

# Masters Program in **Geospatial Technologies**



## ***Virtual reality in Urban Search and Rescue***

- *a time and accuracy assessment of the use of Virtual Reality as a tool for Urban Search and Rescue after earthquakes*

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Dissertation submitted in partial fulfilment of the requirements for the Degree of *Master of Science in Geospatial Technologies*

# ***Virtual reality for Urban Search and Rescue***

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## ***a temporal requirement and accuracy assessment of the use of Virtual Reality as a tool for Urban Search and Rescue after earthquakes***

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*At the Westfälische Wilhelms-Universität Münster*

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**i. Authors declaration**

I, Lisa Fischell (Martikelnummer 447020), hereby confirm that the following Master Thesis titled

*“Virtual reality for Urban Search and Rescue*

- *a temporal requirement and accuracy assessment of the use of Virtual Reality as a tool for Urban Search and Rescue after earthquakes “*

was completed by myself as a requirement for the M.Sc. in Geospatial Technologies. All other work, diagrams and tables used in this work have been truthfully referenced.

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Date & Place

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Signature

## ii. Acknowledgements

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**iii. Abstract**

This thesis investigates the elements of both time and accuracy that Virtual Reality (VR) has to offer in support of Urban Search and Rescue (USAR) following an earthquake disaster. After an earthquake, most casualties are found in or under collapsed buildings. With limited nutritional resources and potential injuries, survival rates decrease rapidly after 72hrs. To quickly and accurately assess the overall and individual damage grade of buildings is therefore of fundamental importance to the recovery of victims. The utilised strategies of USAR teams are currently challenged by several limitations. Virtual Reality has been used to visualise three-dimensional data across many scientific research areas. The special characteristics of VR allow a more immersive and engaged interaction for the user. So far VR has been utilised to train USAR personnel, but it has not been applied as a data visualisation method. This concept could support USAR teams across the globe by enabling them to assess overall structural damage extent, visually inspect inaccessible areas and identify optimal access points in a three-dimensional environment. This thesis therefore compares standard USAR approaches, such as Street View images, 2D aerial images and videos, to 3D building models in Virtual Reality. A user study was conducted to investigate the accuracy of information obtained from the different USAR methods, as well as the time it took for the users to obtain the required information. After an explorative data analysis, a Friedman test followed by a Wilcoxon test was applied to results of the user study. The results of the test showed a significant difference between VR and Aerial Imagery. However, the trends in average task completion time as well as task completion rate suggest that VR can be identified as a useful tool to Urban Search and Rescue, improving both temporal requirement and accuracy assessment in comparison to current methods.

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**vii. Abbreviations and Acronyms**

<b>ASR</b>	Assessment, Search and Rescue.
<b>EM-DAT</b>	Emergency Events Database
<b>FEMA</b>	Federal Emergency Management Agency
<b>FPS</b>	Frame rate per second
<b>FPV</b>	First Person View
<b>GIS</b>	Geographic Information System
<b>GPS</b>	Global Positioning System
<b>HCI</b>	Human Computer Interaction
<b>HMD</b>	Head Mounted Display
<b>INSARAG</b>	International Search and Rescue Advisory Group
<b>I.S.A.R. Germany</b>	International Search And Rescue Germany
<b>LEMA</b>	Local Emergency Management Authority
<b>ML<sub>(x)</sub></b>	Richter Scale
<b>OCHA</b>	UN Office for the Coordination of Humanitarian Affairs
<b>SAR</b>	Search and rescue
<b>SDK</b>	Software Development Kit
<b>SfM</b>	Structure from Motion
<b>TBE</b>	Time based efficiency
<b>THW</b>	Bundesanstalt Technisches Hilfswerk
<b>UAV</b>	Unmanned Aerial vehicle
<b>UN</b>	United Nations
<b>UNISDR</b>	United Nations Office for Disaster Risk Reduction
<b>USAR</b>	Urban Search and Rescue
<b>VR</b>	Virtual Reality

**viii. Keywords**

Virtual Reality, VR, Urban Search and Rescue, USAR, UAV

## **1. Introduction**

In common with the rest of the world the population of global disaster-prone regions has risen dramatically. As a result of this the importance of disaster management is also proportionally increasing. Over the last decade earthquakes have been the cause of over 50% of natural disaster related deaths. Research has shown that the majority of these victims have been trapped either in or beneath collapsed buildings. If the victims are not located and rescued within 72 hours of the earthquake their chance of survival becomes significantly reduced. Therefore, it is of the utmost importance to locate and assess building damage as efficiently as possible.

USAR (Urban Search and Rescue) , a specialised team of Search and Rescue, has been established specifically to operate in highly populated urban areas which have suffered an earthquake. Following an earthquake event, the main challenges faced by USAR personnel are twofold, firstly the need to respond within the shortest time frame as possible and secondly exhaustion caused through extreme exertions from walking up to 12 hours per day over altitudes between ground level and 1500m.

USAR personnel utilise a range of data collection methods to enable prioritisation of action required including pre-event maps (not always available), satellite and UAV imagery as well as visual inspection - none of which are without problems. Each of these is discussed in the literature survey.

Using the above methods, USAR teams only receive a two-dimensional visualisation of the data this is extremely limited when dimensional information is required to analyse not only spatial extent but also the grade of damage to collapsed buildings. To reduce this two-dimensional limitation this thesis posits the use of Virtual Reality (VR) for use in Urban Search and Rescue. The concept and idea of this thesis is discussed in the next Chapter.

**a. Motivation**

This thesis explores the potential that virtual reality has to offer in supporting USAR personnel during their building damage assessment. The motivation is therefore academic, but also has practical applications.

1. The lack of a structured system to collect information of building damage:

As described in the background Chapter, although many different forms of data acquisition methods currently exist, they are still subject to considerable limitations. Providing a system for USAR personnel to collect and visualise three-dimensional and georeferenced data could help to reduce levels of physical exhaustion and lead to more effective decision making in a more time efficient manner.

2. The lack of research regarding both VR in disaster response and the use of VR to acquire information on damaged buildings:

VR has previously been used in several ways to train USAR and emergency personnel in disaster response. However, the use of VR during a disaster or earthquake event itself has not yet been investigated. In order to conclude whether VR could be an advantageous tool, the time frame and accuracy to assess the obtained models have been investigated in this thesis.

3. Future work:

Another, more personal, motivation for this thesis is the potential for the further development of an integrated system. Such a system, could convert drone collected imagery into VR models which could be shared on an online platform and facilitate the support of remote experts or crowdsourced damage assessment.

**b. Concept and Idea**

Through an in-depth Literature Survey, Virtual Reality (VR) has been identified as a tool to aid in the damage assessment of buildings by USAR. Due to its special characteristics, which are discussed later in the Literature Survey, VR offers a new perspective to view three-dimensional data.

Three-dimensional models from UAV data have already been developed not only for research, but also practical applications in many scientific fields. These three-dimensional models have so far been used as a tool to collect and preserve data, e.g. to keep the heritage of landforms or monuments at risk of destruction. More recently, some studies have utilised these three-dimensional models after earthquake events. This will further be examined in the Literature Survey.

These three-dimensional models provide a new perspective for USAR personnel. However, viewing three-dimensional data in a two-dimensional environment still leads to severe limitations. Using First Person View (FPV) in a Virtual Reality Environment can vastly reduce these limitations.

This method of visualising information for USAR has not yet been studied, and neither have applied projects been developed. Furthermore, no studies that compare current methods of building damage assessment after earthquakes have been found to date.

The idea behind this thesis is to investigate how VR can support USAR missions. Due to the time limitation of this degree, only a small proportion of the overall research topic has been investigated. Figure 1. displays the conceptualised idea behind this thesis and the way that VR would be integrated into USAR damage assessment progress.

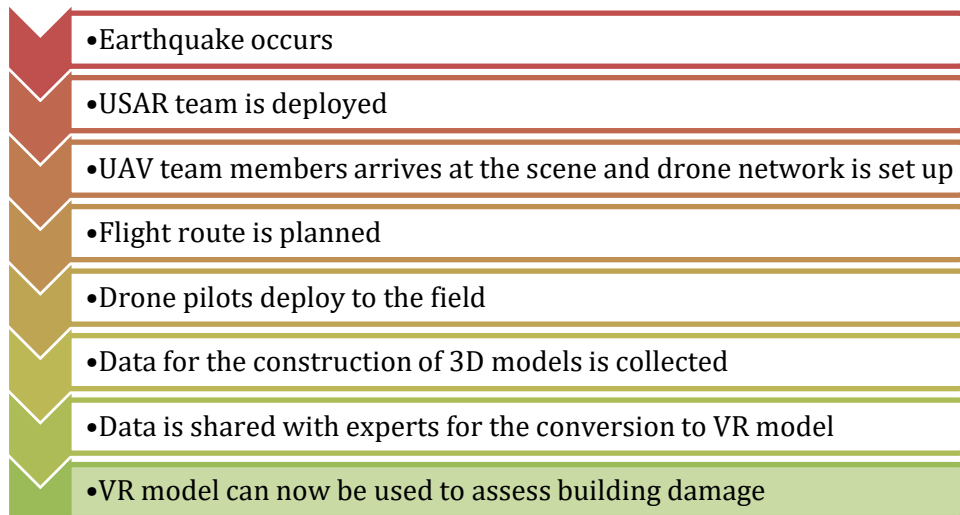


Figure 1 - Thesis concept and focus area (in green)

During the Literature Survey it became apparent, that time frame as well as information accuracy were of the utmost importance during USAR deployments. These two factors were therefore explored in a user study which is further discussed in Chapter 3.

This concept could support USAR teams across the globe by enabling them to assess overall structural damage extent, visually inspect inaccessible areas and identify optimal access points in a three-dimensional environment.

The digital data collection would negate the necessity for USAR teams having to extensively survey the area, an otherwise exhausting temporal and physical effort. This visualisation method requires reduced levels of local knowledge and less manpower, whilst making data accessible to multiple organisations and support communities during the reconstruction process. It would additionally allow experienced disaster managers to remotely assess the situation and provide strategic support.

**c. Research goals**

This thesis explores the prospect that virtual reality could provide more accurate information or more time efficient information on the damage to buildings after an earthquake event. To do so the following research goals were established:

1. Conduct a Literature Survey to:
  - a. Establish current methods and tools employed by USAR personnel
  - b. Investigate development of 3D building models from UAV data.
  - c. Investigate the use of VR itself and its use in GIS and USAR.
  - d. Identify the optimal methodological and analytical approach for the user study.
2. Create imagery, Video, and VR environment products to simulate a destroyed city for a user study.
3. Conduct a user study to:
  - a. Investigate the level of accuracy obtained when using standard method for building damage assessment compared to VR.
  - b. Investigate time requirements for building damage assessment comparing standard methods to VR.
4. Evaluate the user study to establish the accuracy and temporal effort of the use of VR in comparison to standard methods.

**d. Chapter overview & thesis organisation**

This thesis is organised into 6 chapters as follows:

Chapter 1 introduces the thesis topic, explains the thesis motivation as well as the concept and the idea of the thesis. The research goals were also set in this Chapter.

Chapter 2 is concerned with the Literature Survey of this thesis. In addition to achieving one of the research goals, it additionally provides an insight into the chosen methodology of the research approach and the methodology of the user study.

Chapter 3 describes the methodology and user study process. This includes the research hypothesis, the design of the study, the equipment used during the study as well as the design of the product.

Chapter 4 presents the results of the user study.

Chapter 5 discusses the results of the user study, describes the limitations of this thesis and provides a final conclusion.

Chapter 6 describes future work in this research topic.

## 2. Literature Survey

The Literature Survey for this thesis has been divided into three sections. The first one provides a background to the thesis topic. The second discusses methods and tools that USAR teams are currently using to obtain information on the state of buildings after earthquake disasters as well as their limitations. The third section examines the development of 3D building models from UAV imagery to establish the process and time frame required to get imagery VR ready, as well as limitations of this method. The current use of VR itself, and its application in GIS and in USAR, are discussed in section three. Combined, these sections provide an overview of the current baseline of methods used by USAR teams, the state of technology of both the establishment of 3D models from UAV imagery, the use of VR in USAR, and limitations of all the above. They also provide the basis for some development of the user study and the first research goal.

### a. Background

Disaster Management is concerned with the *“organization, planning and application of measures preparing for, responding to and recovering from disasters”* (UNISDR, 2017). Sometimes used interchangeably with the term “Emergency management”, it is important to note that developed strategies are aimed at reducing the risks of disasters and increasing preparedness rather than eradicating the cause of the event itself. With an increasing percentage of the global population at risk, Disaster Management is becoming an interdisciplinary ever-growing field.

During the last decade, different types of disasters resulted in over 800,000 deaths, 2 million injuries and left approximately 15 million victims homeless (EM-DAT, 2018). According to the United Nations, 55% of disaster related deaths are directly related to earthquake events with a magnitude above  $ML_7$  (Holzer and Savage, 2013; UNISDR, 2016).

Because of these high mortality rates, the cause of death in earthquakes has been intensively investigated, both in case studies, and also in technical papers. All papers studied in the initial investigation during the development of this thesis concept conclude that the main cause of deaths in earthquakes is the collapse of buildings (Alexander, 1985; Coburn and Spence, 1992; Spence *et al.*, 2011). Although building style and material have been identified to cause significant variations in the extent of the damage, this is where most victims are recovered. The unpredictable nature of an earthquake prevents evacuation and leaves victims trapped in voids, or under debris and collapsed structures.

The survival rate of earthquake victims decreases significantly as time passes, especially after 72 hours. This has been reported by many case studies and also by medical journals. (Schultz, Koenig and Noji, 1996; MacIntyre, Barbera and Smith, 2006; Qi *et al.*, 2016; Kang *et al.*, 2017).

The lack of pre-warning and the rapid onset of an earthquake elevates pressure on Disaster Management in conjunction with Search And Rescue (SAR) personnel. SAR personnel are often first and secondary responders. Their primary assignment is to determine the location of potential victims, move and remove debris, and most importantly identify, rescue and recover injured victims (Baker *et al.*, 2016; Silk *et al.*, 2018). Schweier and Markus (2006) argue that, in order to recover victims, the correct building damage assessment is of vital importance (Schweier and Markus, 2006).

Increased global population has led to rapid urbanisation in earthquake prone regions (Hewitt, 1997). The increased potential risk in densely populated areas has led to the establishment of Urban Search and Rescue Teams, a select task force of SAR personnel. The Federal Emergency Management Agency of the United States (FEMA, 2018) states that “*Urban Search and Rescue (US&R) involves the location, rescue (extrication), and initial medical stabilization of individuals trapped in confined spaces*”.

The terms SAR and USAR are often used interchangeably in literature, but a distinct differentiation needs to be made. The teams often have different training backgrounds and perform different duties during their missions. Since most earthquake casualties are found in collapsed buildings, this thesis refers specifically to USAR personnel throughout the document.

Gathering accurate and reliable post-event data of the spatial extent and distribution of destruction has been a major limitation and challenge for USAR personnel. As aforementioned, the collapse of buildings is the primary cause of death in earthquakes. It is considered that the first 36-72 hours are of fundamental importance towards the recovery of victims (Fiedrich, Gehbauer and Rickers, 2000). In addition to the temporal pressure, USAR personnel often face exhaustion from performing tasks that require a high physical effort.

Silk *et al.*, (2018) investigated the activities which USAR personnel perform while deployed. It was found that 83% of USAR personnel identified "*Perform moderately paced walking over slightly undulating open terrain*" as a task that they undertake frequently. This includes a walking duration of 8-12 hrs over varying altitudes (up to 1500m) per day.

Incoming USAR personnel, with limited or non-existing spatial knowledge of the area, regularly face challenges when attempting to identify areas in need of the most urgent help, and gain access to those areas. To combat the shortage of access to information, a range of methods have been suggested as a solution to this problem.

Pre-event maps, visual inspection and satellite imagery as well as videos and imagery acquired from Unmanned Aerial Vehicles (UAVs), have been used to identify damaged buildings (Renwick, Klein and Hamann, 2016). Various problems have arisen with these currently used methods, which will be further discussed in the Literature Survey.

Once data on the spatial extent and damage grade has been collected, and the analysis phase has started, USAR personnel are faced with a further challenge. The previously described and currently applied techniques visualise the data using only a two-dimensional system. As aforementioned, most victims are found in collapsed buildings, an environment where dimensionality is of substantial importance.

In order to reduce the limitations that USAR personnel face, this thesis posits the use of Virtual Reality for Urban Search And Rescue. The next section will discuss the concept and idea of this thesis.

**b. Current USAR methods**

USAR teams make use of several strategies to gain information on the state of buildings after earthquakes. These range from simple excursions on foot to complex analytic algorithms. This section will discuss a number of those strategies.

