activities captivated participants' attention, the relevance of the learning content as well as student confidence and satisfaction after completing the activities.

The system's usability was measured through the *System Usability Scale (SUS)* [13] questionnaire. Since our users were not English speakers, we used

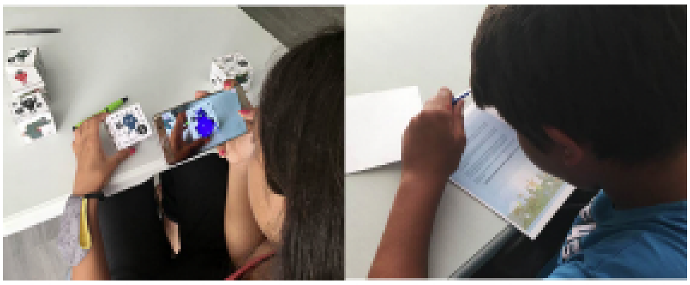

Fig. 7 left: Experimental condition - right: Control condition

a validated Portuguese version [60]. Data was again collected using a questionnaire with a Smileyometer [79]. Likert scale of 5 levels - "1" for totally disagree and "5" for totally agree. We gather subjective assessments of usability to identify the efficiency, effectiveness, learnability (questions 4 and 10) and users' satisfaction in regards to our system (see Table 2). The scale uses reverse form in some questions (2, 4, 6, 8 and 10) as to avoid bias.

In our study, we employed the *Again-Again* tool to assess users' post-activity enjoyment levels. Participants were asked to indicate their willingness to replay the game by selecting one of the following response options:"Yes," "No" or "Maybe."

Qualitative data was also collected by observation using a guideline by Devan Scheme [10] and semi-structured interviews. Some of the observation guidelines were related to execution problems, impatience (repeatedly clicking or expression), stopping the activity before reaching the final goal, doubt, surprise, unclarity as to whether the action was appropriately executed, difficulty, puzzlement when executing the action, being bored, being unable to perform the task without help, and comments while experiencing the activity. The interviewees were selected randomly, with open questions about the activity that had just been performed.

Two researchers were involved in the study; one observed and took notes during the intervention and the other supported and helped the participants in case of technical difficulties. In the end, the researchers interviewed 9 participants from the AR activity.

Finally, a comparative analysis was undertaken to determine the participants' learning outcomes between the participants who used the AR app versus those who used the textbook (between-subjects analysis). We also examined and compared pre and post-tests to assess the learning differences between groups (within-subject analysis).

For Data Analysis, we used the Statistical Package for Social Science (IBM - SPSS) to compare and measure the results of the data gathering (means, standard deviations).

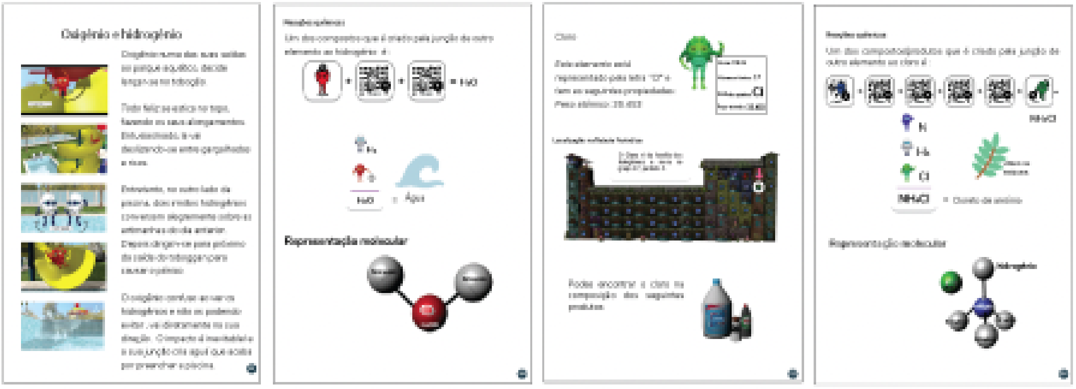

Fig. 8 Example of some of the information provided in the textbook

5 Results

In Portugal, the school system is organized as pre-school (3-5- year old), primary (6-14) and finally secondary grade level (15-18). Primary education is organized in three cycles (grades 1-4, 5-6, and 7-9). According to the demographic results our users were mostly fifth-grade level students (53.3%); others were in the sixth-grade (26.7%), seven (10%), and eight (10%) grades. The majority of the participants (13) were 10 years old (43.3%); six were 9 (20%); six were 11 (20%); three were 12 (10%); two were 13 (6.7%). All the users had access to or owned a mobile device. Most participants were unfamiliar with Augmented Reality (56.7%), and only 11 participants had used it previously (36.7%). We also asked the students about their familiarity with the content: "Do you know or have you heard about the Periodic Table of Elements?" Ten students (33.3%) responded "yes."

5.1 Learning Outcome

A Shapiro-Wilk's test ($p > 0.05$) and a visual inspection of histograms, normal Q-Q plots and box plots showed that the difference of post-pretest results was normally distributed for both methods, Textbook and AR approaches, with skewness of 0.412 (SE=0,580) and kurtosis of 0.010 (SE=1.121) for textbook method and skewness of 0.034 (SE=0.580) and kurtosis of 0.047 (SE=1.121) for AR method. Since normality is assumed, we identify the parametric test as the tool for our analysis. To evaluate the differences in the efficiency of learning outcomes, we used the total score (0 - 25) of the post-test minus the pre-test score (0 -25). We evaluated the difference of these results using an independent T-test to compare the learning effect of the participant using the AR method compared to the participants using the textbook method. The experimental group that used the AR app as their method of learning had higher learning outcomes (M=11.67, SD=6.98) than the group that used a Textbook as their method of learning (M=6.67, SD=5.56), resulting in a mean increase (M=5.00, SD=2.306). The difference between means was significant,

Table 1 Learning outcome (between-subjects)

Method	AR	Textbook	Sig. (2 tailed)	Effect size
Results	(M=11.67, SD=6.98)	(M=6.67, SD=5.56)	0.03	r=.39

Table 2 Usability Results

Q#	Question	Mean	SD
Q1	I think that I would like to use Periodic Fable frequently	5.00	0.000
Q2	I found the system unnecessarily complex	4.40	1.242
Q3	I thought that Periodic Fable was easy to use	4.67	1.047
Q4	I would need the support of a technical person to be able to use this app.	4.27	0.884
Q5	I found the various functions in this app. were well integrated	4.00	1.254
Q6	I thought there was too much inconsistency in this application	4.60	0.828
Q7	I would imagine that most people would learn to use this app. very quickly	4.40	0.910
Q8	I found the system very cumbersome to use	4.53	0.915
Q9	I felt very confident using Periodic Fable	4.60	0.507
Q10	I needed to learn a lot of things before I could get going with using the app.	4.40	1.242

$t(28) = 2.16$,($p=0.03$) $p \leq 0.05$, two-tailed. The effect size is $r=.39$ representing a medium effect (see Table 1).

We also conducted a repeated measures test (since participants had contact with the learning content before the experience and during the experience) to evaluate the effect of the activity in both groups, using Paired sample statistic analysis. The total score of the pre-test (0 - 25) and the post-test (0-25) was again used. The mean number of post-test (M=13.67, SD=6.68) was higher than the mean for the pre-test (M=4.50, SD=4.01), resulting in a mean increase (M=9.167, SD=6.706). This increase was statistically significant, $t(29) = 7.48$, $p < 0.001$, two-tailed. The effect size r=0,45 represents a fairly substantial effect. In the specific case of Periodic Fable, constructivism /experiential and situated learning proved to be valid and valuable approaches (RQ2). The Usability questionnaire was applied only for the participants that used the system, n=15. Usability standards are supported by the Cronbach's alpha coefficient report of $\alpha > 0.88$.