Before doing so, it is important to note that the approach and scale of damage assessment vary between different USAR teams, literature, and organisational guidelines. An often-used damage assessment scale in both literature and practical application is the European Macroseismic Scale (EMS) by Grünthal, Figure 2. The EMS classes different levels of structural damage to buildings into a range of Grades. These range from 1-5 where Grade 1 signifies no damage and Grade 5 means total destruction.

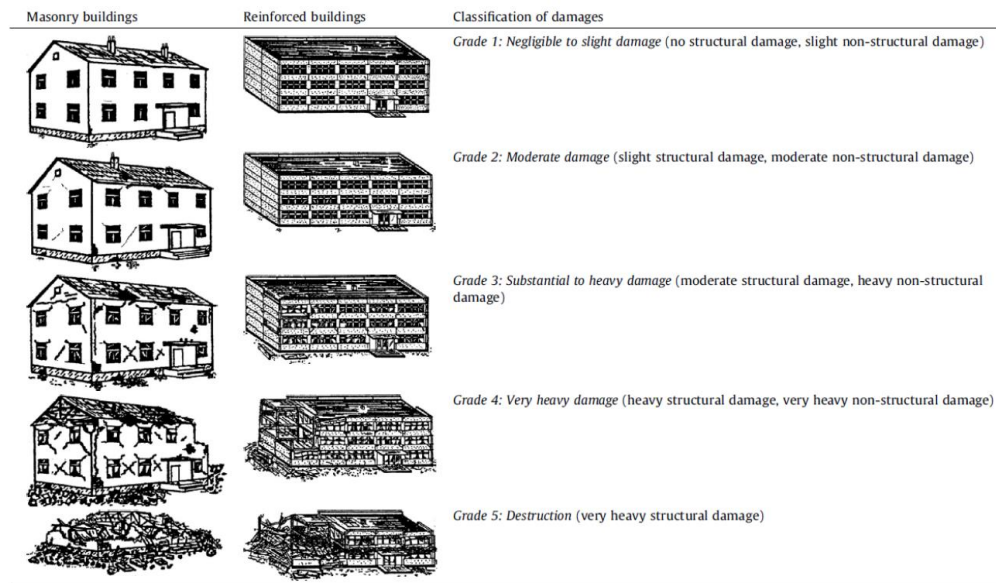


Figure 2 - European Macroseismic Scale – EMS 98 (Grünthal, 1998)

#### On foot search:

The simplest and most often utilised approach to Search And Rescue is the simple “on foot” search. It is often practiced by first responders who do not follow any strategy when they are searching for victims. Mirhashemi *et al.*, (2007) provide an overview of the first response during the 2003 Bam earthquake. They found that 89.2 % of first responders were local, out of which 59.5% were relatives, 29.7% local residents and 10.8% were other local groups. This type of search is often unorganised and responders use basic tools or their bare hands (Statheropoulos *et al.*, 2015). Consequently, damage to the buildings are not assessed and subsequent risks for both first responders and the victims are high. In addition, no data is gathered on the damage extent, whether the building has been searched, or the number of victims.

Once the first professional USAR teams arrive, they conduct a simple on foot search to gain an overview of the damage grade and extent. The search and rescue missions on foot are conducted by Light and Medium USAR teams (INSARAG and OCHA, 2012).

USAR teams employ a range of tools to support their missions. These range from specialised search dogs, UAVs, small robots and medium duty equipment. Following large scale earthquake disasters, the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) coordinates the operation of all international USAR teams. A guideline called “*Assessment, Search and Rescue levels*” (INSARAG, 2012) is then implemented. After the first wide area assessment (ASR Level 1) OCHA divides the affected areas into sectors in communication with the International Search and Rescue Advisory Group (INSARAG) and the USAR. They then conduct primary, secondary, and full coverage search and rescue. These Levels can be seen in Table 1, which was adapted from the earlier mentioned INSARAG & OCHA Guidelines.

ASR Level	Description	Definition & Purpose	Carried out who/ when
1	Wide area assessment	Preliminary survey of the affected areas for developing the Sectorisation plan, BoO options and overall plan of action	LEMA/UNDAC/first Responder few USAR teams in country at the onset
2	Sector assessment	Fast pace methodical assessment to identify viable live rescue sites within assigned sector	USAR teams assigned to respective sector
3	Primary Search & Rescue	Conduct in early stages – Fairly rapid progress through assigned worksite to maximize lifesaving opportunities	USAR team(s) assigned to respective side
4	Secondary Search & Rescue	Thorough search through all survivable voids involving full range of USAR capabilities usually at one worksite	USAR team(s) assigned to respective side
5	Full Coverage Search & Rescue	Complete search of entire worksite to locate all life and deceased victims. 2 options for use complete delayering of collapsed structures or room to room clearance of non-collapsed structures	LEMA, sometimes together with USAR teams at the of rescue phase

Table 1 – ASR Levels – adapted from (INSARAG and OCHA, 2012)

During each level, data on the state of buildings is collected and communicated to the OCHA communication centre. It is then placed in an overall database. A major limitation to this method is that performing a simple foot search is a long and exhausting process. As previously described, SAR personnel spend ca. 8-12 hrs conducting searches and as a result are often exhausted whilst carrying out the actual victim recovery (Silk *et al.*, 2018).

To combat the disadvantages of simple on foot searches, other technology-based methods have been developed, studied, and applied. This includes the use of 2D Street View images collected by USAR personnel, 2D aerial optical images collected either by satellites or, more recently, UAVs. UAVs are also used to collect videos of the destroyed buildings. These methods will be discussed in the following sections.

### Street View images

During ASR Levels 1 and 2, Street View images are often collected to document the assessed areas. These images are shared between the USAR teams assigned to each specific sector and are used as a reference for later assessments. The functionality of these images has not been scientifically investigated; however, since social media has become a tool to share information on damage extent and grade, researchers have increasingly focussed on their use to assess building damage (Hwang, Evans and Hanke, 2017; Nguyen *et al.*, 2017).

### Aerial imagery

High resolution satellite imagery has long been utilised to identify and grade building damage after earthquakes. An aerial perspective, with a high pixel resolution, provides much data on a large spatial coverage. More recently, research has focussed on the use of UAVs to collect this data, because of the existing limitations which are discussed further on.

To assess building damage using aerial imagery two analysis types have proven promising - one using single images collected after an earthquake and the other using multiple, pre-and post-earthquake imagery.

A method called visual interpretation is often used in crowdsourced or targeted damage assessment. Visual interpretation is defined as an “*interpretation of images based on the feature’s tone, pattern, shape, size, shadow, texture, and association*” (Saito *et al.*, 2004).

Initially, the user visually identifies and grades the observed damage to a building. This data is then either digitised or GPS point referenced. The accuracy of visual interpretation has long been challenged, and is arguably dependent on a) the quality of the imagery and b) the training or experience of the user.

In research, varying conclusions about visual interpretation have been made. Saito *et al.*, (2004) assessed imagery of the 2001 Gujarat Earthquake, and conclude that visual interpretation provides results accurate enough for search and rescue missions. However, they do not provide any form of accuracy assessment. Yamazaki *et al.*, compared results from visual interpretation to a later conducted ground survey and concluded, that visual interpretation produced only “reasonably accurate results” (Yamazaki, Yano and Matsuoka, 2005) . This finding was also confirmed by a later study from Kerle, who concluded that data obtained can support USAR personnel but does not provide accuracy results (Kerle, 2010). One limitation to this analysis method has long been the low spatial and temporal resolution of satellite imagery and the potential obstruction by high cloud cover. This limitation has been vastly nullified due to the use of very high-resolution imagery collected by UAVs, which provide multiple advantages over traditional satellite imagery.

These advantages include the ability to a) collect data at any time or on any day b) collect data without visual obstruction c) collect data from different oblique angles. In addition, the imagery collected can be of much better pixel resolution and can be taken at different angles to the object of interest. When UAVs are utilised to collect data for disaster response, a few limitations have been identified by Erdelj *et al.* (2017). The first, and most important one, was found to be the battery life of the UAV itself.

This limitation arises when data over a large spatial area needs to be collected, as the battery life of a UAV is limited. It is also argued that these limitations can be compensated for when the integration of UAVs is a part of the disaster preparedness stage, and the so called “Duty-cycling” of the UAVs has been carefully planned. Other limitations were found to be the skill of the UAV pilot, the ability to ensure personal freedom to members of the public, and the careful optimisation strategies required to successfully collect data (Erdelj *et al.*, 2017).

Another analysis technique for aerial imagery is the use of semi- or self-automated mapping processes, where a system is trained to identify damaged buildings using pre-and post-event imagery. Both methods are based on changes in the colour composition, texture and structure of pixels in the same geographic location (Tu *et al.*, 2017), or they investigate the change in the geometric shape of objects (e.g. buildings or large structures) (Bitelli *et al.*, 2004). This requires the availability of pre-earthquake collected aerial imagery, which is not always available at the required quality (Cao *et al.*, 2016). Because the collection of suitable data, the process of training the system, and the analysis of the complex data output is very time intensive, it is rarely used to support USAR missions.

### UAV videos

Since the use of UAVs in USAR missions has become more established, and technology has improved, video recordings have become an often-used tool to collect data on both specific buildings and also overall damage assessment.

Following the emergence of video data for disaster response in the early 90s, many analysis methods have been investigated. As in the case for aerial imagery, visual interpretation and automated analysis approaches have been applied.

Due to the complexity of automated analysis in a moving image frame, this approach has only delivered limited success (Kerle *et al.*, 2005). Subsequently, visual interpretation has been established as the main analysis method for UASR.

During the Literature Survey, it became apparent that few research papers that have been published that specifically relate to earthquake building damage. Often, the use of UAVs to collect video data is mentioned, but no further analysis is conducted. On the contrary, an explorative web search found many reports about the use of UAV videos in USAR. In 2014, OCHA released a paper supporting the use of UAVs that highlighted the general use of UAV videos for humanitarian causes. It did not however, specify any particular scenario (OCHA, 2014). The Bundesanstalt Technisches Hilfswerk (THW) and the International Search And Rescue Germany (I.S.A.R Germany) also note the use of UAVs on their webpage and also the use of live video transmission (I.S.A.R Germany, 2017; THW, 2017)

One multi-mission study was found. After the 2013 Lushan Earthquake (ML<sub>7</sub>), where a UAV was used to support search and rescue personnel and the concluding results were examined. It was found, that the collection of aerial videos, in real-time and recordings, were more valuable in the analysis than static images (Qi *et al.*, 2016).

While it can be argued that the collection of videos is currently the most established use of UAVs in damage assessment for USAR, the lack of available research-specific literature is a limitation of this Literature Survey.

c. **Development of 3D data from UAV collected imagery**

Ever since UAVs have been able to collect high resolution imagery, the development of 3D Models of structures has been an often-used approach in numerous multidisciplinary research fields.

Most often, for the development of 3D models from UAV imagery, a Structure from Motion (SfM) technique is used. A number of overlapping aerial 2D images (ca. 100 per building) are fed into software for 3D feature extraction. Figure 3 provides a schematic overview of the SfM concept. (Westoby *et al.*, 2012). It is also argued that the use of ground images notably increases the quality of the obtained 3D models (Yamazaki *et al.*, 2017).

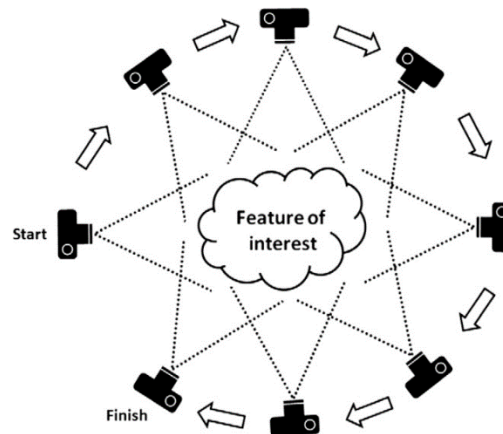


Figure 3 – SfM Concept (Westoby *et al.*, 2012)

After the L'Aquila earthquake in 2009, drone imagery was collected to develop three-dimensional models of buildings for damage assessment (Dominici, Alicandro and Massimi, 2017). This imagery was successfully utilised for detailed damage assessment but was not used to support USAR. In literature, it has often been suggested that the development of such models would require too much processing time for a successful implementation in rapid USAR (Kerle *et al.*, 2005). Two recent studies have proved that, with a prepared set up, generating this data would be possible within a sufficient time frame. (Hein *et al.*, 2017; Verykokou *et al.*, 2017).

d. **VR, and its application in 3D-GIS and disaster response**

Since its development in the early 90s, many applications of Virtual Reality (VR) have been developed across a range of scientific research fields. The definition of VR has long been sought, but has been difficult to establish (Portman, Natapov and Fisher-Gewirtzman, 2015). The most suitable definition was found in the English Oxford Living Dictionaries and is worded as follows: “*The computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors.*” (English Oxford Living Dictionaries, 2018). Milgram *et al.*, (1995) discuss the relationship, or “continuum” as they call it, between VR and the real world. This relationship results in multiple special characteristics that make VR such a valuable tool.

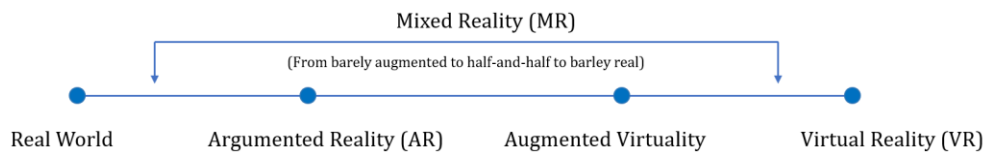


Figure 4 - Adapted from (Milgram *et al.*, 1995)

These special characteristics provide an immersive and interactive visualisation, whist enabling the user to maintain a sense of space and mass (Richards-Rissetto *et al.*, 2013). VR also allows the “existence” of the user, either through a First Person View (FPV) operation or provided through different levels of perception (Steuer, 1992; Kamel Boulos *et al.*, 2017). To successfully utilise VR many requirements must be met. First, the accuracy of a VR model must nowadays meet certain criteria. The expectation of the “realness” of a VR environment have increased with the availability of 360 videos and VR gaming engines (Portman, Natapov and Fisher-Gewirtzman, 2015). In addition, the frame rate and image quality must meet specific standards which vary greatly depending on the device used to view and interact with the VR model. The current high standard of GIS data usually meets these specific requirements.

A long-discussed issue of many GISs has been the representation of a three-dimensional space in a two-dimensional system (Boér, Çöltekin and Clarke, 2013). This is where the use of Virtual Reality as a GIS tool can provide a new perspective.

In the context of USAR, VR has been utilised as a training tool in multiple studies. Some of the training was developed for specialised USAR missions, while others were focussed on preparing individuals on how to act in case of an earthquake disaster (Tarnanas and Manos, 2001; Li *et al.*, 2017; Takahashi *et al.*, 2017).

A Literature Survey using the following, or a mix of, keywords did not result in the identification of relevant literature for the use of VR for USAR, USAR, SAR, VR, damage assessment, earthquake, visualisation.

e. **User studies and analysis methods in both HCI and VR**

This section describes the Literature Survey conducted for both the user study itself and the statistical analysis methods chosen.

As discussed by Kosara *et al.*, (2003) user studies provide useful insights on the task completion rate when users are provided with a range of visualisation methods. In a review by Kim, (2012) it was found that most studies use less than 24 users. The review also states that the number of participants in user studies is likely to rise. In consideration of the review and the central limit theorem a participant number of over 30 was found to be optimal for this thesis.

Designing a user study that incorporates the use of a Head Mounted Display (HMD) requires a number of special precautions (Sousa Santos *et al.*, 2009). To reduce any safety hazards the users should complete the tasks in a hazard free environment. In addition, recording answers that users give after finishing a task have to be recorded by the researchers instead of the users themselves.

Nausea or virtual reality sickness was also identified as a potential limitation for user studies using HMD or VR in general (McGill *et al.*, 2015). It is suggested to keep the time that users spend to a minimum and consider a number of design guidelines (Jerald, 2016), these are further described in Chapter 3.

When analysing result of user studies in VR a number of factors need to be considered. Jared (2016) discusses that due to the fact that researchers and users cannot see the information displayed miscommunication can be an issue. He also states that due to high sensory response to VR environments users can perceive time and space differently as they otherwise would in the real world.

The statistical analysis of the data is depended on the distribution of the data itself. A descriptive data exploration should be conducted (Young and Wessnitzer, 2016). Since the user study was conducted in an within-group style (one user gets exposed to all test methods) the type of statistical test chosen must be a repeated measures test (Fry, Wazny and Anderson, 2016). As the there were more than two matched groups that were compared a repeated measure ANOVA and the Friedman test were identified as the best option for the data analysis (Wobbrock and Kay, 2016). To further confirm these results, a post hoc test should be applied, in the case of this thesis data the Wilcoxon Signed Rank test was identified as the prime option.

f. **Results and summary of Literature Survey**

The research goals of the Literature Survey have been set as follows. Each section contains the relevant findings.

*Goal a: Establish current methods and tools employed by USAR personnel.*

The most commonly used methods were found to be – On-foot search, Street View imagery, Aerial Imagery and UAV collected Videos. Each of these methods were found to be susceptible to multiple limitations.

On- foot search, which is the simplest form of SAR, was found to be limited because of the time it consumed. Also, data is either not collected or of poor quality. When a mission is planned, the lack of accurate pre-event maps or other outdated geoinformation can lead to increased deceleration of victim recovery.

Street View imagery was found to only have limited use in USAR. The images were often used for reference and not the assessment of building damage.

Aerial imagery was found to be used in many research papers as well as USAR missions. Both UAV and satellite collected imagery were utilised in different studies. Depending on the analysis method, the use of aerial imagery produced varying accuracy results in a range of time frames. Both visual interpretation, and semi- or fully automated analyses were found to be susceptible to a number of constraints. The quality and repetition time of satellite acquired imagery were identified as a drawbacks, while the necessity for exceptional pilot skills as well as quality of image were the drawbacks of UAV imagery.

As with Street View imagery, only a small range of research papers relating to the use of UAV videos for USAR were found. When mentioned, it was found that the long review time was a predominant problem. No studies regarding the accuracy of this method were discovered.

*Goal b: Investigate development of 3D building models from UAV data.*

This Literature Survey identified Structure from Motion (SfM) as the main method to extract three-dimensional models from both UAV- collected videos and imagery. The processing time of different software was found to vary greatly depending on the quality of the images as well as the technical equipment used.

*Goal c: Investigate the use of Virtual Reality itself and its use in GIS & USAR.*

VR has been applied in a number of GIS based projects, especially in Urban Planning and Archaeology. Its characteristics were identified to be the immersive First-Person View (FPV) and the retention of dimensions and mass, as well as the interactive operation. A downside to the use of VR can be nausea and motion sickness.

*Goal d: Identify the optimal methodological and analytical approach for the user study.*

In order to create a VR Environment that a suitable for a user study a number of requirements have to be met. The special characteristics of a Head Mounted VR require further precautions when it comes to the data collection, these can be more practical – such as health and safety or based on the actual data collection itself – how the data is collected when the users cannot fill out questionnaires. As an analysis method repeated measured ANOVA or Friedman test were identified as the best analysis option depending on the distribution of the data. In both cases, if significance is found, a post hoc test needs to be applied.

### **3. Research Method**

This chapter is split into four sections. One contained with the design of the user study itself, one focussed on the data collection process, one describing the product design and finally the approach to the data analysis.

#### **a. Research Hypothesis**

In order to investigate both the temporal requirements as well as the accuracy obtained when assessing building damage using current USAR methods the following research hypothesis were developed.

*H<sub>1</sub> = There is no significant difference in the temporal requirements that users need to assess building damage after an earthquake when using Aerial Imagery, Street View Imagery, Video and a head mounted VR.*

*H<sub>2</sub> = There is no significant difference in the successful task completion rate when users assess building damage after an earthquake when using Aerial Imagery, Street View Imagery, Video and a head mounted VR.*

#### **b. Study design**

The user study was designed based on the findings of the Literature Survey. In order to investigate the user study hypothesis, 32 users were asked to complete a set of tasks, of which each set of tasks were concerned with a specific visualisation method. These Tasks can also be found in the Annex. The tasks which the users completed were established from the current baselines of disaster response data collection and reports as well as practical guidelines from the UN, INSARAG and OCHA. The users were asked to identify multiple aspects of the buildings, including use, type, plan, damage grading (according to EMS98), local damage, and the identification of possible voids and access points. The time the users took for each individual task was timed and a pressure environment, to mimic the time pressure in a search and rescue mission, was created by maximally allowing the users 2 minutes to answer per question and orally announcing the 30 second, 1 minute and 1 minute and 30 second mark.

To control the learning effect, the user was first provided with a training set of one aerial image, a street view image a video and a virtual reality environment so that they could accustom to each method. To reduce the effect further, the task sets and the task within the sets were randomised. A script was written to ensure that all candidates were guided with the same instructions and standards. A copy of the script is provided in the Annex. To start, the users answered a set of standard questions as well as questions about previous VR experience and any known adverse effects, which can be found in the Annex.

The users were then given a set of forms including the informed consent form and the standard question form. A randomised user identification number was assigned to each candidate to anonymise the study.

After each task section the users answered comparative questions. At the end of the study the users were asked to comparative questions regarding the different data collection methods. Both of these documents can be found in the Annex. Figure 9 is an example of the standard set up used during the user study.

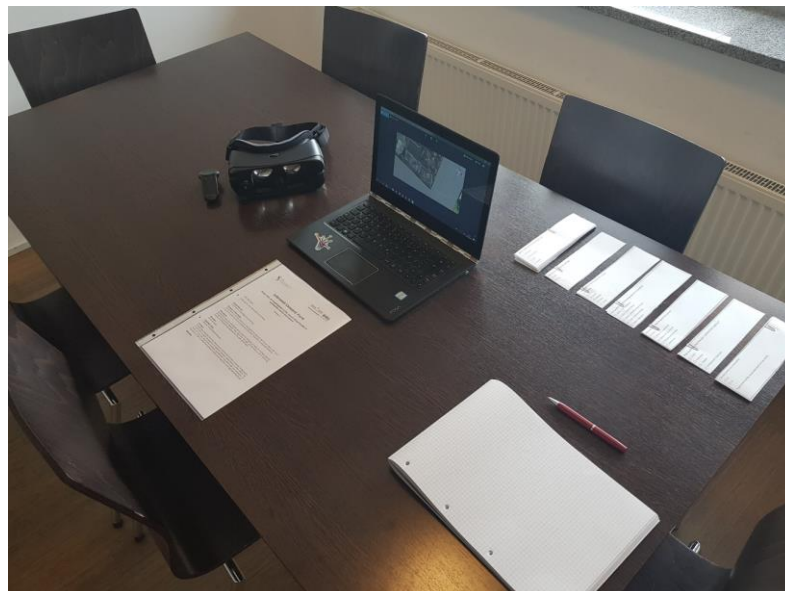


Figure 9 –User Study setup

**c. Equipment**

For the user study a Samsung Gear VR was used together with a Samsung Galaxy S8. This set up can also be seen in Figure 9. A notebook was used to manually record the results of the user study (time taken for the user to complete a task). This time was taken on a phone which cannot be seen in Figure 9 as it was used to record the image.

**d. Data collection process**

The data for the user study was collected from different online platforms such as turbosquid.com and assetstore.com. Four main packs were used, “Ruined City” by Dexsoft Games, Buildings & Ruins by Neckom Entertainment, Destroyed City by Profi Developers and Free HDR Sky by Proassets.

**e. Product design**

The data for the user study was collected from different online platforms such as turbosquid.com and assetstore.com. A grading scheme was developed to assess which buildings were the most suitable for the user study. The grading scheme can be found in the Annex. The individual buildings were selected based on factors such as floorplan, use/type, architecture, and spatial extent. The selection of the building and their location pattern, e.g. detached, semi-detached, terraced, as well as the scenes were, in all cases based on a survey undertaken. The individual models were then compiled into mini city scenes in Unity (Unity, 2018). To do so thirteen countries with the highest frequency of earthquakes were researched and building styles for both rural and urban areas were investigated. This allows a more realistic representation of the challenges faced by USAR personnel. To reduce learning effects 12 buildings were selected and the questions within the visualisation types were randomised. The development of each of the products are described in the following section. The process was the same for all the selected buildings to reduce any potential bias. A control building with no damage was also selected.

### Aerial imagery

Standard 2D products were created to mimic the use of orthophotos from both, high resolution satellites and drones. The product was generated by obtaining bird eye view images of each building. Figure 5 is an example of an image used in the user study.



Figure 5 – Aerial Imagery used in user study

### Direct view images

The direct view images were creating by mimicking the view a human would have when viewing the building directly. The product was generated by obtaining FPV images of each building. Again, Figure 6 is an example of an image used in the user study.



Figure 6 – Direct view image used in user study

## Video

The videos for the user study were produced to represent a drone video. The videos were recorded based on flying plans observed from USAR videos which were available to the public on a range of platforms.



Figure 7 – Screenshot of a video used in user study

## Virtual Reality

The Virtual Reality model was also created from the obtained Unity files. A range of factors have to be considered when developing Virtual Reality models for HCI. These were extensively investigated by Jerald (2016). He discusses object and subject relativity which was considered when selecting the range of damaged or destroyed buildings. This mostly effected the mesh structure as well as surface structure of the objects. In addition, perceptual modalities such as colour were also considered when setting shading effects and colour saturation when creating the final VR models for the user study. Jerald also ranks perception of space as an important factor to consider when designing VR environments. It was decided to re-create space as it would be found in urban environments. During the initial investigation for building styles it was found that urban environments in earthquake prone regions were sometimes extremely densely populated. For the ease of users who were expected to have no prior experience of VR the distances towards the objects when first entering the VR environment were slightly increased.

The users could alter this distance themselves when moving towards and away from the objects through tracked head movements. This allowed the continuous perception of space in the most realistic way. It was also suggested to remove any task-irrelevant objects to reduce the performance of users. Originally the obtained building models were often covered with ivory or other vegetation objects. These were removed. In order to maintain a complex visual scene other stimuli such as rubble were added to the scene instead. An often-discussed limitation of VR is motion sickness and eye strain. The scenes were designed with a calm sky and object colours were kept in a matching colour scheme to reduce this effect. Under the consideration of the above described factors a range of available SDKs (Software Development Kit) were utilised to make the created models ready for their use in the Gear VR. The main kits used were Java SE Development Kit 8u161 (Java and Oracle, 2018), to allow set up of handling options, Android Nougat 7.0 SDK with an API of 27 (Google, 2018) to allow the VR models to function on the mobile phone as well as Oculus' Platform SDK 1.20 and Avatar SDK 1.20 (Oculus, 2017). to allow compatibility of the VR model, the mobile device, and the Gear VR display. Frame rate was set to 60 FPS which allows the most realistic simulation of the real world and the texture compression was set to Adaptive Scalable Texture Compression to compress the file size. To finally run the game on a Samsung Galaxy 8 the phone was set into developer mode and USB debugging was enabled.

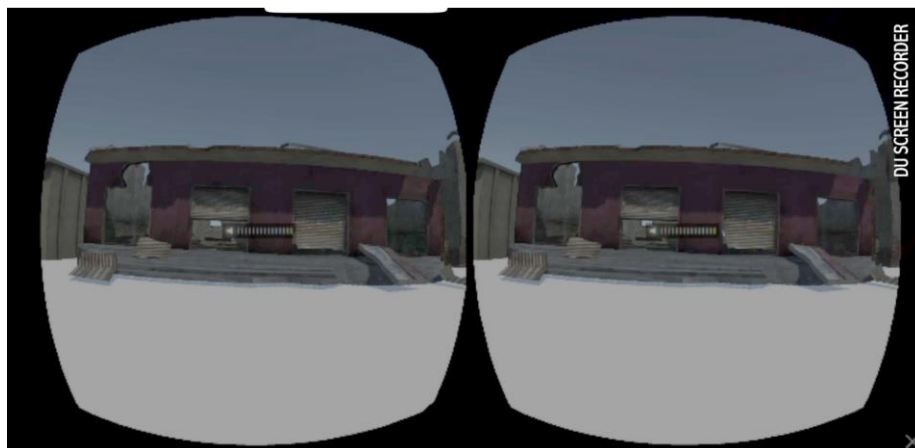


Figure 8 – Screenshot of VR model used in user study

**f. Approach to data analysis**

The user study was developed to investigate the perspective that virtual reality can bring to Disaster Management in earthquake disasters. In the user study 32 participants were asked to complete randomised tasks collecting information on buildings similar to a situation of an earthquake disaster. The tasks were based on UN, INSARAG and OCHA Guidelines and can be found in the Annex. To measure the factors which are relevant to obtaining the data required the user study metrics, discussed in Chapter 3, were chosen to be the following:

1. Success rate

The success rate measures the number of successfully completed tasks.

2. Descriptive statistics

An exploratory data analysis was undertaken using descriptive statistics.

3. Friedman Test

A Friedman test was conducted for the data analysis as the data was found to not be normally distributed. A Friedman test is used to test for differences within a group. To further specify the result, a post hoc Wilcoxon test was also applied after the Friedman test. For this the alpha value was changed to 0.666 by applying the Bonferroni correction (number of groups compared was always 3).

#### 4. User study results

##### User study demographics

This section will describe some of the user study demographics that were recorded with the standard questionnaire in the beginning of the study.

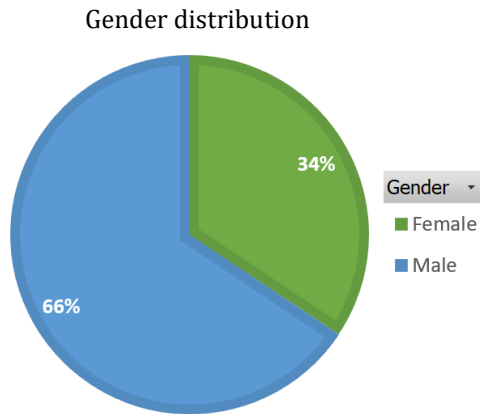


Figure 9 – Gender distribution

The average age of the users was 31.56 years and standard deviation of 15.49. Most of the study participants were male (Figure 10). Of the 32 users only one person had experienced sickness when using a VR headset before.

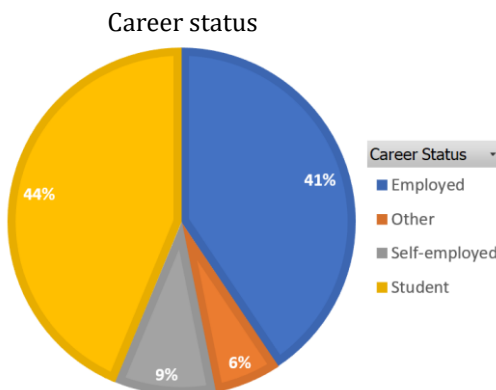


Figure 10 – Career status

Only two users had some prior experience in disaster management. Most of the users were either employed or students. Only a small range were self-employed or occupied otherwise.

Do you have any prior experience of virtual reality?

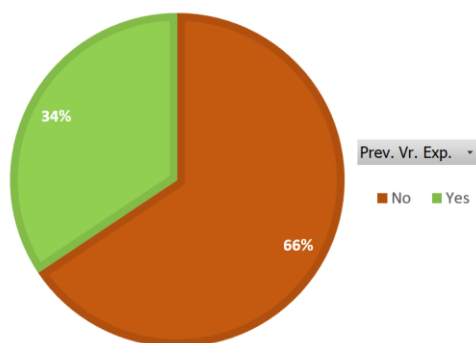


Figure 11 – Prior experience of VR

There was a higher number of users with none than users with prior experience with Virtual Reality. The users experience was (as stated) mostly based on gaming experiences or movies but no scientific applications.

### Building use

The users were asked to identify the use of the buildings with the following question:

**How would you class the use of this building?**

*Mark only one oval.*

- Residential
- Office
- School
- Commerce
- Factory
- Hospital

Figure 12 – User study question about building use

The standard statistics for the collected data was found to be the following:

	<i>Aerial Imagery</i>	<i>Street View</i>	<i>Video</i>	<i>VR</i>
<b>Mean</b>	16.92333333	12.3792	19.47423077	14.83692308
<b>Standard Error</b>	1.585057207	1.82031123	2.291125634	1.608751907
<b>Median</b>	16	10.53	16.015	12.79
<b>Standard Deviation</b>	6.138900165	9.101556149	11.68249431	8.203057366
<b>Skewness</b>	1.605530266	1.432652574	1.105008759	2.9276751
<b>Minimum</b>	10.28	1.51	4.96	6.4
<b>Maximum</b>	33.9	38.2	49.62	48.29

Table 2 – Standard statistics for building use question

The minimum time for a user to complete this task was 1.51 seconds while classing the use of the building by a Street View images. The maximum time for a user to successfully complete the task was 49.62 seconds. The standard deviation was found to range between 6.13 and 11.68 seconds, considering the maximum and minimum values the standard deviation is rather high. All of the tested assessment methods were highly skewed.

The average time for the users to complete the tasks was the lowest for users who classified the building use via Street View imagery (7.8 seconds). This was then followed by the VR, aerial imagery and finally by the video with the highest average of 19.47 seconds.