5.1.1 Usability

The Usability and learnability dimension of the system is very positive (see Table 2). Since some questions were inherently negative (Q2,Q4,Q6,Q8 and Q10), before analysing the results, we reverse them. Learnability factors (involving question Q4 and Q10) mean (M=8.66, SD=1.91) imply that the participant's interaction with Periodic Fable was easy. The Usability factor (Q1,Q2,Q3,Q5,Q6,Q7,Q8 and Q9) means (M=36.20 , SD=5.36) showed that the system's acceptance was very high. The average SUS score for our system is 87.1 > 68), which is very positive and considered over average.

Again-and-Again table results to the question: Would you like to repeat this activity again? showed a higher enjoyment among the participants using AR as their method to learn (MD=1.20, SD= 0.41) than the ones using Textbook (M=1.07 SD=0.59).

5.1.2 Motivation

The overall reliability of the scales on standardized Cronbach alpha was 0.95 (n=30 on 36 items) and the internal consistency for all IMMS Scale was 0.75, which suggested good reliability of the IMMS result. The Cronbach's alpha values also of the four dimensions were 0.843, relevance 0.857, confidence 0.857 and satisfaction 0.853, respectively.

Results from IMMS displayed higher motivation to learn, from the experimental group (that used Periodic Fable) (M=161,93, SD=15,243) in comparison to those that used the traditional method (the textbook) (M=142,666, SD =11,505). Analysis of the four motivation factors underlying user motivation showed that AR-based learning activities fostered higher levels of attention, relevance, confidence and satisfaction than traditional teaching activities. All the factors (relevance, confidence and satisfaction), except for attention, showed significant effects when compared to the traditional method (see Table 3). We believe that this positive outcome from the Periodic Fable experience results from the capability of the AR system to visualize the learning content in real-world contexts. Following a constructivism approach, the participants interpret the information through observation and are proactive in the learning experience by performing practical tasks to access the learning content. These results also could be associated with factors, which according to Thomas Malone, triggers intrinsic motivation (internal motivation to do something) like challenge, curiosity, control and fantasy [57].

Periodic Fable mechanics challenge the participants to find and combine the appropriate elements to create a reaction; use fantasy in the characters with analogies to the elements; users have unrestricted control of the information and decide which elements and areas to visualize and finally, the use of stories and AR technology can inspire the children curiosity. Unblocking the last facet of the cube to assemble a map and then reach the end of the game could also contribute to extrinsic motivation (a means to reach a goal); however, further research needs to be conducted to corroborate these statements. We also conducted a correlation test to perceive if there was a relationship between the variables motivation, engagement and the participant learning outcome performance. Based on the results obtained, there is a significant correlation between the variables in both conditions. In the group that used the AR application there was statistical significant between motivation and learning outcome ($r= .732$, $n=15$, $p=0.002 \leq 0.05$), engagement and learning outcome ($r= .634$, $n=15$, $p= 0.011 \leq 0.05$) and also the motivation and engagement ($r= .767$, $n=15$, $p=0.001 \leq 0.05$). In the group that used the textbook we also found statistical significant between motivation and learning outcome ($r= .712$, $n=15$, $p=0.003 \leq 0.05$), engagement and learning outcome ($r= .620$, $n=14$, $p= 0.014 \leq 0.05$). However, there was not statistical significance between motivation and engagement ($r= .390$, $n=15$, $p= 0{,}151 \geqslant 0.05$) (see Table 4 and 5).

Regarding the acceptance of the system – motivation and enjoyment –the qualitative results from the informal interviews are aligned with the results

Table 3 IMMS measurement data results

		Textbook		AR		
IMMS measurement	n	M	SD	M	SD	t
Attention	15	47.13	3.889	52.53	6.357	$0.063 \geq 0.05$
Relevance	15	35.73	2.987	39.80	4.828	$0.029 \leq 0.05$
Confidence	15	37.13	3.461	41.73	3.751	$0.023 \leq 0.05$
Satisfaction	15	22.67	3.716	27.87	2.503	$0.003 \leq 0.05$

Table 4 AR correlations data results

		Learning outcome	Engagement	Motivation
Learning outcome	Pearson correlation	1	.634**	.732**
	Sig. (2 -tailed)		.011	.002
	N	15	15	15
Engagement	Pearson correlation	.634 **	1	.767**
	Sig. (2 -tailed)	.011		.001
	N	15	15	15
Motivation	Parson correlation	.732**	.767**	1
	Sig. (2 -tailed)	.002	.001	
	N	15		

Table 5 Textbook correlations data results

		Learning outcome	Engagement	Motivation
Learning outcome	Pearson correlation	1	.620**	.712**
	Sig. (2 -tailed)		.014	.003
	N	15	15	15
Engagement	Pearson correlation	.620 **	1	.300
	Sig. (2 -tailed)	.014		.003
	N	15	15	15
Motivation	Parson correlation	.712**	.390	1
	Sig. (2 -tailed)	.003	.151	
	N	15	15	15

from the questionnaires in proving the Periodic Fable is a highly appreciated and engaging system to learn about chemistry domains. The children were excited about almost all the system features. When asked what they liked the most, around 80% answered "Everything!". More articulated participant's answers stressed different aspects of the system: "The creatures are so cute!"; "To see that when I scanned the image something happened!"; "I like to watch the videos and learn about the elements"; "I like when the creature moves and does stuff"; "I like to put together things and make reactions"; "To view the curiosities and videos." When asked "What didn't you like?", the majority answered "Nothing!". One participant replied: "The app keeps closing," and another said: "Sometimes I lost what I was looking at." We also asked if they thought the app would help them in the school and if they would like to keep using AR in their learning activities. 100% replied "Yes." Our last question was If they could change anything, what would it be? None wanted changes, except for a student who said afterwards: "Perhaps the color of the characters because oxygen is air and so it should be blue." During the observation, we also gathered comments like: "I just created water, whoa!"; "I want to see oxygen now"; "This is cool!"; "The creature disappeared, oh!"; "I want to touch nitrogen!". Their facial expression were also of excitement and satisfaction. While watching the story clips and characters animations, more than half of the participants were eager to keep visualizing the story of each one of the elements. They rotate the cubes to look for the markers with icons dedicated to that area of exploration and scanned them. When finishing viewing the animation clips, the children would look around for their colleagues and smile. We also observed that two participants showed frustration because the rendering of the information took longer (oxygen info). We attribute this to the system not recognizing the markers because of light conditions and the image on the oxygen cube not containing as much detail as others. However, as reported in previous studies [55], technical problems and usability issues can reduce engagement, especially for younger users. In this particular case, the game-play flow was interrupted, leading to the participants' reaction. One participant also complained that the mobile device was very hot, and sometimes the program application crashed.

6 Discussion

The specific research questions of this study aim to understand whether Augmented Reality serious games while exploring concepts about the Periodic Table affect learning outcomes and student motivation compared to traditional teaching methods (RQ1). We also sought to investigate, how can AR serious games design elements (technology, aesthetics, story and mechanics) contribute to facilitating the learning process of scientific concepts?(RQ2).

Quantitative and qualitative positive results confirm that children can benefit from the affordance of Augmented Reality games to explore content in the chemistry domain for the first time. The visualization of 3D information, instead of using the printed information of the textbook, resulted in a more effective method for the understanding of the content administrated, similarly to the findings of P.Maier and Klinker [56]. While the participants that used the textbook had to rely in the mental images and the reading of the material to understand the information, the experimental group transfer of information was facilitated by the visualization of the content using the AR technology.

PFD provided students with a unique and immersive learning experience, especially when it comes to visualizing complex concepts such as molecular structures. By using AR, students can view phenomena from different angles and perspectives, including depth, which can help them better understand the spatial relationships between atoms within a molecule. This type of interactive learning can also help students avoid common misconceptions and deepen their understanding of the subject matter. By experiencing these concepts in a 3D space, students can engage with the material in a more tangible way, which can help increase their retention and comprehension of the subject matter.

Using a participatory design approach towards the use of proper analogies, aesthetics, the selection and validation of the information taking into consideration the different educational stakeholders was crucial in the effectiveness of the Periodic Fable. Children's learning motivation towards the periodic table also showed significant statistical results advocating that AR game-based applications are more likely to motivate the learning activity than a more traditional method. These results are consistent with results of other studies that claim that AR-based applications promote higher levels of motivation than traditional methods of teaching.