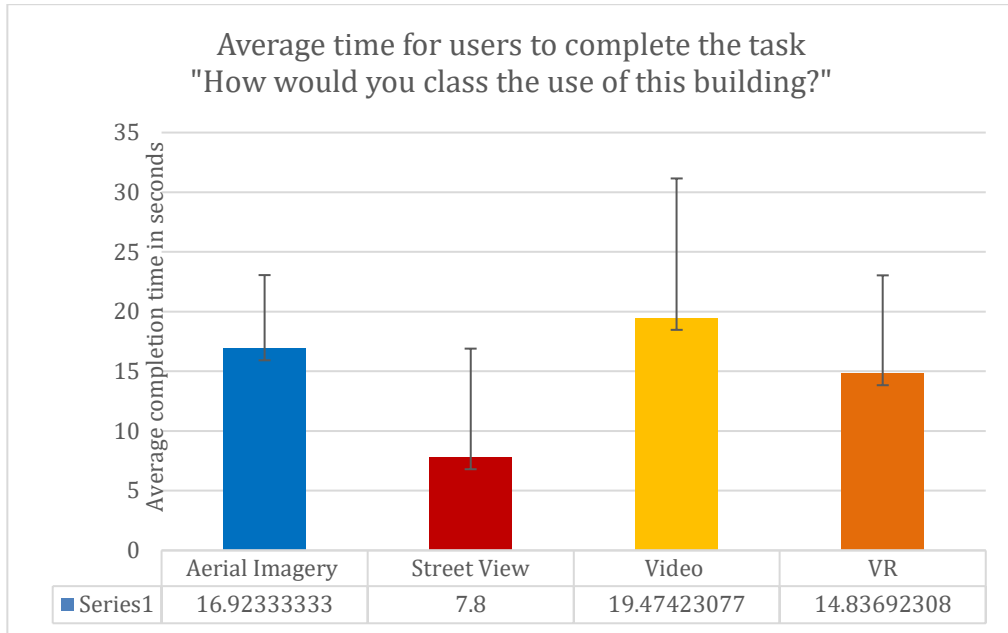


Figure 13 – Average time for “use” task completion showing S.D in error bars

The task completion rate was over 50% for all the assessment methods. Video and both that the highest completion rates. Both video and VR had the highest task completion rate with 81.25%.

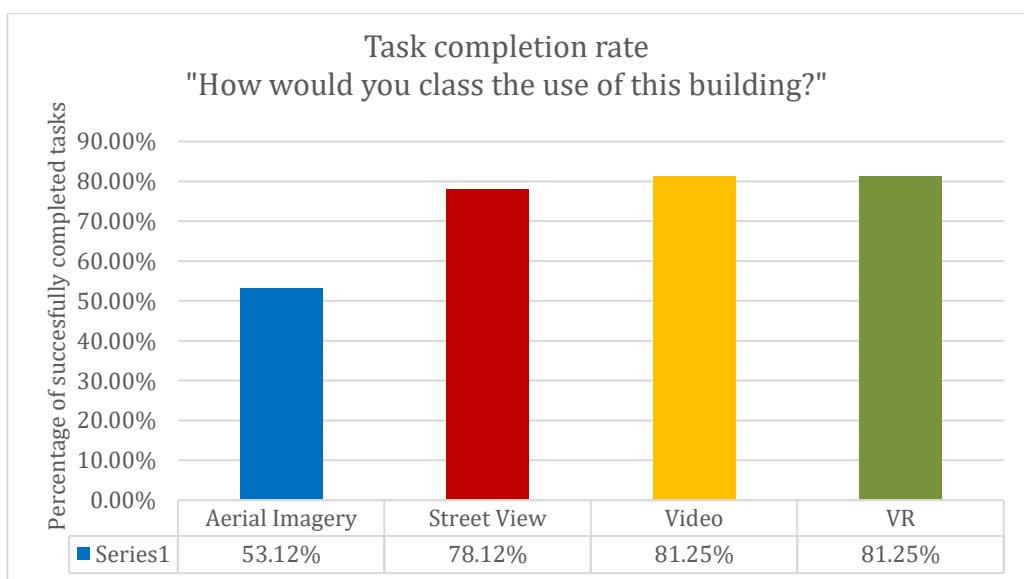


Figure 14 – Task completion rate for “use”

### Building type

The users were asked to class the type of the buildings based on the following question:

**How would you class the type of this building?**

*Mark only one oval.*

- Stone / Adobe
- Masonry with a wooden roof
- Masonry with a concrete roof
- reinforced concrete structure
- steel structure

Figure 15 – User study question about building type

The standard statistics for the collected data was found to be the following:

	<i>Aerial Imagery</i>	<i>Street View</i>	<i>Video</i>	<i>VR</i>
<b>Mean</b>	48.56307692	8.5235	23.805	19.06182
<b>Standard Error</b>	7.154786759	1.49045477	2.603516	1.893278
<b>Median</b>	46.6	6.765	24.3	17.17
<b>Standard Deviation</b>	25.79695053	6.66551635	11.64328	8.880259
<b>Skewness</b>	0.117374833	0.84074593	0.159349	0.440439
<b>Range</b>	89.1	22.23	41.74	30.29
<b>Minimum</b>	5.61	1.22	3.82	5.49
<b>Maximum</b>	94.71	23.45	45.56	35.78

Table 3 – Standard Statistics for building type question

The minimum values for all tested assessment methods were under 6 seconds with the lowest one being Street View with a value of 1.22 seconds and Aerial Imagery being the highest 5.61. Aerial Imagery was also found to have the highest maximum value (94.71) seconds. All of the tested assessment methods were slightly positively skewed. The standard deviation was the highest for Aerial Imagery and the lowest for Street View Imagery.

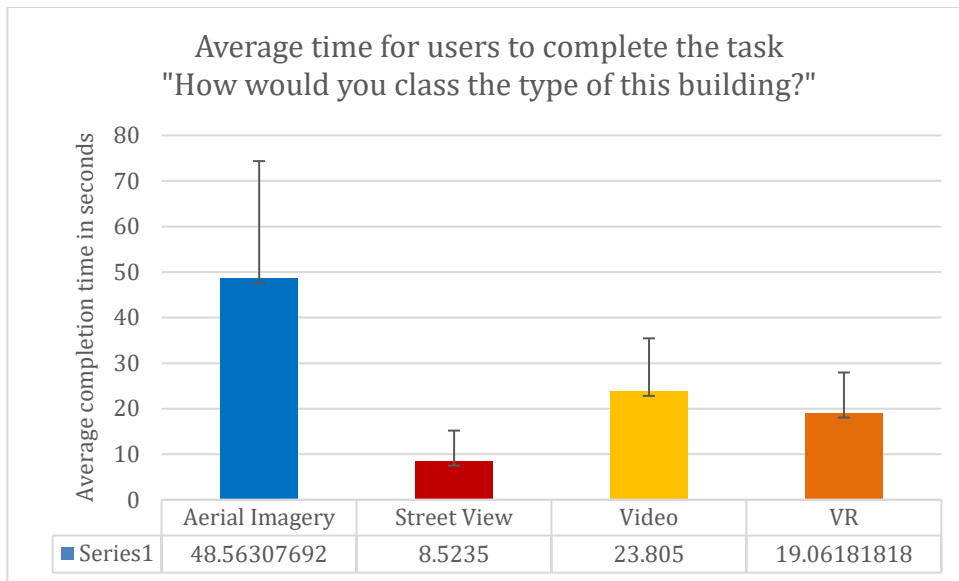


Figure 16 – Average time for “type” task completion showing SD in error bars

Users using Street View imagery completed the tasks with an average of only 8.52 seconds, followed by VR and Video. Aerial imagery had a higher average in comparison to the other methods. The standard deviation error bars indicate a significant difference between Aerial Imagery and other methods.

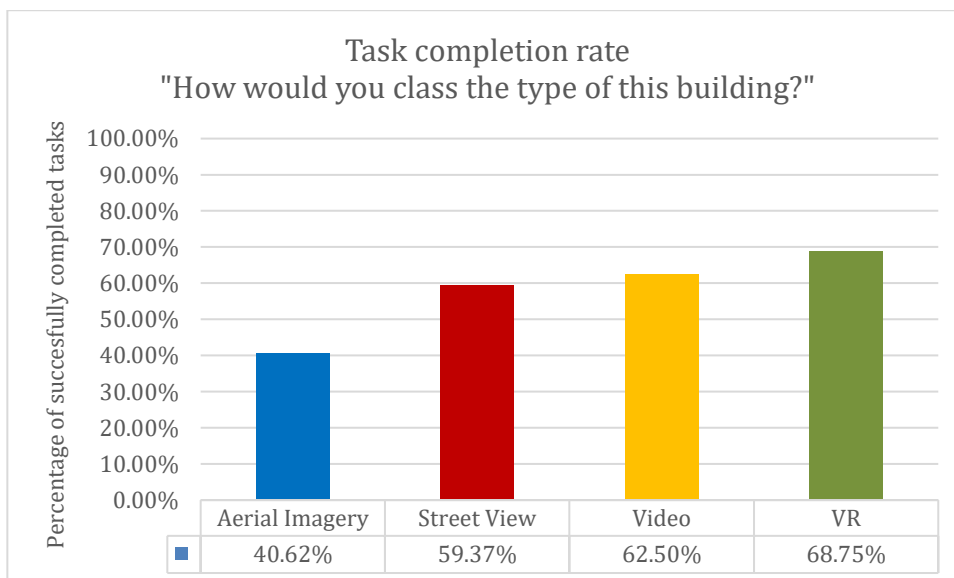


Figure 17 – Task completion rate for “type”

The task completion rate was found to be over 50% for Street View, Video and VR. Only aerial imagery had a lower task completion rate (40.62%). The standard deviation bars do suggest no significant difference in the task completion rate.

### Building plan

The users were asked to class the plan / outline of the buildings based on the following question:

**How would you class the plan / outline of this building ?**

*Mark only one oval.*

- Square
- Rectangular
- L-Shaped
- Unrecognisable / Destroyed

Figure 18 – User study question about building plan

The standard statistics for the collected data was found to be the following:

	<i>Aerial Imagery</i>	<i>Street View</i>	<i>Video</i>	<i>VR</i>
<b>Mean</b>	6.794138	29.26333	31.05727	25.15577
<b>Standard Error</b>	0.696882	4.169958	2.695466	2.64007
<b>Median</b>	5.76	31.28	27.8	22.795
<b>Standard Deviation</b>	3.752827	10.21427	12.64286	13.46177
<b>Skewness</b>	0.907336	-0.41902	0.64394	0.76221
<b>Range</b>	14.68	24.76	41.69	54.5
<b>Minimum</b>	1.7	15.84	15.52	5.8
<b>Maximum</b>	16.38	40.6	57.21	60.3

Table 4 – Standard Statistics for building plan question

For this task users using aerial imagery to assess the building plan were the quickest, this can be seen when looking the mean which was 6.79 seconds, the minimum value which was 1.7 seconds and the maximum value which was 16.38 seconds. All other methods had averages ranging from 25.15 sec (VR) to 31.05 sec (Video). All of the assessment methods apart from Street View Imagery were positively skewed. The standard deviation for Street View, Video and VR were in a similar range (between 10.21 and 13.46) while the SD for Aerial Imagery was only 3.75 seconds.

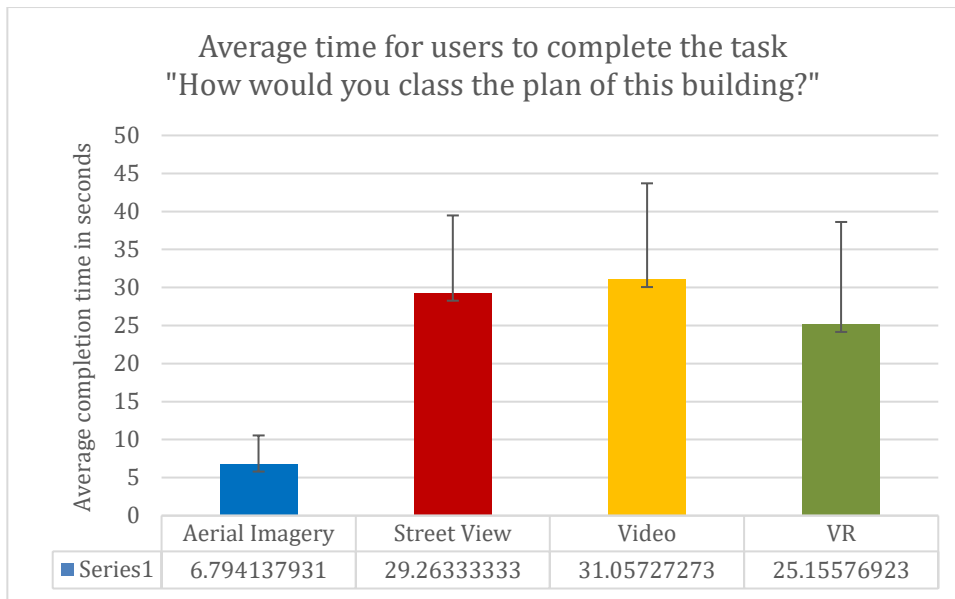


Figure 19 – Average time for “plan” task completion showing S.D in error bars

The average times for users to complete the plan task was the lowest for aerial imagery. The standard deviation (seen in error bars) was also lower than for the other methods. In comparison Street View Imagery, Video and VR produced similar results with a similar S.D.

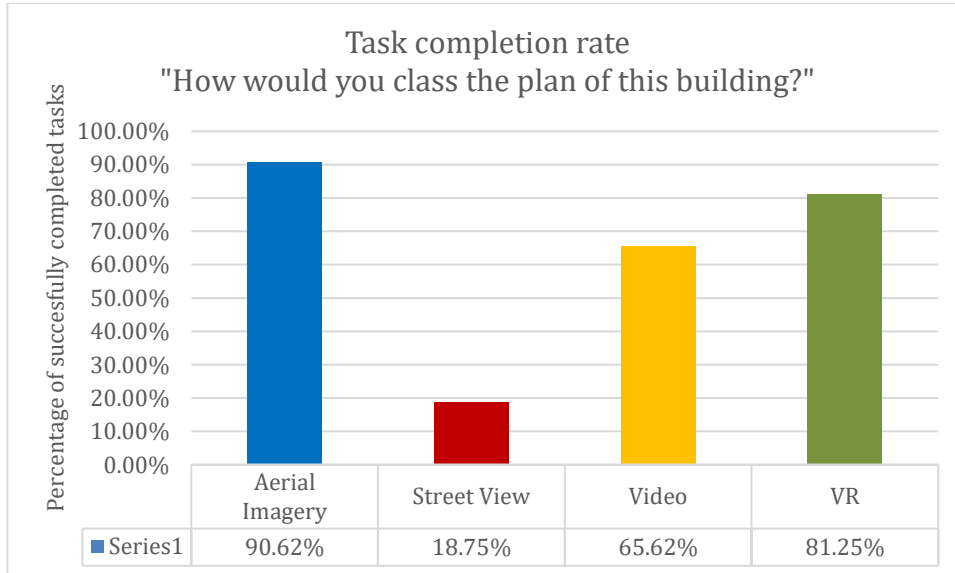


Figure 20 – Task completion rate for “plan”

The task completion rate for users assessing the building plan was highest for Aerial Imagery (90.65%) and lowest for Street View Imagery (18.75%).

Damage grade

The users were asked to class the damage of the buildings based on the following question:

**How would you class the damage grade of the building?**

*Mark only one oval.*

- Grade 1 – No visual damage
- Grade 2 - Moderate damage
- Grade 3 - Substantial to heavy damage
- Grade 4 - Very heavy damage

Figure 21 – User study question about damage grade

	<i>Aerial Imagery</i>	<i>Street View</i>	<i>Video</i>	<i>VR</i>
<b>Mean</b>	35.105	55.949	26.27875	17.70238
<b>Standard Error</b>	7.706425	7.603351	2.648943	1.509903
<b>Median</b>	30.125	56.665	25.85	17.12
<b>Standard Deviation</b>	21.79706	24.04391	10.59577	6.919246
<b>Skewness</b>	0.986743	-0.04288	0.469467	0.379757
<b>Range</b>	64.08	70.25	40.23	24.89
<b>Minimum</b>	10.3	19.09	7.47	7.22
<b>Maximum</b>	74.38	89.34	47.7	32.11

Table 5– Standard Statistics for damage grade question

To assess the damage grade users took a minimum of 7.22 seconds (VR) and a maximum of 89.34 seconds (Street View). The data was once again positively skewed apart from the Street View Imagery. The standard deviation was high for both Aerial Imager (21.97 seconds) and Street View Imagery (24.03 seconds). The video method had a S.D of 10.59 sec and VR had a S.D of 6.91 sec.