We also believe that the higher learning outcome is the result of the game balance of the elements corroborating Jessy Schell [86] claims, whereby each game element is part of a whole system and support each other as to help the user experience. The game mechanics with a constructivism approach provided freedom and control over the time and type of information that the user wanted to explore, allowing a pro-active and dynamic learning process. By scanning markers and revealing information through AR, students can have a more interactive and engaging experience with the learning content, which can help pique their interest and encourage them to explore it further leading to better retention of information. By using PFD, students can view information at their own pace and in a way that is tailored to their individual learning style having the ability to view information multiple times, which is particularly beneficial for students who may need extra time to process or review the content knowledge. This can help to reinforce their understanding and consolidate their knowledge, leading to better long-term retention of content.

PFD also provides the opportunity for the participants to view the information in different levels simultaneously (macroscopic, microscopic and representational), helping to solidify the students understanding of the concepts.

The use of analogies, fun stories, and links to the children's environment (routine products) also contributed to their continued desire to explore the different areas. The use of simple icons and images to illustrate how to interact with the areas of exploration avoided the employment of extended written instructions, making the user's focus on the content and facilitating the mechanics of the game-play. The aesthetics of the characters and animations were appealing, hankering the children's interest in viewing the elements' representation by rotating the cubes to gather the corresponding marker. The observation confirms their enthusiasm once the stories and other digital information are visualised. There seem to be compelling reason to argue that an ideal entertainment and learning experience is the result of the combination of pedagogic (using the collaboration of educational stakeholders) delivered with the support and adequacy of game balance elements (technology, mechanic, aesthetics and storytelling).

7 Limitations and Future Work

Some limitations of our research are related to the technology, especially the malfunctioning of some markers affected by the light conditions, making it sometimes difficult for the participants to upload the information and creating frustration. This is a significant issue because of the young age of the participants, where frustrations and negative experiences can bias their attitudes towards the subject or the technology in the future. Luckily in our study, only two users among 30 were affected by this issue; nevertheless, consideration should be taken towards this potential problem in the future. Moreover, one user in our study reported the overheating of mobile devices when using AR, and in this instance, it caused the system to crash. This episode highlights how special care and constant supervision of the equipment must be in place during these events. Furthermore, if the system crashes because of the device's overheating, a substitute device should be provided to the user so as not to ruin his/her experience.

We believe that this work will benefit from future studies with a larger sample group and expanding our age gap. In future studies, we also envision assessing and comparing the effects of the mediums per se (textbook, AR and VR) as factors that can affect the learning outcome and engagement of the participants.

8 Conclusion

Based on the results presented in this study, we concluded that the AR-based edutainment application Periodic Fable was more effective than the traditional textbook method of teaching chemistry to young first-time learners of the subject. Period Fable promoted students' knowledge of basic principles of the Periodic Table and fostered motivation toward the instructional material. The results also suggest that AR edutainment can be an effective learning tool in non-formal learning contexts. We believe that the playful approach to teaching chemistry to young children will help demystify the perception of that subject as difficult and facilitate their learning experience. We also propose that to establish a positive role of immersive technologies in education and improve their effectiveness, we need to design the scientific content with reasonable pedagogical goals according to the cognitive development and cultural reality of the students, understand the balance between the game elements, and finally evaluate and verify the effectiveness of the tools according to learning goals.

Finally, we advocate for the need for further studies investigating AR potential in young children's scientific learning environments, long-term retention and novelty effect of the technology. The study highlighted the need for strategies for attendance on non-formal context studies that required more than one session (for example, a week post-test questionnaire). Our research will benefit from testing long-term retention .

In the future, we plan to extend the Periodic Fable experience to all the chemical elements, allowing users to position each physical cube within the proper location and to construct their own physical Periodic Table.

9 Selection and Participation of Children

Prior to conducting the study, we contacted the Regional Secretary for Education, Science and Technology of Madeira to approve the studies. The Consents forms, study protocols and questionnaires were analyzed and approved by this entity to conduct the studies at the different institutions. Since the studies were conducted in a non-formal educational context, we also gathered the approval of the coordinators of each institution where the studies took place.

The recruitment was done through three different institutions: Doutorecos (summer camp), Associação Olhar (occupational social association for children) and CAB associação desportiva (sport club). We contacted the coordinators from the different institutions, showcased the AR experiences and guided them through the study design and procedure. We sent an informed parental consent form which, besides requiring approval for the study, photos and video recording, included a brief description of the study. The parents were also informed about the confidentiality of the data. We relied on the coordinators to gather information regarding participants with special needs and to collect the signed forms.

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11 Statements and Declarations

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References

[1] 000 AIVS (2020) AR VR Molecules Editor. https://apps.apple.com/us/app/ar-vr-molecules-editor/id1287093721

[2] Alchemie (2020) Modelar. https://www.alchem.ie/

[3] Anderson A (2019) Virtual reality, augmented reality and artificial intelligence in special education: a practical guide to supporting students with learning differences. Routledge

[4] Anikina O, Yakimenko E (2015) Edutainment as a Modern Technology of Education. Procedia - Social and Behavioral Sciences 166(Procedia - Social and Behavioral Sciences 166:475-479):475–479. https://doi.org/10.1016/j.sbspro.2014.12.558

[5] Arnseth HC (2008) Activity theory and situated learning theory: contrasting views of educational practice. Pedagogy, Culture & Society 16(3):289–302

[6] Asyiah EN, Irwansyah FS, Farida I (2019) The making augmented reality technology-based learning media in molecular hybridization concept. J Phys Conf Ser 1402(5):055045. https://doi.org/10.1088/1742-6596/1402/5/055045

[7] Augmentifyit (2020) Aumentifylt AR Elements, The Periodic Table of Me. https://augmentify.myshopify.com/products/augmentifyit-ar-elements-the-periodic-table-of-me

[8] Azuma RT (1997) A survey of augmented reality. Presence: teleoperators & virtual environments 6(4):355–385. https://doi.org/https://doi.org/10.1162/pres.1997.6.4.355

[9] Bacca Acosta JL, Baldiris Navarro SM, Fabregat Gesa R, et al (2014) Augmented reality trends in education: a systematic review of research and applications. Journal of Educational Technology and Society, 2014, vol 17, núm 4, p 133-149

[10] Barendregt W, Bekker MM (2006) Developing a coding scheme for detecting usability and fun problems in computer games for young children. Behavior research methods 38(3):382–389

[11] Bi T, Song S (2011) Problems and solutions of educational game development. In: 2011 International Conference on Consumer Electronics, Communications and Networks (CECNet), IEEE, pp 3364–3367

[12] Bower M, Howe C, McCredie N, et al (2014) Augmented reality in education–cases, places and potentials. Educational Media International 51(1):1–15

[13] Brooke J, et al (1996) Sus-a quick and dirty usability scale. Usability evaluation in industry 189(194):4–7

[14] Butterworth MGeorge. & Harris (1994) Principles of developmental psychology. Psychology Press Ltd (ISBN 0-86377-280-3):51

[15] Cai S, Wang X, Chiang FK (2014) A case study of Augmented Reality simulation system application in a chemistry course. Computers in Human Behavior 37:31–40. https://doi.org/10.1016/j.chb.2014.04.018

[16] Campos P, Pessanha S, Jorge J (2011) Fostering collaboration in kindergarten through an augmented reality game. International Journal of Virtual Reality 10(3):33–39

[17] Capsulate AT (2020) Capsulate toys. https://www.springwise.com/new-toy-uses-ar-teach-elements

[18] Chen P, Liu X, Cheng W, et al (2017) A review of using augmented reality in education from 2011 to 2016. Innovations in smart learning pp 13–18

[19] Chen R, Wang X (2008) Tangible augmented reality for design learning: An implementation framework. CAADRIA 2008 - The Association for Computer-Aided Architectural Design Research in Asia: Beyond Computer-Aided Design pp 350–356

[20] Chen SY, Liu SY (2020) Using augmented reality to experiment with elements in a chemistry course. Computers in Human Behavior 111:106418. https://doi.org/https://doi.org/10.1016/j.chb.2020.106418

[21] Chi S, Wang Z, Liu X, et al (2017) Associations among attitudes, perceived difficulty of learning science, gender, parents' occupation and students' scientific competencies. International Journal of Science Education 39(16):2171–2188

[22] Chu JH (2016) Design space for tangible and embodied interaction with cultural heritage. In: Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems, pp 27–28

[23] Colakoglu OM, Akdemir O (2012) Motivational measure of the instruction compared: Instruction based on the arcs motivation theory vs traditional instruction in blended courses. Turkish Online Journal of Distance Education 11(2):73–89

[24] Cortex P (2020) Dáskalos - chemistry. https://prefrontalcortex.de/en/projects/daskalos/

[25] Davydov VV (1995) The influence of ls vygotsky on education theory, research, and practice. Educational researcher 24(3):12–21

[26] Druin A (2002) The role of children in the design of new technology. Behaviour and information technology 21(1):1–25

[27] Duan X, Kang SJ, Choi JI, et al (2020) Mixed Reality System for Virtual Chemistry Lab. KSII Transactions on Internet and Information Systems (TIIS) 14(4):1673–1688. https://doi.org/10.3837/tiis.2020.04.014

[28] Dunleavy M (2014) Design principles for augmented reality learning. TechTrends 58(1):28–34

[29] Dunleavy M, Dede C (2014) Augmented reality teaching and learning. In: Handbook of research on educational communications and technology. Springer, p 735–745

[30] Dunleavy M, Dede C, Mitchell R (2009) Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. Journal of science Education and Technology 18(1):7–22

[31] Fatemah A, Rasool S, Habib U (2020) Interactive 3d visualization of chemical structure diagrams embedded in text to aid spatial learning process of students. Journal of Chemical Education 97(4):992–1000

[32] FitzGerald E, Ferguson R, Adams A, et al (2015) Augmented Reality and Mobile Learning:. International Journal of Mobile and Blended Learning 5(4):43–58. https://doi.org/10.4018/ijmbl.2013100103

[33] Games S (2021) Hololab champions. https://www.schellgames.com/games/hololab-champions/.

[34] Green M, Sulbaran T (2006) Motivation assessment instrument for virtual reality scheduling simulator. In: E-learn: World conference on e-learning in corporate, government, healthcare, and higher education, Association for the Advancement of Computing in Education (AACE), pp 45–50

[35] Habig S (2020) Who can benefit from augmented reality in chemistry? Sex differences in solving stereochemistry problems using augmented reality. Br J Educ Technol 51(3):629–644. https://doi.org/10.1111/bjet.12891

[36] Helmenstine T (2019) Science notes – learn science do science. http://sciencenotes.org/category/chemistry/periodic-table-chemistry/page/2/

[37] Hinske S, Langheinrich M, Lampe M (2008) Towards guidelines for designing augmented toy environments. ResearchGate pp 78–87. https://doi.org/10.1145/1394445.1394454

[38] Jesionkowska J, Wild F, Deval Y (2020) Active learning augmented reality for steam education—a case study. Education Sciences 10(8):198. https://doi.org/https://doi.org/10.3390/educsci10080198

[39] Kallery M, Psillos D (2001) Pre-school teachers' content knowledge in science: Their understanding of elementary science concepts and of issues raised by children's questions. International Journal of Early Years Education 9(3):165–179. https://doi.org/10.1080/09669760120086929

[40] Kalmpourtzis G (2018) Educational Game Design Fundamentals: A journey to creating intrinsically motivating learning experiences. CRC Press

[41] Kamarainen AM, Metcalf S, Grotzer T, et al (2013) Ecomobile: Integrating augmented reality and probeware with environmental education field trips. Computers & Education 68:545–556

[42] Keller JM (1987) Strategies for stimulating the motivation to learn. Performance and instruction 26(8):1–7

[43] Kelly A (2003) The role of design in research. Educational Researcher 32(1):3–4

[44] KL NS, Chavan PS, Murthy S (2018) Stereochem: Augmented reality 3d molecular model visualization app for teaching and learning stereochemistry. In: 2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT), IEEE, pp 252–256

[45] Klopfer E, Sheldon J (2010) Augmenting your own reality: Student authoring of science-based augmented reality games. New directions for youth development 2010(128):85–94

[46] Kolb DA (2014) Experiential learning: Experience as the source of learning and development. FT press

[47] Kuang Y, Bai X (2019) The feasibility study of augmented reality technology in early childhood education. In: 2019 14th International Conference on Computer Science & Education (ICCSE), IEEE, pp 172–175, https://doi.org/10.1109/ICCSE.2019.8845339

[48] Lam MC, Tee HK, Nizam SSM, et al (2020) Interactive augmented reality with natural action for chemistry experiment learning. TEM Journal 9(1):351

[49] Lampropoulos G, Keramopoulos E, Diamantaras K, et al (2022) Augmented reality and gamification in education: A systematic literature review of research, applications, and empirical studies. Applied Sciences

12(13):6809. https://doi.org/https://doi.org/10.3390/app12136809

[50] Li MC, Tsai CC (2013) Game-based learning in science education: A review of relevant research. Journal of Science Education and Technology 22(6):877–898

[51] Liu Y, Taber KS (2016) Analysing symbolic expressions in secondary school chemistry: their functions and implications for pedagogy. Chemistry Education Research and Practice 17(3):439–451

[52] Loorbach N, Peters O, Karreman J, et al (2015) Validation of the instructional materials motivation survey (imms) in a self-directed instructional setting aimed at working with technology. British journal of educational technology 46(1):204–218

[53] Luraschi M, Rezzonico R, Pellegri G (2012) The chemist, that madman! how children perceive science. CHIMIA International Journal for Chemistry 66(11):820–825

[54] Lutfi A, Suyono S, Erman E, et al (2019) Edutainment with computer Game as a Chemistry Learning Media. JPPS (Jurnal Penelitian Pendidikan Sains) 8(2):1684–1689. https://doi.org/10.26740/jpps.v8n2.p1684-1689

[55] Maguire M (2001) Methods to support human-centred design. International journal of human-computer studies 55(4):587–634

[56] Maier P, Tönnis M, Klinker G (2009) Dynamics in tangible chemical reactions. In: Proceedings from the International Conference on Chemical Engineering (ICCE 2009)

[57] Malone TW (1981) Toward a theory of intrinsically motivating instruction. Cognitive science 5(4):333–369

[58] Martin F, Bolliger DU (2018) Engagement matters: Student perceptions on the importance of engagement strategies in the online learning environment. Online Learning 22(1):205–222

[59] Martín-Gutiérrez J, Fabiani P, Benesova W, et al (2015) Augmented reality to promote collaborative and autonomous learning in higher education. Computers in human behavior 51:752–761

[60] Martins AI, Rosa AF, Queirós A, et al (2015) European Portuguese Validation of the System Usability Scale (SUS). Procedia Comput Sci 67:293–300. https://doi.org/10.1016/j.procs.2015.09.273