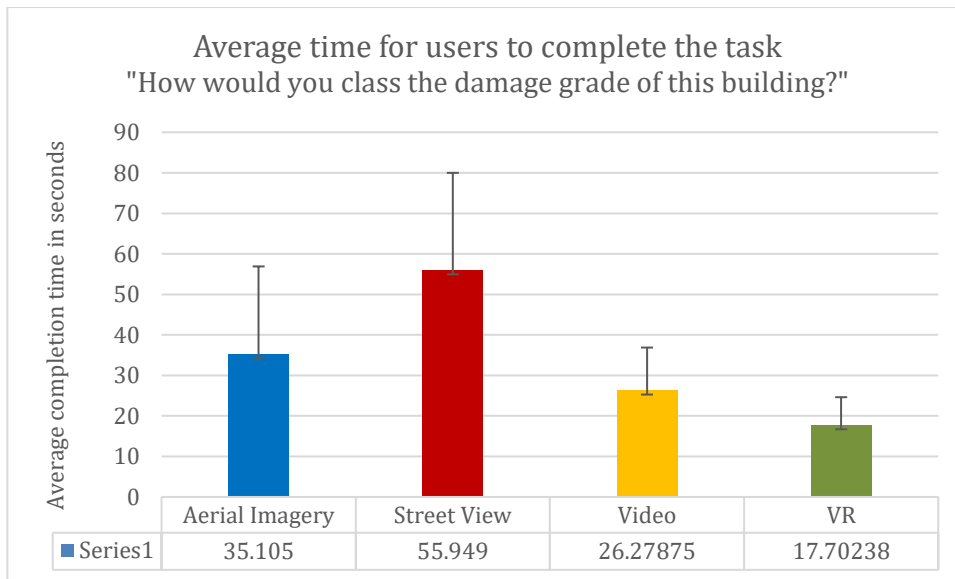


Figure 22 – Average time for “damage grade” task completion showing S.D in error bars

The average time for the users to assess damage grade was lowest when users were using the VR headset as an assessment method. The standard deviation was also lowest for this method (6.91 seconds). In contrast Street View Imagery was the method that took users the longest on average (55.94 seconds).

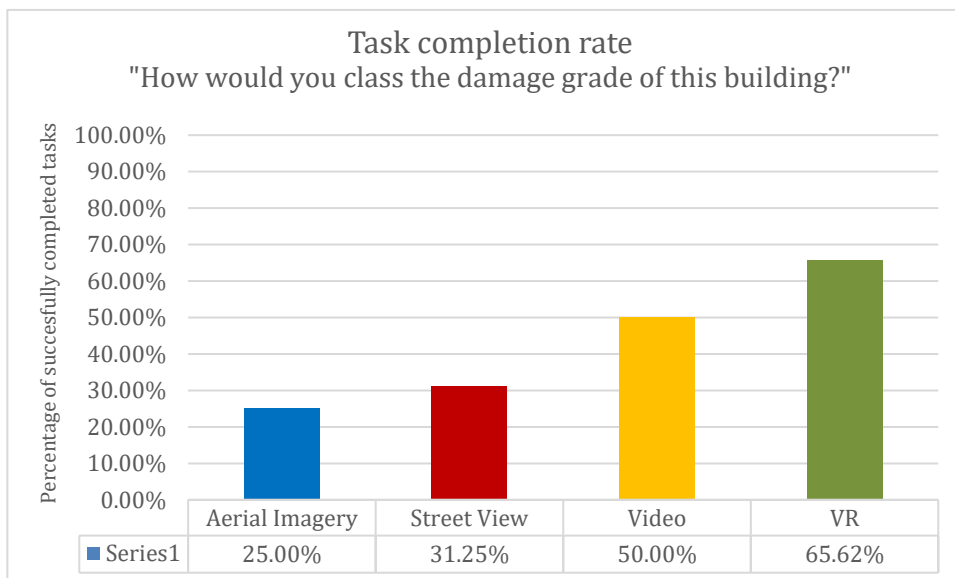


Figure 23 – Task completion rate for “damage grade”

The task completion rate was relatively low for the Aerial Imagery, Street View and Video (below 50%). Only the VR method produced a task completion rate of 65.62%.

### Local damage & local damage identification

The users were asked to identify local damage and in a further question to specifically identify damage to buildings based on the following question:

**Can you identify any local damage?**

*Mark only one oval.*

- Yes
- No

**If yes, where can you identify the damage?**

*Mark only one oval.*

- Damage to columns
- Damage to load-bearing walls
- Damage to beams
- Damage to floors
- Damage to connections
- Damage to roof

Figure 24 – User study question about local damage and local damage identification

	<i>Aerial Imagery</i>	<i>Street View</i>	<i>Video</i>	<i>VR</i>
<b>Mean</b>	4.8104	8.241379	15.59167	6.767097
<b>Standard Error</b>	0.792504	0.824027	1.129103	0.675446
<b>Median</b>	3.5	7.31	14.74	6.17
<b>Standard Deviation</b>	3.962518	4.43752	6.184351	3.760724
<b>Sample Variance</b>	15.70155	19.69158	38.2462	14.14305
<b>Skewness</b>	1.480802	0.331146	1.160545	0.424274
<b>Range</b>	15.79	14.88	30.37	13.88
<b>Minimum</b>	0.6	1.38	4.47	1.45
<b>Maximum</b>	16.39	16.26	34.84	15.33

Table 6 – Standard Statistics for local damage question

	<i>Aerial Imagery</i>	<i>Street View</i>	<i>Video</i>	<i>VR</i>
<b>Mean</b>	36.19333	41.35	45.13857	19.98
<b>Standard Error</b>	6.86004	5.105995	1.95796	2.434194
<b>Median</b>	32.81	41.6	45.36	19.735
<b>Standard Deviation</b>	11.88194	11.41735	5.180275	6.88494
<b>Skewness</b>	1.177464	-0.32599	0.001672	0.37966
<b>Range</b>	23.03	31.39	13.31	19.45
<b>Minimum</b>	26.37	24.83	38.87	11.45
<b>Maximum</b>	49.4	56.22	52.18	30.9

Table 7 – Standard Statistics for local damage identification question

When the users were asked to identify any local damage, the minimum time was between 0.6 seconds (Aerial Imagery) and 4.47 seconds (Video). In contrast when users where asked to specifically identify damage the minimum time users took rose up to 11.45 seconds (VR). The standard deviation for any local damage identification ranged between 3.76 seconds (VR) and 6.18 seconds (Video). In contrast the standard deviation for specific damage identification was much higher (ranging between 5.18 seconds and 11.88 seconds).

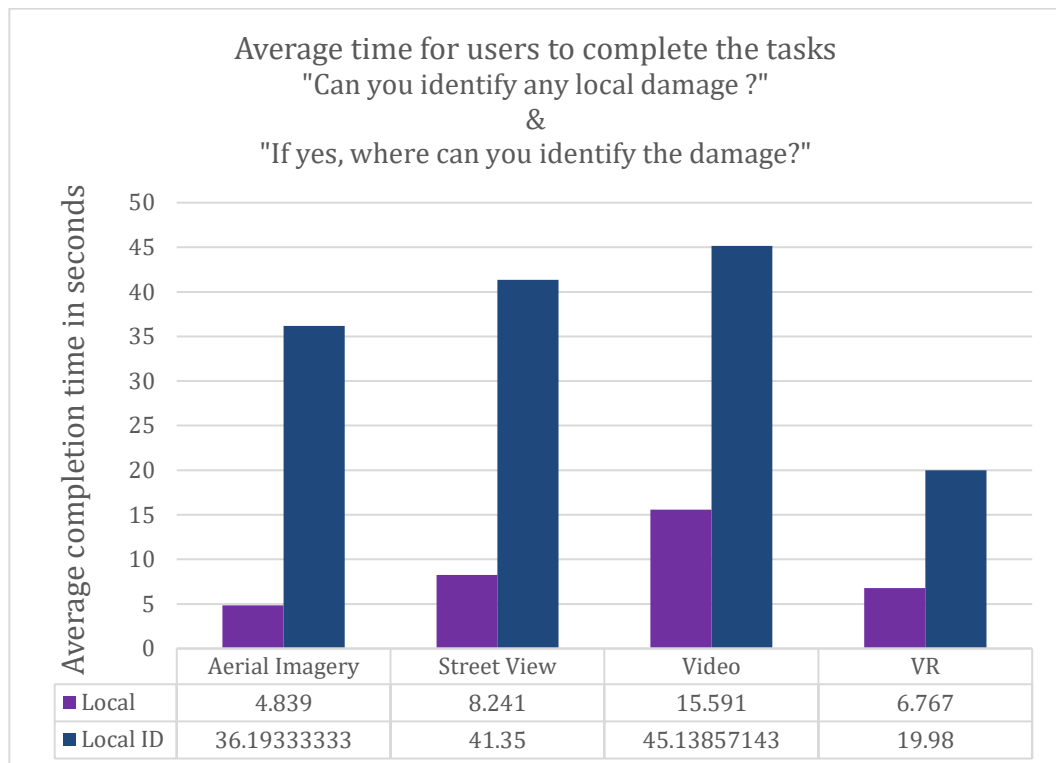


Figure 27 – Average time for “local damage” and “local damage identification” task completion

The average task completion time was significantly higher when users were trying to identify specific building damage. Video had the highest average for both tasks. When the users were asked to identify any damage Aerial Imagery produced the lowest average, for the specific local identification VR had the lowest average.

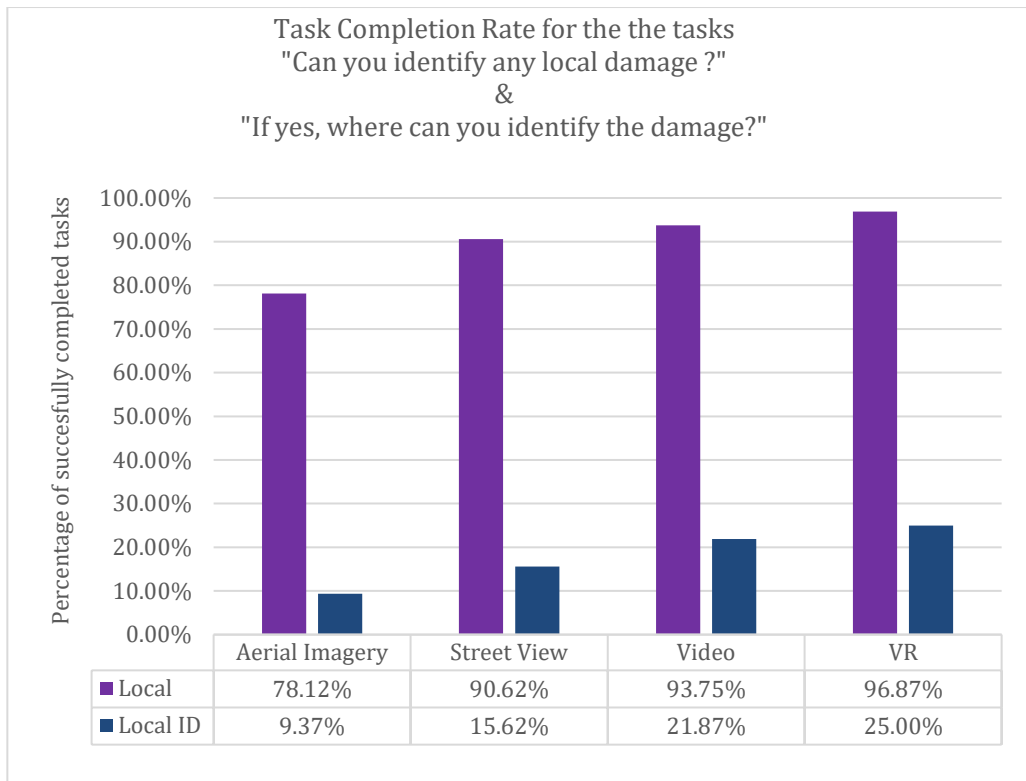


Figure 28 – Task completion rate for “local damage” & “local damage identification” task

The task completion rate when users where identifying damage was found to be very high. All methods produced completion rates over 75%. Rather contrasting, the users asked to identify specific damage only had a task completion rate ranging between 9% (for Aerial Imagery) and 25% for Virtual Reality. The method with the highest task completion rate was found to be VR, this counts for both, general and specific damage identification.

### Access points

The users were asked to identify any access points based on the following question:

**Can you identify any access points?**

*Mark only one oval.*

Yes

No

	<i><b>Aerial Imagery</b></i>	<i><b>Street View</b></i>	<i><b>Video</b></i>	<i><b>VR</b></i>
<b>Mean</b>	9.275714286	15.35667	14.558	4.877143
<b>Standard Error</b>	1.394562326	1.341218	1.29014021	0.625773
<b>Median</b>	9.18	15.61	15.305	3.62
<b>Standard Deviation</b>	3.689665103	4.023655	4.07978158	2.867654
<b>Skewness</b>	0.099480469	-0.38619	-0.4862177	1.063745
<b>Range</b>	9.97	12.41	12.81	9.92
<b>Minimum</b>	4.58	8.3	7.41	1.87
<b>Maximum</b>	14.55	20.71	20.22	11.79

Table 8 – Standard Statistics for access point identification question

When users were asked to identify access points to the damaged buildings the minimum time a user required was 1.87 seconds in the VR, followed by Aerial Imagery with 4.58 seconds, Video with 7.41 seconds and Street View Imagery with 8.3 seconds. The maximum time followed similar trends with the VR having the lowest maximum time (11.79 seconds), followed by Aerial Imagery with 4.58 seconds. Street View Imagers and Video had similar results of 20.71 seconds and 20.22 seconds respectively. The Standard Deviation was comparatively low with a range of 2.86 seconds for the VR and 4.07 seconds for the Video. Aerial Imagery and VR were both highly positively skewed while Street View Imagery and Video were minimally negatively skewed.

The average time that users took to complete the task was lowest for VR (4.87 seconds). This was followed by Aerial Imagery with an average of 9.04 seconds. Street View and Video had similar average times of 15.35 and 14.58 seconds respectively.

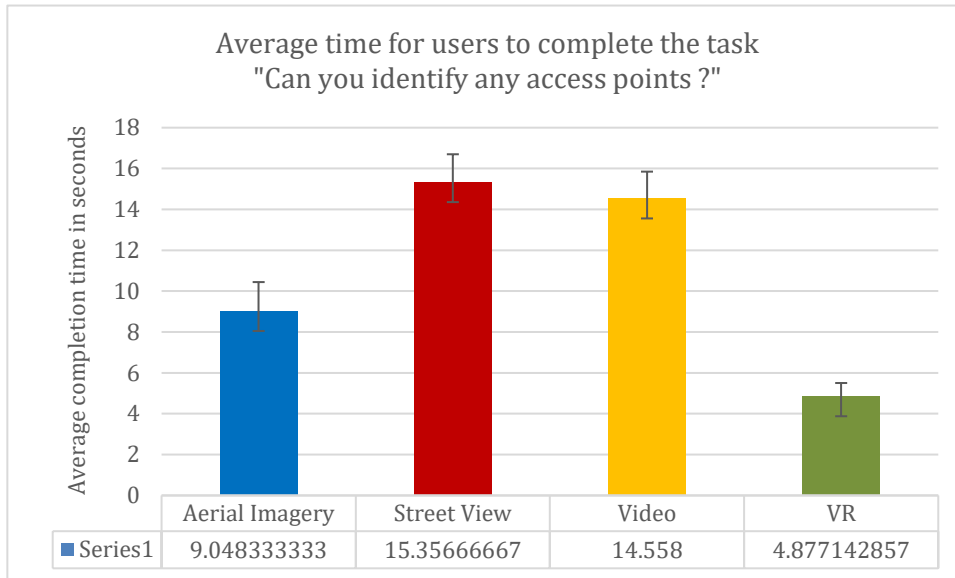


Figure 29 – Average time for “Can you identify any access points” task completion

The task completion rate when users were asked to identify any access points was the highest for VR (65.62%). The other methods did not produce high task completion rate as the second highest value was found for the Video (31.25%). Aerial Imagery had the lowest successful task completion rate which was found to be 19.44%.