Appendix D

Game Designers and HCI Experts Feedback

Game Designer's Assessment																		
Nome:	**Age**	**How easy was it to follow the story**	**How easy was it to start the game?**	**How easy was it to figure out the correct sequence of actions to take you to the next task?**	**How motivating was it?**	**How entertaining was the game Oxygenio?**	**How were the game's graphics and layout**	**Name your three favorite things about the game.**	**Name your three least favorite things about the game.**	**Do you think some people would have problems playing PF? What kinds of people? What kinds of problems?**	**If you could change one thing on this game, whether it is major or minor, what would be at the top of the "to do" list?**	**How easy or difficult is it to start the game, read and navigate through it, to completion?**	**Is it engaging and fun for the player?**	**Does the story stimulate curiosity and gain the attention of the user?**	**Does the game allow choice in order to increase the user's motivation?**	**Does the game allow players to feel successful and that objectives were met in a meaningful way?**	**Does the game provide feedback and reinforcement and provide a sense of achievement?**
Dina	27	4	5	4	5	5	5	learning about the combination of the different elements and its reaction; graphic elements; game dynamic is easy to understand	maybe try to relate more the colours of the elements; explain with more detail the "reactions" while combining the elements	since its an AR game, maybe people with lack of "tecnology knowledge", elder people might struggle with the interaction	Colour of the Oxygen*: Make more clear the interaction between the cube elements of the real physical world vs the AR cube- maybe during the 1st level in tutorial; Allow to make multiple combinations between the elements to make it more playfull and explore more element's reactions, even if they are not the correct combinationss	4	5	Yes	Yes	Yes	Yes
Paulo Bala	34	4	3	4	3	4	5	I enjoyed the game world, the game mechanics of joining different elements and the story.	The interaction was confusing, the cubes seemed redundant and the difficulty level of the puzzles seemed to be very easy.	I think very young children would have problems with the switching between cubes and the game world and because it has too many types of interactions.	Simplify the interactions with the cubes and the game world, and the back and forward switch between them.	4	3	Yes	No	Yes	Maybe
Ana	29	5	4	5	5	5	5	the interaction, the animation and the learning story. I also love the graphics and believe that it is adequate for children.	just one - in the last action, i could not understand how to join the 3 elements	older people may struggle interacting with the device	just in the final action - some information about how to combine the last 3 elements	5	5	Yes	Yes	Yes	Yes
Rui Trindade	26	4	4	5	4	4	3	The ability to interact with the different characters (the periodic table elements), the fact that the game is subtle about being educational (kids can have fun, and learn while doing so), and how easy it was to pick up.	Sometimes it was not clear how one screen transitioned to another (for example, at the end of each level), the 2nd and 3rd levels seem to be same in terms of difficulty (the 3rd level could be more challenging).	I think that the problems that could arise could be more related to the technology - if it is possible to scan the cubes without disrupting the gameplay. Kids could have some difficulty to scan the cubes if that means stopping the gameplay.	Add some feedback to the game actions/interactions. For example, how/why does an explosion happen when 2 characters combine to clear an obstacle.	5	4	Maybe	Maybe	Yes	Yes
Mara	44	5	4	5	5	5	5	It was engaging and I like the part of the reactions I like the use of a physical cube to gather different type of information The use of combining elements to overcome the obstacles	I will like more combination of elements More stuff happening in the world Better feedback at the end of the levels	Very yonge children - Usability and using the AR world	Feedback at the end - more grandiose	5	5	Yes	Yes	Yes	Yes

Appendix E

Spatial Skills Tests

Section 3 of 4

Teste de rotação mental (MRT-A)

Por favor, responde às seguintes perguntas. Lembra-te que não há respostas certas ou erradas.

Image title

Por favor, observa estas cincos figuras:

Nota que todas as 5 primeiras figuras são representações do mesmo objeto, mostrado de diferentes ângulos. Imagina o movimento do objecto ou o teu movimento ao redor do objecto. As últimas duas figuras são de um objecto diferente, que não é o resultado da rotação do objeto mostrados no 5 desenhos iniciais.

objeto 0a.

Observa o objeto

1 2 3 4

Duas destas imagens mostram o mesmo objeto da imagem 0a. Seleciona só duas opções.

As respostas corretas são 1 e 3, porque são o resultado do objeto 0a. rodado em diferente ângulos

Seguindo o exemplo, seleciona dois desenhos que representam o mesmo objeto mostrado de diferentes ângulos. *

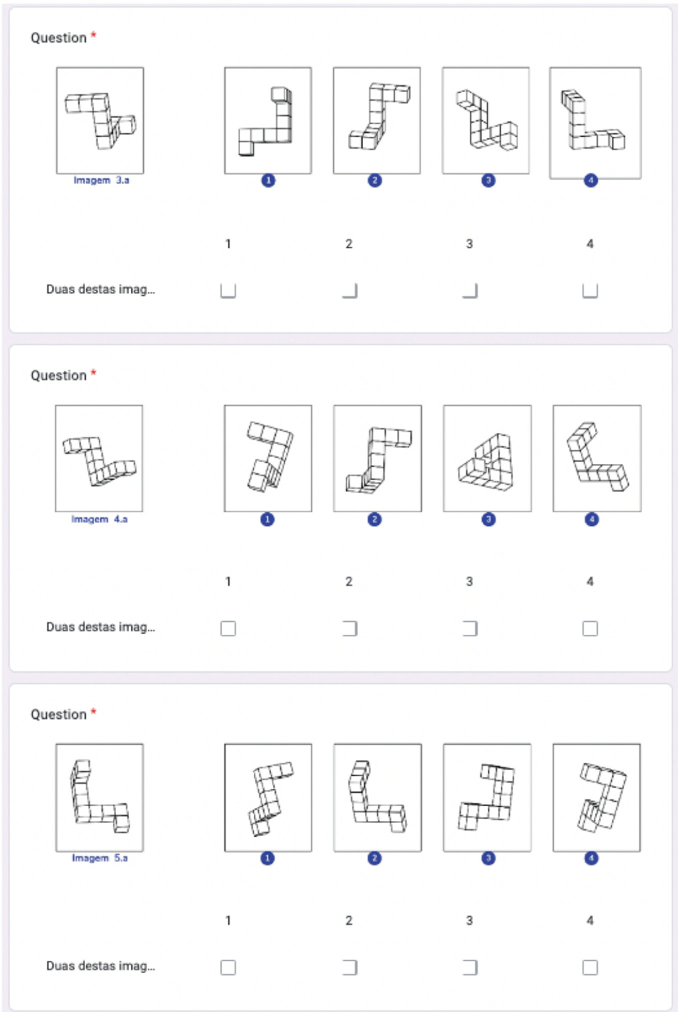
Imagem 1.a

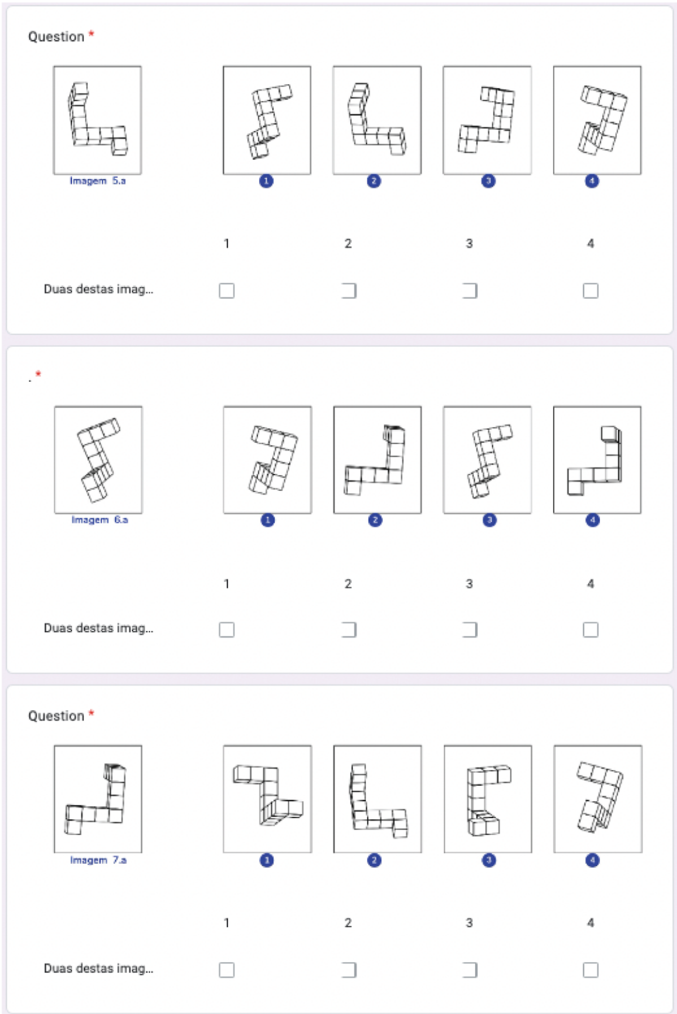
	1	2	3	4
Duas destas imag...	☐	☐	☐	☐

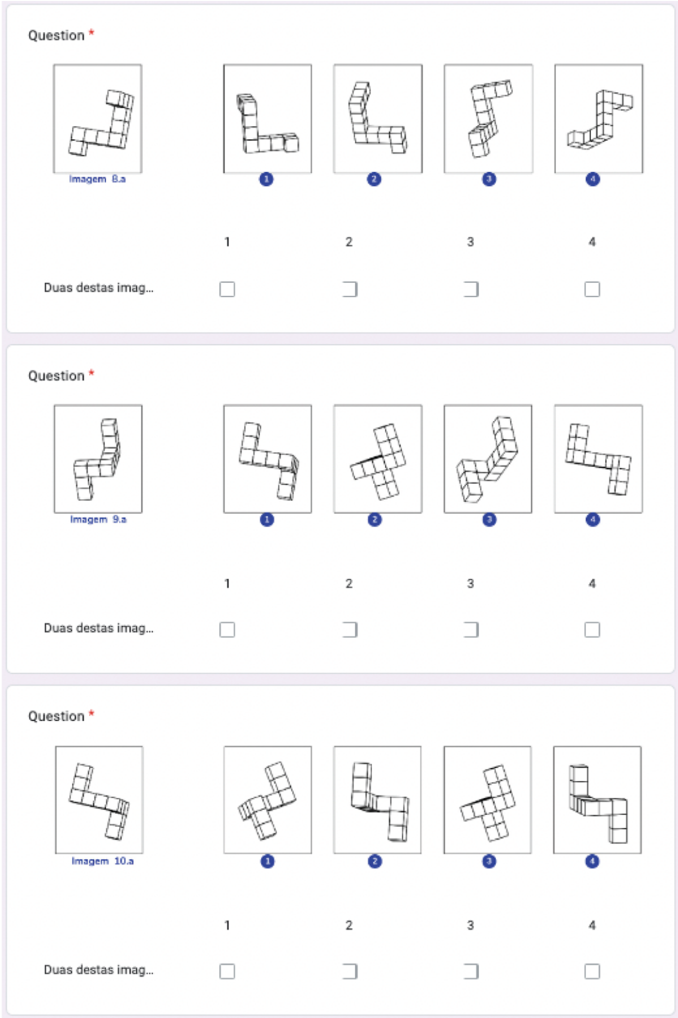
Question *

Imagem 2.a

	1	2	3	4
Dois destas image...	☐	☐	☐	☐


Question *
Imagem 3.a
1
2
3
4
Duas destas imag...
Question *
Imagem 4.a
1
2
3
4
Duas destas imag...
Question *
Imagem 5.a
1
2
3
4
Duas destas imag...

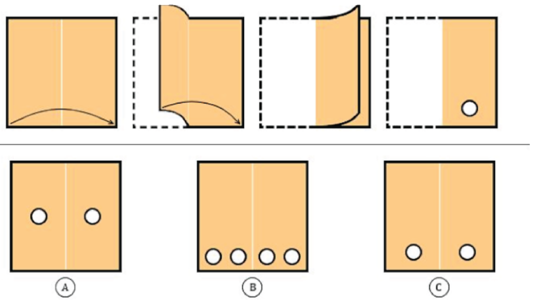

Question *
Imagem 5.a
1
2
3
4
1
2
3
4
Duas destas imag...
. *
Imagem 6.a
1
2
3
4
1
2
3
4
Duas destas imag...
Question *
Imagem 7.a
1
2
3
4
1
2
3
4
Duas destas imag...


Question *
Imagem 8.a
1
2
3
4
1 2 3 4
Duas destas imag...
Question *
Imagem 9.a
1
2
3
4
1 2 3 4
Duas destas imag...
Question *
Imagem 10.a
1
2
3
4
1 2 3 4
Duas destas imag...


Question *
Imagem 11.a
1
2
3
4
1 2 3 4
Duas destas imag...
Question *
Imagem 12.a
1
2
3
4
1 2 3 4
Duas destas imag...

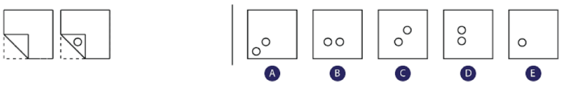
Exercício mental - dobragem de papel

Imagina que tens uma folha de papel quadrado a qual terás que dobrar mentalmente e fazer um furo. Agora imagina qual será o resultado dessa folha uma vez que a abras novamente. No exemplo apresentado a resposta correta é a imagem C.



	A	B	C
1	☐	☐	☑

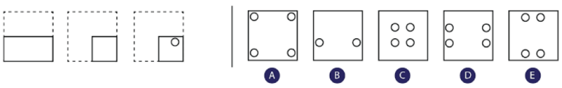
35. Após dobrar o canto do quadrado e realizar o um furo nessa dobra, qual o resultado obtido? Só existe uma resposta certa. *



Mark only one oval per row.

	A	B	C	D	E
1	⬭	⬭	⬭	⬭	⬭

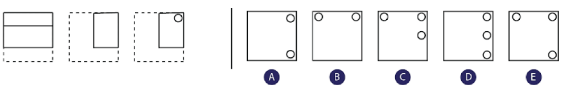
36. Após dobrar duas vezes o quadrado e realizar o um furo nessa dobra, qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
2	⬭	⬭	⬭	⬭	⬭

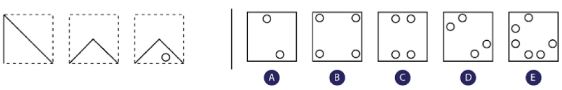
37. Após dobrar o quadrado e realizar um furo na zona indicada , qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
3	⬭	⬭	⬭	⬭	⬭

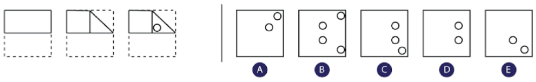
38. Após dobrar o quadrado e realizar um furo na zona indicada , qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
4	⬭	⬭	⬭	⬭	⬭

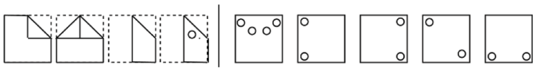
39. Após dobrar o quadrado e realizar um furo na zona indicada , qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
5					

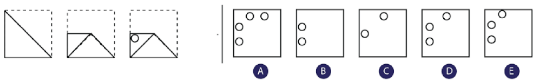
40. Após dobrar o quadrado e realizar um furo na zona indicada , qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
6					

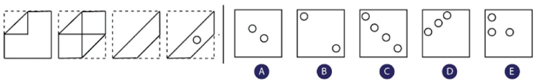
41. Após dobrar o quadrado e realizar um furo na zona indicada , qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
7					

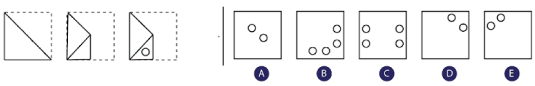
42. Após dobrar o quadrado e realizar um furo na zona indicada , qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
8					

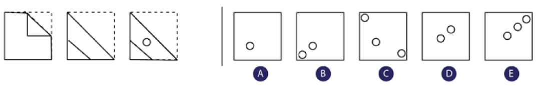
43. Após dobrar o quadrado e realizar um furo na zona indicada , qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
9					

44. Após dobrar o quadrado e realizar um furo na zona indicada , qual o resultado obtido? *



Mark only one oval per row.

	A	B	C	D	E
10					

Appendix F

Periodic Fable Website

A website was created to allow teachers, parents and students to find information about our project. The website also provides the opportunity to download and print a 2D plant of the PF Discovery tangible interaction cubes https://periodicfable.arditi.pt/.