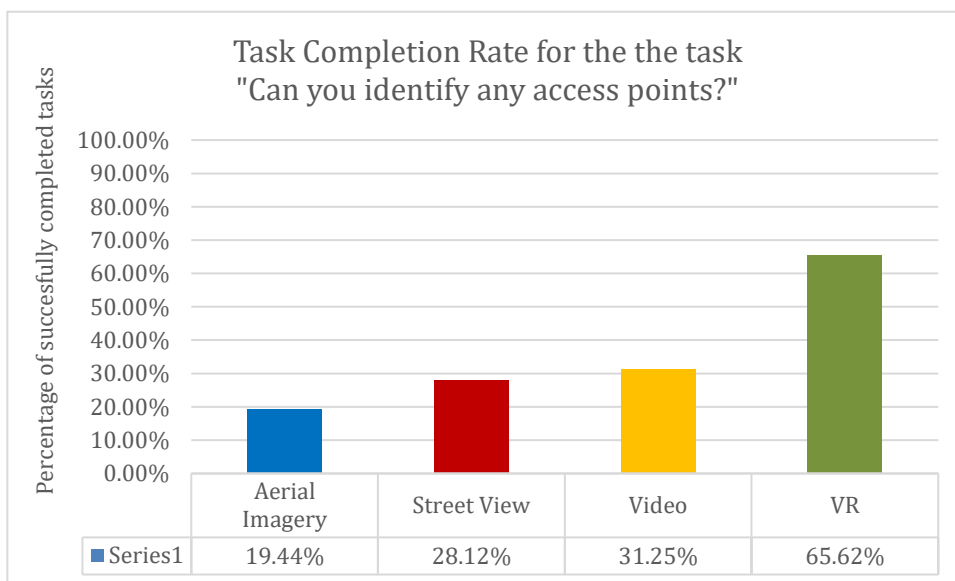


Figure 30 – Task completion rate for “Can you identify any access points” task

### Comparative Questions

The users were asked which method felt of most natural use. More than 40% of the users found that the Video was the most natural form of visualisation. This was followed by the VR with 36% and Street View imagery with 21%.

Which method felt of most natural use?

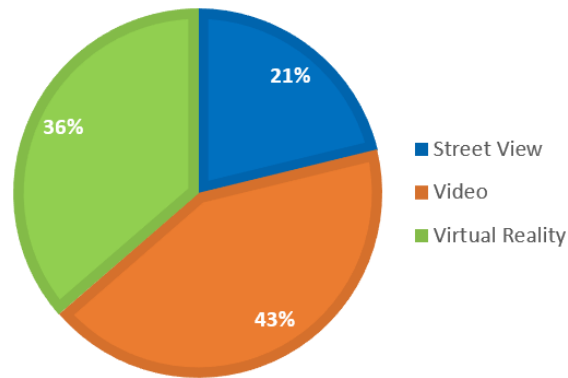


Figure 31 - Which method felt of most natural use?

In another comparative question the users were asked which method felt the most time efficient. Just over 50% of the users stated that they felt that virtual reality was most time efficient. This was followed by the Video assessment method with 24%, Street View Imagery with 15% and finally aerial imagery with 15%.

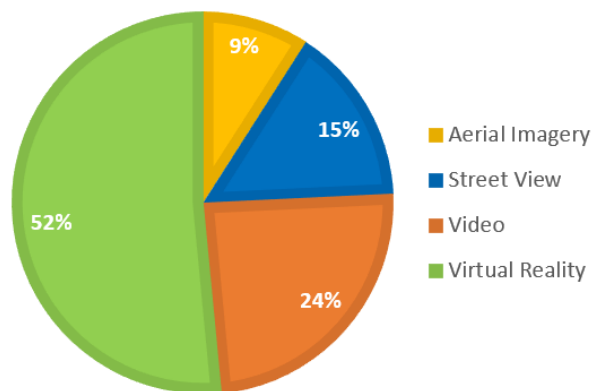


Figure 32 - Which method felt most time efficient ?

Friedman and Post Hoc Wilcoxon test for average time per task

This section presents the results of the Friedman and Post Hoc Wilcoxon test. The detailed Wilcoxon rank results can be found in the Annex.

	<b>Friedman</b>	<b>Post Hoc Wilcoxon test</b>																				
<b>Building Use</b>	<p><b>Test Statistics<sup>a</sup></b></p> <table border="1"> <tr><td>N</td><td>9</td></tr> <tr><td>Chi-Square</td><td>11.000</td></tr> <tr><td>df</td><td>3</td></tr> <tr><td>Asymp. Sig.</td><td>.012</td></tr> </table> <p>a. Friedman Test</p>	N	9	Chi-Square	11.000	df	3	Asymp. Sig.	.012	<i>Not conducted as p value was greater than 0.05</i>												
N	9																					
Chi-Square	11.000																					
df	3																					
Asymp. Sig.	.012																					
<b>Building Type</b>	<p><b>Test Statistics<sup>a</sup></b></p> <table border="1"> <tr><td>N</td><td>9</td></tr> <tr><td>Chi-Square</td><td>15.800</td></tr> <tr><td>df</td><td>3</td></tr> <tr><td>Asymp. Sig.</td><td>.001</td></tr> </table> <p>a. Friedman Test</p>	N	9	Chi-Square	15.800	df	3	Asymp. Sig.	.001	<p><b>Test Statistics<sup>a</sup></b></p> <table border="1"> <thead> <tr> <th></th> <th>AerialImagery - VR</th> <th>StreetView - VR</th> <th>Video - VR</th> </tr> </thead> <tbody> <tr> <td>Z</td> <td>-2.746<sup>b</sup></td> <td>-2.430<sup>c</sup></td> <td>-.686<sup>b</sup></td> </tr> <tr> <td>Asymp. Sig. (2-tailed)</td> <td>.006</td> <td>.015</td> <td>.492</td> </tr> </tbody> </table> <p>a. Wilcoxon Signed Ranks Test b. Based on negative ranks. c. Based on positive ranks.</p>		AerialImagery - VR	StreetView - VR	Video - VR	Z	-2.746 <sup>b</sup>	-2.430 <sup>c</sup>	-.686 <sup>b</sup>	Asymp. Sig. (2-tailed)	.006	.015	.492
N	9																					
Chi-Square	15.800																					
df	3																					
Asymp. Sig.	.001																					
	AerialImagery - VR	StreetView - VR	Video - VR																			
Z	-2.746 <sup>b</sup>	-2.430 <sup>c</sup>	-.686 <sup>b</sup>																			
Asymp. Sig. (2-tailed)	.006	.015	.492																			
<b>Building Plan</b>	<p><b>Test Statistics<sup>a</sup></b></p> <table border="1"> <tr><td>N</td><td>3</td></tr> <tr><td>Chi-Square</td><td>3.400</td></tr> <tr><td>df</td><td>3</td></tr> <tr><td>Asymp. Sig.</td><td>.334</td></tr> </table> <p>a. Friedman Test</p>	N	3	Chi-Square	3.400	df	3	Asymp. Sig.	.334	<i>Not conducted as p value was greater than 0.05</i>												
N	3																					
Chi-Square	3.400																					
df	3																					
Asymp. Sig.	.334																					
<b>Damage grade</b>	<p><b>Test Statistics<sup>a</sup></b></p> <table border="1"> <tr><td>N</td><td>3</td></tr> <tr><td>Chi-Square</td><td>1.800</td></tr> <tr><td>df</td><td>3</td></tr> <tr><td>Asymp. Sig.</td><td>.615</td></tr> </table> <p>a. Friedman Test</p>	N	3	Chi-Square	1.800	df	3	Asymp. Sig.	.615	<i>Not conducted as p value was greater than 0.05</i>												
N	3																					
Chi-Square	1.800																					
df	3																					
Asymp. Sig.	.615																					
<b>Local damage</b>	<p><b>Test Statistics<sup>a</sup></b></p> <table border="1"> <tr><td>N</td><td>23</td></tr> <tr><td>Chi-Square</td><td>28.461</td></tr> <tr><td>df</td><td>3</td></tr> <tr><td>Asymp. Sig.</td><td>.000</td></tr> </table> <p>a. Friedman Test</p>	N	23	Chi-Square	28.461	df	3	Asymp. Sig.	.000	<p><b>Test Statistics<sup>a</sup></b></p> <table border="1"> <thead> <tr> <th></th> <th>AerialImagery - VR</th> <th>StreetView - VR</th> <th>Video - VR</th> </tr> </thead> <tbody> <tr> <td>Z</td> <td>-2.327<sup>b</sup></td> <td>-.455<sup>c</sup></td> <td>-4.400<sup>c</sup></td> </tr> <tr> <td>Asymp. Sig. (2-tailed)</td> <td>.020</td> <td>.649</td> <td>.000</td> </tr> </tbody> </table> <p>a. Wilcoxon Signed Ranks Test b. Based on positive ranks. c. Based on negative ranks.</p>		AerialImagery - VR	StreetView - VR	Video - VR	Z	-2.327 <sup>b</sup>	-.455 <sup>c</sup>	-4.400 <sup>c</sup>	Asymp. Sig. (2-tailed)	.020	.649	.000
N	23																					
Chi-Square	28.461																					
df	3																					
Asymp. Sig.	.000																					
	AerialImagery - VR	StreetView - VR	Video - VR																			
Z	-2.327 <sup>b</sup>	-.455 <sup>c</sup>	-4.400 <sup>c</sup>																			
Asymp. Sig. (2-tailed)	.020	.649	.000																			
<b>Local damage identification</b>	Could not be conducted due to:	<p><b>Warnings</b></p> <p>There are not enough valid cases for processing. No statistics are computed.</p>																				
<b>Access Point</b>	<p><b>Test Statistics<sup>a</sup></b></p> <table border="1"> <tr><td>N</td><td>2</td></tr> <tr><td>Chi-Square</td><td>6.000</td></tr> <tr><td>df</td><td>3</td></tr> <tr><td>Asymp. Sig.</td><td>.112</td></tr> </table> <p>a. Friedman Test</p>	N	2	Chi-Square	6.000	df	3	Asymp. Sig.	.112	<i>Not conducted as p value was greater than 0.05</i>												
N	2																					
Chi-Square	6.000																					
df	3																					
Asymp. Sig.	.112																					

Table 9 – Results of Friedman and Wilcoxon tests

## General Comments

Four users commented that Street View Imagery and the Video were “easier” to analyse as they were more used to the format of the image. Two users stated that the VR allowed them to interact with the data more efficiently, being able to view the areas they were interested in with more ease in comparison to other methods. In addition, one user felt nausea from the VR, the user was then offered water but wanted to continue with the user study. He or she were given a new building to assess to avoid any bias in the successful task completion time.

## **5. Discussion and Conclusion**

Following the same structure as the results chapter this section will discuss the findings.

### **a. Discussion of results**

When comparing the average time users took to successfully complete the tasks Aerial Imagery and Street View Imagery has the lowest average time twice. This seems to correspond with the level of dimensionality required to assess the building correctly. For example, users were the fastest when they were asked to identify the plan/ outline of building. Aerial Imagery provides a direct 2-D birds eye view perspective of the building resulting in a low time average that users needed to complete the task. More complex methods such as Video and VR are more complex to analyse and therefore required more time. When the scene becomes more complex, for example when users were asked to identify any access points VR was the method found to have the lowest average task completion time as the dimension and the interactive approach allow a much faster identification of the access points. Overall Aerial Imagery and Street View Imagery were, as afore mentioned, the fastest methods to assess building damage in 2 tasks each. The Video never scored the lowest average time, users often scrolled back in the video after viewing it for the first time which largely increased their average completion time. Virtual Reality was the method with the lowest average in 3 tasks.

These tasks were more complex and required a 3-Dimensional visual analysis for the users to correctly identify any building damage. When the Friedman test was conducted only 2 tasks showed a significant difference in the average task completion time. The tasks were building type and local damage. After applying the Bonferroni correction to the  $\alpha$  value the new significance value was set to be 0.166. For building type there was a significant difference between Aerial Imagery ( $p=0.06$ ) and Virtual Reality. For Local damage the p value for Video to VR was found to be  $P=0.000023$ , this could most likely be due to the sample size or errors during the analysis and will not be reported as not significant.

Even though VR was only found to have a significant lower average in one case, 52% of users found that VR felt the fastest method to complete the tasks. This is most likely due to the fact that users can perceive time differently in a VR compared to other methods. The high number of sensory stimuli can result in a wrongful perception of time as discussed by Jerald (2016).

In contrast to the average time users took to complete the task the successful task completion rate produced less distributed results. Aerial Imagery produced the highest successful task completion rate when users were asked to identify the building plan, the effect of dimensionality on this specific task has already been previously discussed. There was a tie for the task completion between the Video and the VR for the task where users were asked to identify building use. In most cases (6/7) VR resulted in the highest task completion rates. There are a range of possible causes for this strong trend. During the user studies users were vocally interacting with the VR on a much higher rate than they were for the other tasks. As aforementioned, two users also stated that the VR allowed them to interact with the data more efficiently, being able to view the areas they were interested in with more ease in comparison to other methods.

When users were asked which method felt of most natural use most users chose Video analysis with 43%, followed by VR with 36%, 21% of users stated that Street View Imagery felt most natural, Aerial Imagery was never stated to feel most natural. Even though most users only had a limited or no prior experience with VR the high results could be due to the design of the VR that was created in close relation to the standards established by Jerald (2016), this allowed users to handle the VR with ease and to obtain high standards of successful task completion rate.

**b. Limitations**

This thesis compares the standard methods utilised by USAR personnel. One standard method that is often used is on foot search. Since there are no destroyed buildings available in the area and training individual users to assess damage grade would require too much time this method of USAR was not tested in the user study. It could also be argued that the use of drone collected data for the VR model would have been beneficial to create a more realistic environment. Damaged buildings are complex environments with a high number of visual triggers. Research found that humans can only perceive a certain number of triggers before over exceeding their cognitive processing capacity (Mayer and Moreno, 2003). This could be a potential disadvantage for USAR personnel when assessing damaged buildings. However, this is a problem that the personnel would face in both a real scenario or a scene in a VR model. It can also be assumed that further training in the VR could improve the task completion rate as well as improving the time the users required to complete tasks (Jerald, 2016).

Although these factors significantly influence the perception and uptake of information a study by Ragan *et al.*, (2015) found that when testing different levels of visual complexity it did not result in a significant difference in the uptake of information and task performance as well as the strategy applied by users to scan the field of view. Another study conducted by Maffei *et al.*, (2016) compared simulated models of urban

scenes to real imagery and found no significant difference in the perception and evaluation between both. Under consideration of the factors discussed by Jerald (2016) (see Chapter 3) and the conclusions from Ragan *et al.*, (2015) and Maffei *et al.*, (2016) the conclusion that using simulated environments instead of real imagery should not significantly affect the outcome of the study can be made. Due to the large number of individual building models required for the user study to reduce the learning effect and again the temporal restriction of the user study it was decided to use a 3-dimensional model. Within the user studies the demographics of the users were slightly unbalanced. There was a higher male to female ratio and the lack for prior VR and disaster management experience could change the outcomes of the user study results favourably. Within the time scale of this thesis it was not possible to recruit a high number of users with either VR experience and/ or disaster management skills. This could be further developed in future studies and is further described in Chapter 6.

Some limitations applied to the statistical tests of the user study. Only the time for successfully completed tasks were recorded the n-number was often found to be very low and could influence the test results. The task “local damage identification” produced such a low n-number that the analysis was rejected in SPSS.

### **c. Conclusion**

Considering the limitations of this study it can be stated that there are strong recognisable trends that VR is a useful tool for Urban Search and Rescue in earthquake disasters. Although only one significant difference in the average time users took to successfully complete tasks was found this result could potentially be further improved when users were provided with more detailed training in both assessment strategies and the handling of the VR. It can also be concluded that the successful task completion rate was most often the highest for the VR. Since VR was identified as a useful

tool to USAR further work that explores the limitations of this study needs to be conducted. This is discussed in the next Chapter.

## **6. Future work**

One motivation for this thesis was the potential for future work. As established during the literature survey the time frame to recover victims in earthquakes is limited to around 72 hours. Further investigation towards the temporal requirement of the concept presented in Chapter 1 (section b) are needed. This should be focussed on collecting real UAV imagery of destroyed buildings and transforming them into a VR. Recording the time it requires to collect the data and running it on a range of computers to establish a standard processing time could further validate the suitability of VR as a tool for USAR. In addition, another user study testing a range of handling methods of the VR could also be further studied.