Playful-Educational Games "The Periodic Fable"

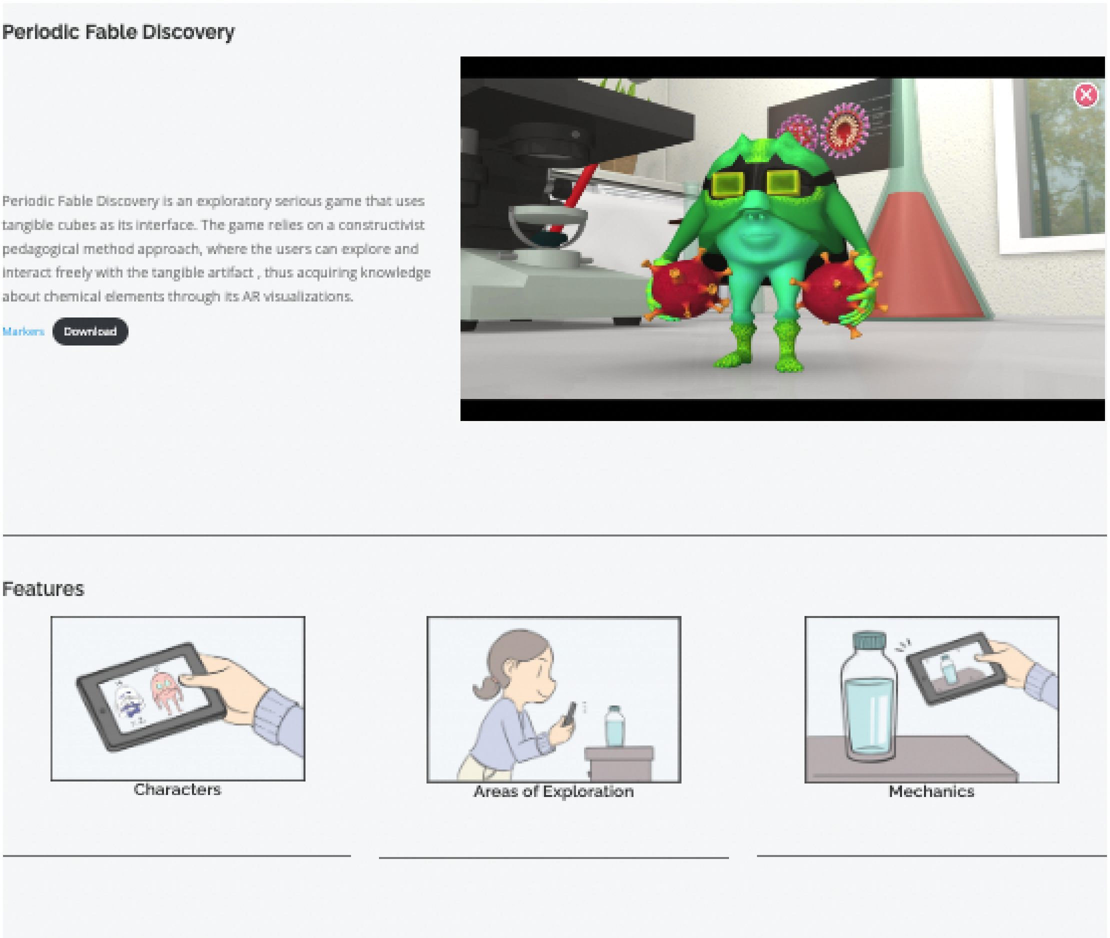
Periodic Fable is a serious AR game for android mobile devices (with gyroscope, accelerometer and compass sensor), designed and produced to target 9 to 13-year-old children that come into contact with chemistry for the first time. The game developed using ARCore, Autodesk Maya, Mudbox and Adobe Photoshop, provides basic concepts about chemical elements like their symbols, atomic numbers and atomic weight, reactions with other elements, and products that contain the element. Inspired by previous studies and projects, framed by the urgency of the current sustainability and environmental problems including the limited supply and overuse of the chemical elements, this project tackles the need to educate and increase chemistry literacy among a broader and younger population

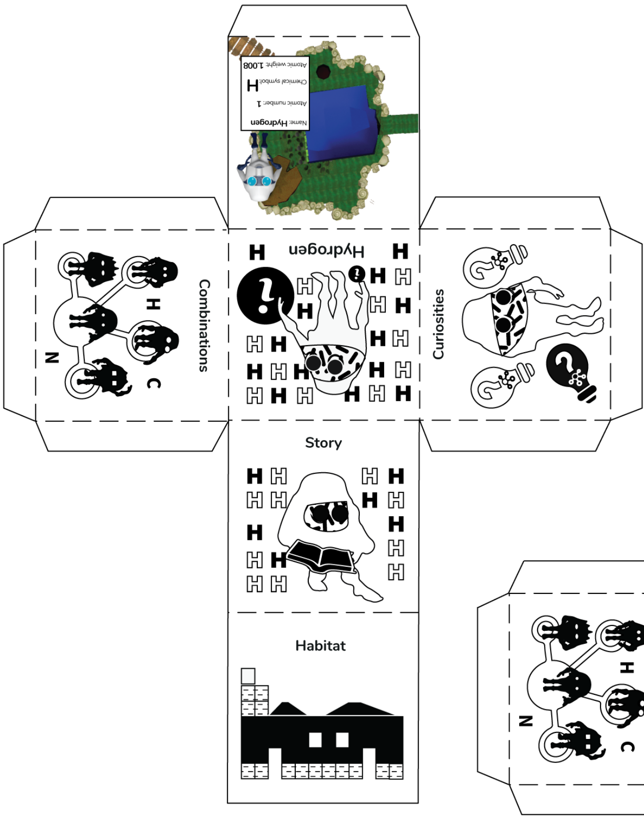
Games

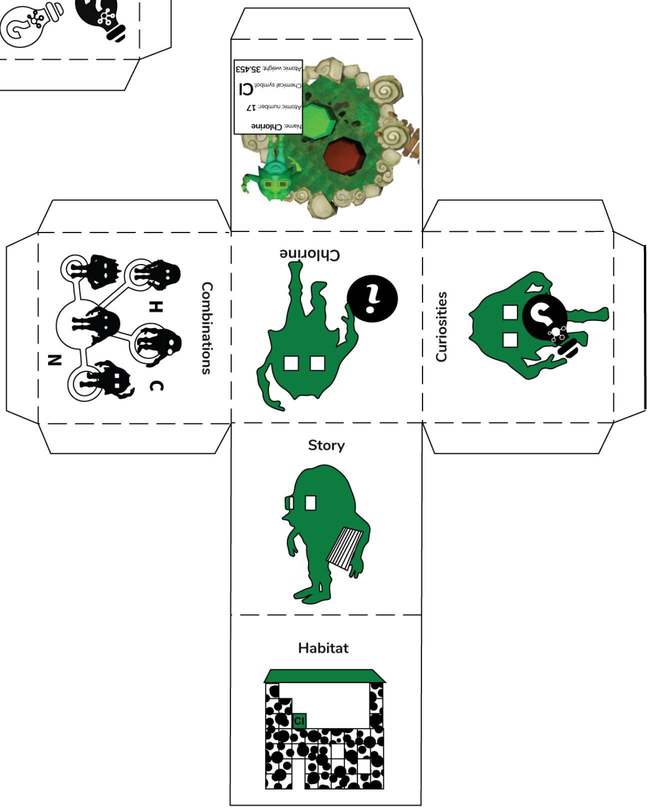
Periodic Fable Discovery

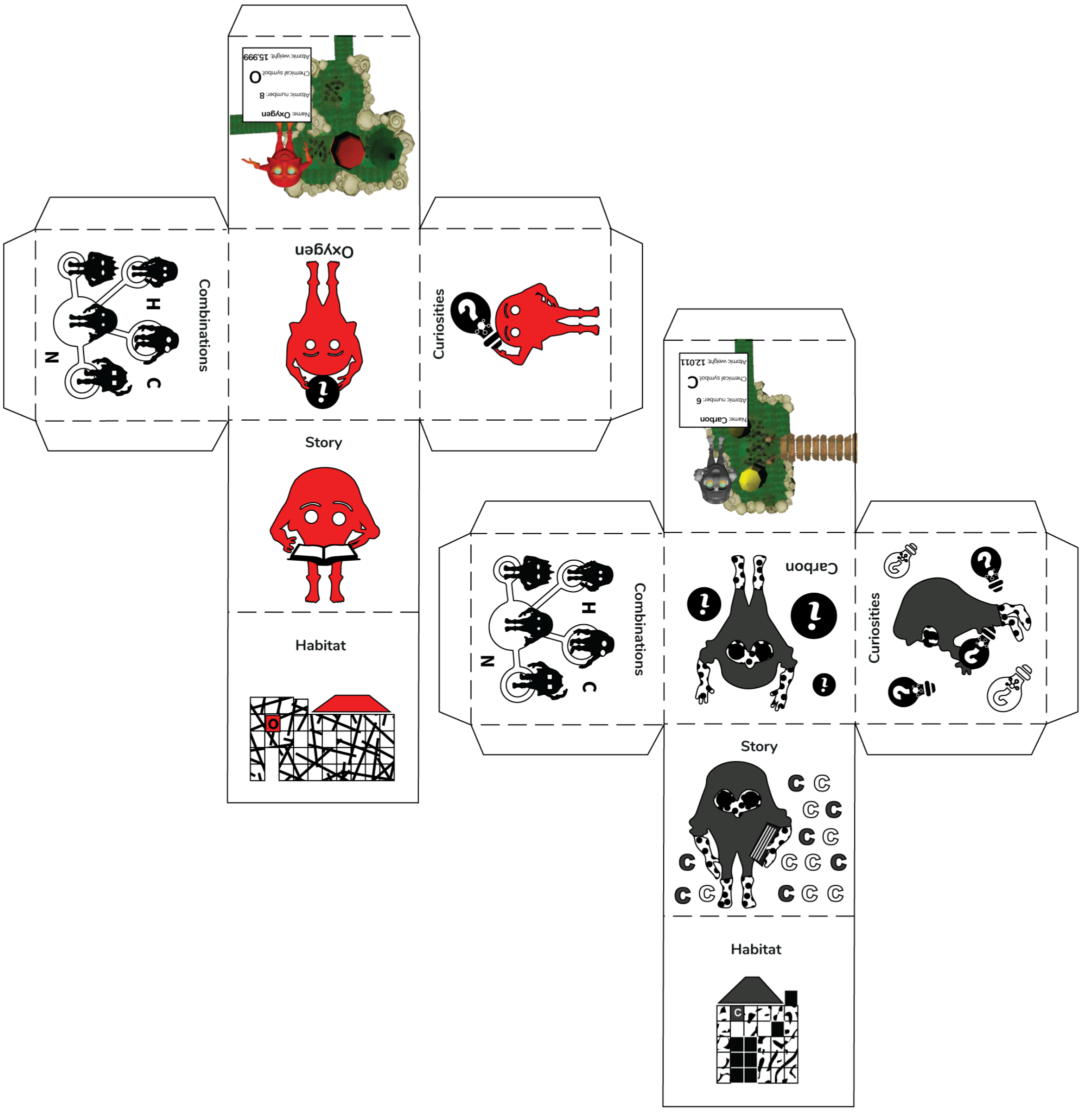
Periodic Fable An Augmented Journey

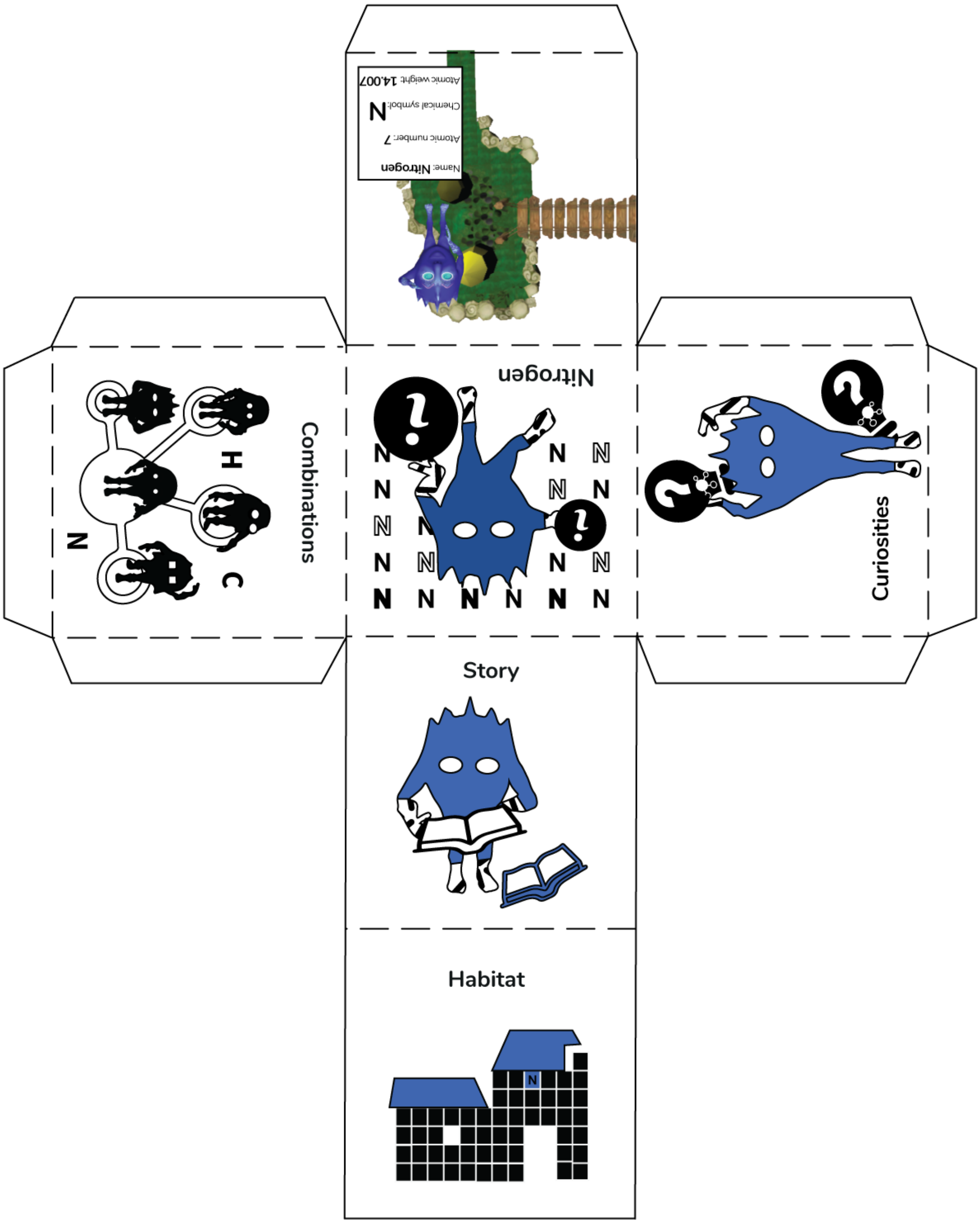
The Periodic Fable In the Wild


Periodic Fable Discovery
Periodic Fable Discovery is an exploratory serious game that uses tangible cubes as its interface. The game relies on a constructivist pedagogical method approach, where the users can explore and interact freely with the tangible artifact , thus acquiring knowledge about chemical elements through its AR visualizations.
Markers
Download
Features
Characters
Areas of Exploration
Mechanics


Hydrogen
Combinations
Curiosities
Story
Habitat


Chlorine
Combinations
Curiosities
Story
Habitat


Oxygen
Combinations
N
H
C
Curiosities
Story
Habitat
O
Carbon
Combinations
N
H
C
Curiosities
Story
Habitat
C


Name: Nitrogen
Atomic number: 7
Chemical symbol: N
Atomic weight: 14,007
Nitrogen
Combinations
H
C
N
Curiosities
Story
Habitat

2023 AUGMENTED REALITY SERIOUS GAMES TOWARDS INTRODUCING AND PROMOTING CHEMISTRY TO PRETEENS

UNIVERSIDADE NOVA DE LISBOA

OMNIS CIVITAS CONTRA SE DIVISA NON STABIT