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**Annex**

**INSARAG Field Guideline**

**Annex W: Worksite Triage Form – Front**

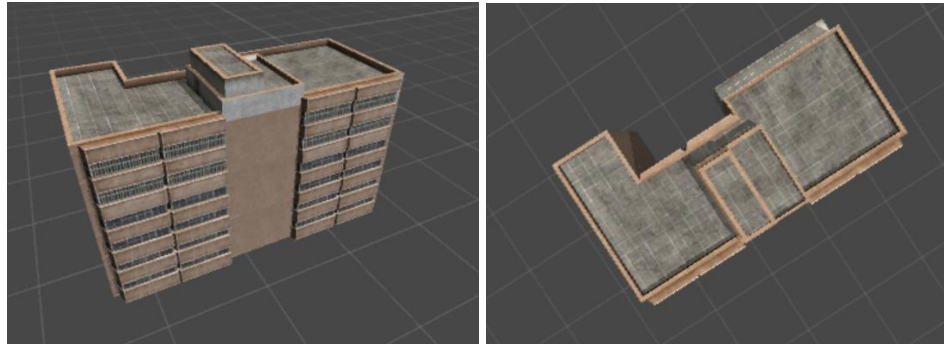
<b>Worksite Triage Form</b>																	
Used during assessment to identify worksites with rescue opportunities																	
E1. Worksite ID			E2. GPS Coordinates <b>Decimal format</b>		±dd.dddd °		E2. GPS Coordinates <b>other format</b>			±ddd.dddd °							
			or														
E3. Address																	
E4. Worksite boundary description:																	
F1. Team ID		AAA		00		F2. Date		DD		MMM		F3. Time		hh		mm	
F4. Building Use																	
F5. Construction type																	
F6. Floor area			m x m		F7. No. of floors			F8. No. of basements									
F9. Total number of missing/unknown persons at the Worksite												Level 3 Rapid SAR needed	Level 4 Full SAR needed				
F10. Of the total number, how many are confirmed live?																	
F11. Triage category: Input letter using matrix: →												→ ↘ F11					
F12. Degree of Damage (%)								Confirmed live victims		A	B						
F13. Type of collapse:								Unknown victims and big voids		C	E						
F14. Any unusual hazards at the Worksite?								Unknown victims and small voids		D	F						
F15. Assess the main USAR operations likely to be needed at this Worksite:																	
Indicate main work needed:						Give an estimate of the time, personnel and equipment needed:											
A: Dog/technical search		x		Details:													
B: Shoring and propping		x															
C: Breaking, Breeching		x															
D: Lifting and moving		x															
E: Rope/height working		x															
F: Medical Needs		x															
F16. Local Safety/Security situation:																	
F17. Other Information:																	
Completed by: Name								Title/position									

## Building grading scheme

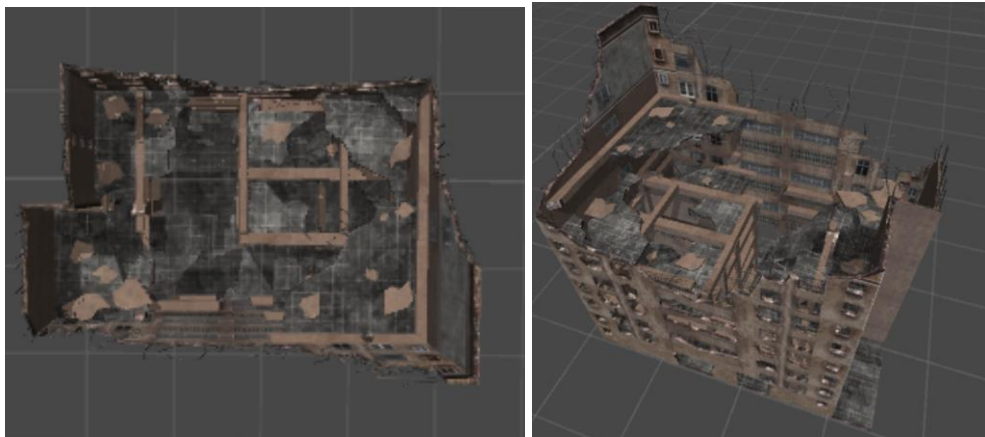
Building Number	Link	Use Identifiable	Use	Type identifiable	Type	Plan identifiable	Damage grade identifiable
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	factory	Yes	stone, adobe	Yes	rectangular
13	<a href="https://www.assetstl">https://www.assetstl</a>	Yes	residence	Yes	masonry/concrete roof	Yes	multiple but mostly rectangular
1	<a href="https://www.assetstl">https://www.assetstl</a>	Yes	office / residence	Yes	reinforced concrete structure	Yes	square
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	commerce / factory	Yes	reinforced concrete structure	Yes	L shapes
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	residence	Yes	reinforced concrete structure	Yes	rectangular
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	residence	Yes	stone, adobe	Yes	rectangular
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	school	Yes	masonry/concrete roof	Yes	rectangular
52	<a href="https://www.assetstl">https://www.assetstl</a>	Yes	multiple	Yes	multiple / mostly concrete	Yes	multiple
<b>Building Number</b>							
<b>Link</b>							
<b>Local Damage identifiable</b>							
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	Local Damage identifiable	Yes	Possible voids identifiable	voids created by structural elements and the pattern of collapse	
13	<a href="https://www.assetstl">https://www.assetstl</a>	Yes	Local Damage identifiable	Yes	Yes	multiple	
1	<a href="https://www.assetstl">https://www.assetstl</a>	Yes	Local Damage identifiable	Yes	Yes	none	
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	Local Damage identifiable	Yes	Yes	voids created by structural elements and the pattern of collapse	
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	Local Damage identifiable	Yes	Yes	multiple	
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	Local Damage identifiable	Yes	Yes	multiple	
1	<a href="https://www.turbosq">https://www.turbosq</a>	Yes	Local Damage identifiable	Yes	Yes	voids created by structural elements and the pattern of collapse	
52	<a href="https://www.assetstl">https://www.assetstl</a>	Yes	Local Damage identifiable	Yes	Yes	multiple	
							grade 4
							multiple but mostly g3 & g4
							grade 4
							grade 3
							grade 3 or 4
							grade 5
							grade 3
							grade 1, grade 3 and grade 4

### Building Models used in User Study

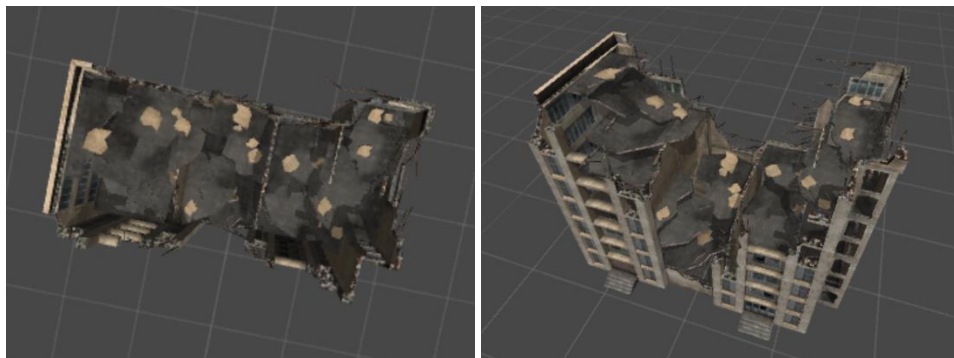
Control building 1 in mesh environment



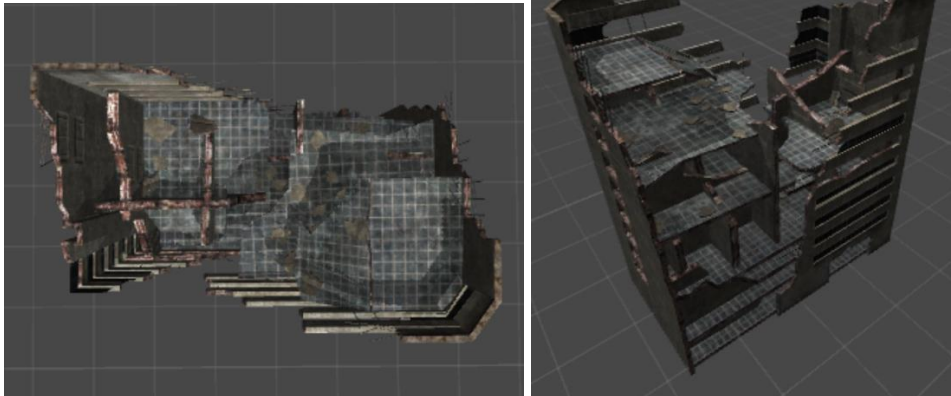
Urban Building 2 in mesh environment



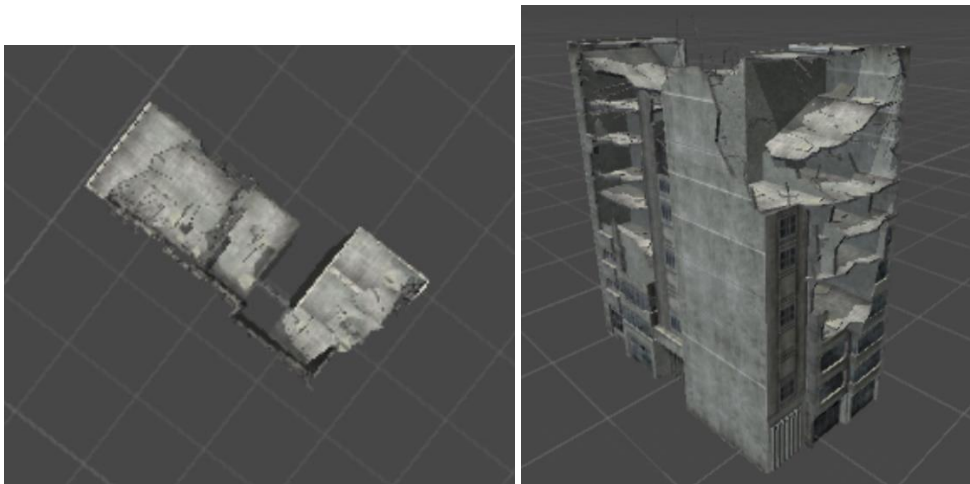
Urban building 3 in mesh environment



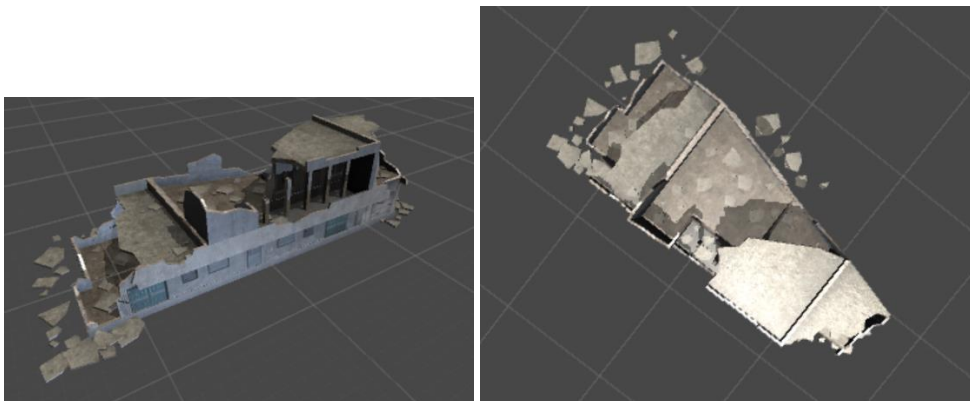
Urban building 4 in mesh environment



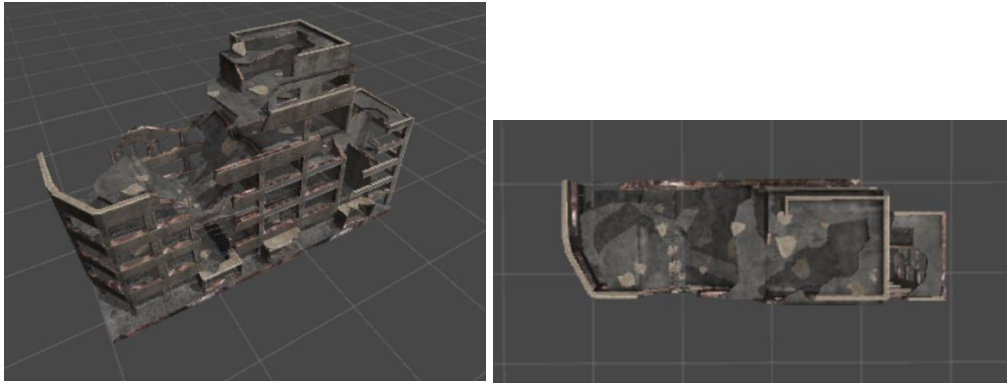
Urban building 5 in mesh environment



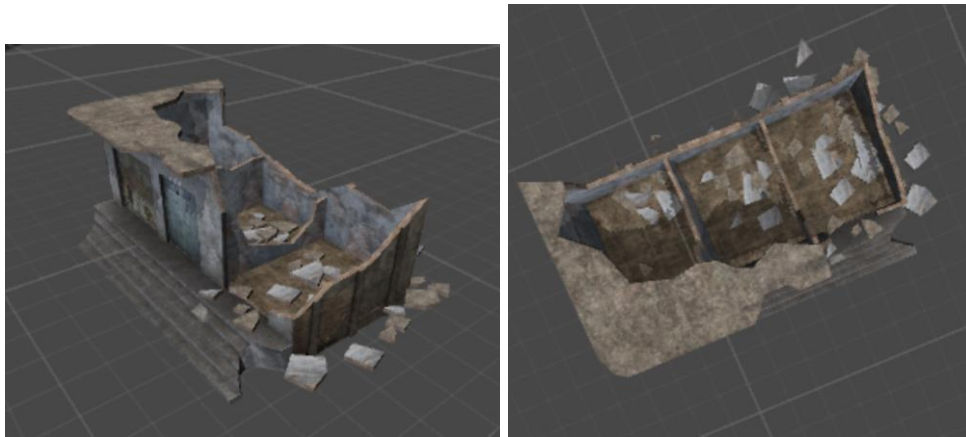
Urban building 6 in mesh environment



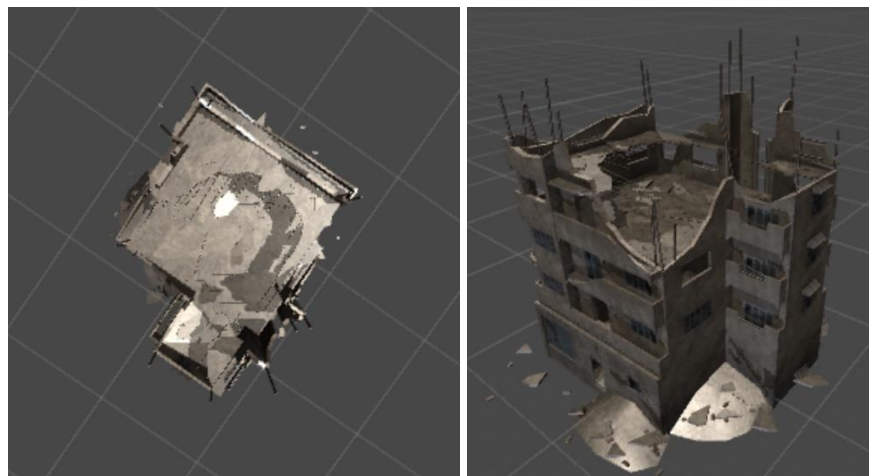
Urban building 7 in mesh environment



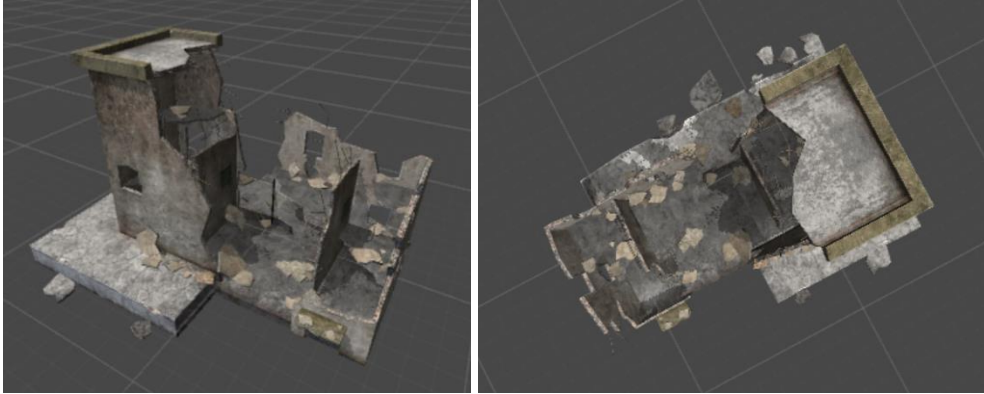
Urban building 8 in mesh environment



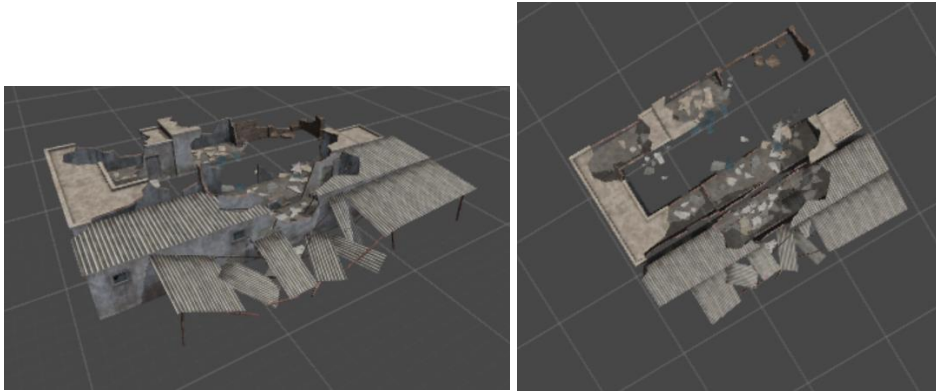
Urban building 9 in mesh environment



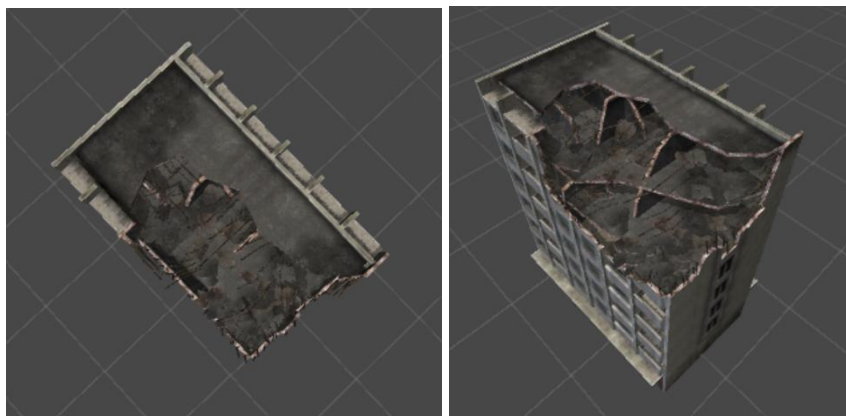
Urban building 10 in mesh environment



Urban building 11 in mesh environment



Urban building 12 in mesh environment



## User study Script and plan

00.00 Greet user & let them settle in

Script :

Part 1 - Hello, my name is Lisa and I will be going through this user study session with you today. I am conducting this user study as part of my Master in Geospatial Technologies. My thesis investigates the use of virtual reality in disaster response.

I will show you different buildings using different visual formats and kindly ask you to answer a set of questions. It is important to mention that no answers that are right or wrong and that you can take a break if needed after any of the 10-minute sessions. Since we will be working with a Virtual Reality Headset please let me know if you experience any nausea or sickness.

Feel free to think aloud or make any comments during the progress, if you have any questions I will happily answer them at the end of the user study.

I would also kindly ask you to sign the consent form. If you have any questions about the content of the consent form, please feel free to ask.

Part 2 - This is the EMS98 building classification. Destroyed buildings are classed into different categories ranging from minor and no damage to complete destruction. Please study the scale for a minute.

Tasks:

- Hand them the required forms
- While they are reading and signing the form - setup the first task-set
- Collect the form
- Start Part 2 of the script
- Hand them EMS98

Part 3 – I will now pass you the VR Headset, if you want I will help you adjust it.

00.10 Standard questions form

Script:

Please fill out the following set of questions.

Tasks:

- Pass them the standard question form
- Collect the form

00.15 “Satellite imagery”

Script:

I will now show you an image of a destroyed building. Please answer the questions on the following sheet.

Tasks:

- Hand out the questionnaire sheet
- Turn on the screen and show them the image
- Wait until they answered the Questions
- Collect the sheet

00.25 “Street View images”

Script:

I will now show you a set of images of another destroyed building. Again, please answer the questions on the following sheet.

Tasks:

- Hand out the questionnaire sheet
- Turn on the screen and show them the images
- Wait until they answered the Questions
- Collect the sheet

00.35 Video

Script:

I will now show you a video of another destroyed building. Please answer the questions on the following sheet.

Tasks:

- Hand out the questionnaire sheet
- Turn on the screen and show them the video
- Wait until they answered the Questions
- Collect the sheet

00.45 VR Model

Script:

I will now pass you a VR headset. I can help you adjust it if you want. Please adjust the lenses so that the model is as sharp as possible. I will ask you the same set of questions you have answered for the images and video.

Tasks:

- Hand out the questionnaire sheet
- Help them adjust the VR headset
- Read out the questions and possible answers
- Let them know when they can take the VR headset off
- Collect the sheet
- Offer water if needed

00.55 Comparative Questions

Script:

Thank you very much for your help so far. I will now pass you a sheet of short question regarding your experience with all the visual formats.

Tasks:

- Hand out the questionnaire sheet
- Include TaskLoadIndex
- Collect the sheet

## Standard Questions

### User Study Standard Questions

\*Required

1. Email address \*

---

2. What is your age? \*

---

3. What is your gender ?

---

4. What is your current career status?

*Mark only one oval.*

- Student
- Employed
- Self employed
- Unemployed
- Other

5. Do you have any prior experience of virtual reality?

*Mark only one oval.*

- Yes
- No

6. Have you ever experienced nausea and motion sickness using any electronic devices?

*Mark only one oval.*

- Yes
- No

7. Do you have any experience or interest in disaster management ?

*Mark only one oval.*

- Yes
- No

**Please return this sheet after completion ! Thank you :)**

## Task Questions

8. How would you class the use of this building?

*Mark only one oval.*

- Residential
- Office
- School
- Commerce
- Factory
- Hospital

9. How would you class the type of this building?

*Mark only one oval.*

- Stone / Adobe
- Masonry with a wooden roof
- Masonry with a concrete roof
- reinforced concrete structure
- steel structure

10. How would you class the plan / outline of this building ?

*Mark only one oval.*

- Square
- Rectangular
- L-Shaped
- Unrecognisable / Destroyed

11. How would you class the damage grade of the building?

*Mark only one oval.*

- Grade 1 – No visual damage
- Grade 2 - Moderate damage
- Grade 3 - Substantial to heavy damage
- Grade 4 - Very heavy damage
- Grade 5 - Destruction

12. Can you identify any local damage

*Mark only one oval.*

- Yes
- No

13. If yes, where can you identify the damage?

*Mark only one oval.*

- Damage to columns
- Damage to load-bearing walls
- Damage to beams
- Damage to floors
- Damage to connections
- Damage to roof

14. Can you identify any access points?

*Mark only one oval.*

- Yes
- No

15. If yes, where and how many access points can you identify

---

## Comparative Questions

### 2. Which method felt most natural to use ?

Mark only one oval.

- Aerial Imagery
- Street View Imagery
- Video
- Virtual Reality

### 3. Which method felt most time efficient ?

Mark only one oval.

- Aerial Imagery
- Street View Imagery
- Video
- Virtual Reality

## Raw user study results for the comparative questions

UID	Which method felt most time efficient ?	Which method felt of most natural use ?
1	Virtual Reality	Virtual Reality
2	Street View	Video
3	Video	Video
4	Virtual Reality	Virtual Reality
5	Street View	Street View
6	Virtual Reality	Virtual Reality
7	Street View	Virtual Reality
8	Virtual Reality	Video
9	Video	Street View
10	Virtual Reality	Virtual Reality
11	Video	Video
12	Virtual Reality	Virtual Reality
13	Street View	Video
14	Video	Street View
15	Virtual Reality	Virtual Reality
16	Virtual Reality	Video
17	Video	Video
18	Virtual Reality	Virtual Reality
19	Virtual Reality	Video
20	Video	Virtual Reality
21	Virtual Reality	Video
22	Aerial Imagery	Street View
23	Virtual Reality	Virtual Reality
24	Virtual Reality	Video
25	Aerial Imagery	Street View
26	Virtual Reality	Street View
27	Video	Virtual Reality
28	Virtual Reality	Video
29	Aerial Imagery	Street View
30	Street View	Video
31	Virtual Reality	Virtual Reality
31	Video	Video
32	Virtual Reality	Virtual Reality

**Raw results for the standard questions**

UID	Age	Gender	Career Status	Prev. Vr. Exp.	VR. Sick.	D.M.
1	44	Male	Employed	Yes	Yes	No
2	68	Male	Self-employed	No	No	No
3	67	Female	Self-employed	No	No	No
4	18	Male	Student	Yes	No	No
5	21	Male	Employed	No	No	No
6	19	Male	Employed	No	No	No
7	28	Female	Employed	Yes	No	No
8	31	Male	Employed	Yes	No	No
9	30	Female	Other	No	No	No
10	60	Male	Employed	No	No	No
11	61	Male	Employed	No	No	No
12	23	Male	Employed	No	No	No
13	50	Male	Employed	No	No	No
14	18	Male	Employed	No	No	No
15	31	Male	Employed	No	No	No
16	32	Male	Student	No	No	No
17	23	Male	Student	No	No	No
18	24	Female	Student	No	No	Yes
19	54	Male	Self-employed	No	No	No
20	45	Female	Other	Yes	No	No
21	21	Female	Student	Yes	No	No
22	22	Female	Student	No	No	No
23	23	Male	Employed	Yes	No	No
24	24	Male	Student	Yes	No	No
25	20	Male	Student	No	No	No
26	21	Male	Student	Yes	No	No
27	19	Male	Student	No	No	No
28	25	Male	Employed	No	No	No
29	22	Female	Student	Yes	No	No
30	23	Female	Student	Yes	No	Yes
31	21	Female	Student	No	No	No
32	22	Female	Student	No	No	No

**Raw Results Task “Use”**

UID	Aerial Imagery	Street View	Video	VR
1	13.22	3.08	12.83	11.52
2	18.56	1.51	20.18	21.31
3	11.16	7.8	14.52	10.2
4		18.64	32.47	18.41
5	17.39		20.49	10.77
6		10.53	17.3	15.29
7				
8	18.64	8.42	13.76	9.89
9	17.2	9.63		12.67
10		6.1	11.35	11.26
11		17.38	16.72	13.15
12	14.85		6.37	18.63
13		5.27		8.12
14		11.49	9.66	10
15		13.62	27.86	14.39
16	10.28	3.47	17.23	17.12
17		20	5.62	9.11
18	16	7.58	7.56	6.4
19	11.49			
20		9.14	15.31	12.74
21	13.31		14.67	15.36
22		20.26	12.54	11.98
23	12.21	16.83	40.1	26.17
24		12.37	25.93	
25		12.58		12.84
26	33.9	38.2	49.62	48.29
27				
28		2.41	4.96	13.72
29	24.03	14.97	27.52	19.14
30		34.32	43.14	
31	21.61		25.82	7.28
32		3.88	12.8	

**Raw Results Task “Type”**

UID	Aerial Imagery	Street View	Video	VR
1		2.3	27.36	35.78
2	17.27	13.35	10.14	7.11
3		3.12	34.33	30.51
4				22.38
5	29.1	8.43	21.1	18.69
6		1.6	12.55	26.73
7				
8			32.31	15.45
9	46.6	3.59	11.85	12.64
10				5.49
11		6.37	26.21	
12	74.9		45.56	17.88
13				
14	62.6	5.76	23.94	27.25
15	45			16.46
16				
17		13.24	22.1	11.43
18	26.3	15.1	14.25	8.2
19	36.7	23.45	24.66	10.41
20				14.75
21		10.29		
22		17.31	16.73	19.59
23	5.61	1.22	3.82	23.86
24			42.99	
25	79.46	4.56	36.43	35.7
26				
27		7.16	35.24	29.53
28	52.8	9.38		
29				
30	94.71	2.47	8.63	15.9
31		1.39	25.9	
32	60.27	20.38		13.62

**Raw Results Task “Plan”**

UID	Aerial Imagery	Street View	Video	VR
1	14.65		18.72	28.57
2	3.25	18.36	16.49	13.28
3	2.65			35.49
4	8.31		21.83	13.38
5	5.7		26.31	16.9
6	10.3		57.21	35.24
7				
8	3.92		39.56	14.56
9	5.91	40.6		19.2
10	8.62		19.69	37.58
11	2.39		32.3	12.35
12	16.38		24.1	8.11
13	1.7	29.59		20.36
14	9.34		26.45	
15	4.57	38.22	36.3	25.47
16	5.11		50.35	60.3
17	11.49		28.14	22.26
18	4.51		27.46	44.1
19	3.96			34.72
20	6.3		29.16	23.33
21	8.32		17.13	
22	4.63	15.84		
23	5.76			
24	8.02		46.16	42.21
25	6.92		17.39	26.45
26	10.35		53.22	45.17
27	2.74			15.32
28	12.63		41.6	17.46
29			38.17	27.32
30	3.18	32.97		9.12
31				
32	5.42		15.52	5.8

**Raw Results Task “Damage Grade”**

UID	Aerial Imagery	Street View	Video	VR
1		19.09	23.2	32.11
2	10.3			23.42
3		69.45	33.52	13.8
4				
5	35.21			11.39
6		37.31	21.89	16.75
7				
8		83.69	45.66	24.56
9	74.38		47.7	21.23
10				13.94
11				
12	60.27		20.12	26.82
13				
14			26.42	17.12
15		38.77	31.86	28.92
16				
17	34.43		28.29	19.16
18				
19				
20	21.73	43.88	25.91	10.37
21		70.2	25.79	7.22
22				
23	18.7		18.98	21.7
24				
25		34.16	19.1	18.98
26				7.25
27				13.45
28	25.82	73.6	12.17	19.4
29				
30				
31		89.34	32.38	12.95
32			7.47	11.21

**Raw Results Task “Local Damage”**

UID	Aerial Imagery	Street View	Video	VR
1	1.4	1.7	23.28	12.31
2	2.87	5.34	13.1	8.56
3	3.5	8.37	12.33	9.72
4	5.31	6.15		6.65
5	2.76	7.21	8.29	4.67
6	4.82	10.3	16.13	5.84
7		16.26	15.18	
8	3.27	2.31	12.25	11.1
9	1.24	15.4	14.3	15.33
10		14.36	11.37	3.87
11	7.93	10.17	22.19	2.6
12	12.71	14.22	9.38	7.94
13	0.6	12.35	10.4	10.59
14			17.12	1.93
15	2.1	7.31	15.18	9.5
16	1.95	13.2	28.39	2.11
17	2.23	5.16	18.16	6.78
18	8.62	10.38	12.11	11.81
19		7.14	18.48	2.34
20	3.7	5	8.53	6.17
21	2.84	2.17	17.14	5.14
22	4.2	4.35	34.84	10.92
23	1.31	9.29		3.62
24			11.61	1.45
25	8.14	4.3	4.47	7.94
26	6.36	7.32	19.86	9.2
27	1.19	6.25	12.95	12.45
28			15.77	3.73
29	10.7	10.11	13.41	2.48
30		16.14	20.93	5.34
31	16.39	1.38	11.74	4.16
32	4.12	5.36	18.86	3.53

**Raw Results Task “Local Damage Identification”**

UID	Aerial Imagery	Street View	Video	VR
1			48.78	30.9
2		38.42	52.18	
3				
4				
5				
6			39.36	21.63
7				
8	49.4	24.83		27.25
9				
10				
11	32.81			17.84
12				
13				
14				22.78
15				
16		45.68	38.87	
17				
18				
19				
20				
21	26.37	41.6		
22				
23			42.19	11.45
24				
25				
26				
27		56.22	45.36	14.29
28				
29				
30				
31			49.23	13.7
32				

**Raw Results Task “Access Point”**

UID	Aerial Imagery	Street View	Video	VR
1	5.27	8.3		2.2
2			10.84	3.24
3	7.95			2.63
4				1.87
5		13.72	9.82	
6				3.61
7				
8				2.8
9	4.58		7.41	7
10		11.58	14.95	
11				6.31
12				
13				11.79
14				
15	9.18	20.71	20.22	2.8
16				
17		16.75	18.79	2.44
18				7.92
19				
20				3.62
21		15.61	16.48	4.71
22				
23	14.55	18.99	15.66	1.97
24				
25				4.72
26				5.58
27	12.76	19.21	17.25	
28				2.43
29				
30				10.61
31		13.34	14.16	7.97
32	10.64			6.2

*Detailed Post Hoc Wilcoxon Rank:*

*Building Type*

**Wilcoxon Signed Ranks Test**

		Ranks		
		N	Mean Rank	Sum of Ranks
AerialImagery - VR	Negative Ranks	1 <sup>a</sup>	4.00	4.00
	Positive Ranks	11 <sup>b</sup>	6.73	74.00
	Ties	0 <sup>c</sup>		
	Total	12		
StreetView - VR	Negative Ranks	11 <sup>d</sup>	10.45	115.00
	Positive Ranks	5 <sup>e</sup>	4.20	21.00
	Ties	0 <sup>f</sup>		
	Total	16		
Video - VR	Negative Ranks	7 <sup>g</sup>	8.86	62.00
	Positive Ranks	10 <sup>h</sup>	9.10	91.00
	Ties	0 <sup>i</sup>		
	Total	17		

- a. AerialImagery < VR
- b. AerialImagery > VR
- c. AerialImagery = VR
- d. StreetView < VR
- e. StreetView > VR
- f. StreetView = VR
- g. Video < VR
- h. Video > VR
- i. Video = VR

Building Plan

Damage grade

Local Damage

## Wilcoxon Signed Ranks Test

		Ranks		
		N	Mean Rank	Sum of Ranks
AerialImagery - VR	Negative Ranks	19 <sup>a</sup>	13.11	249.00
	Positive Ranks	6 <sup>b</sup>	12.67	76.00
	Ties	0 <sup>c</sup>		
	Total	25		
StreetView - VR	Negative Ranks	15 <sup>d</sup>	12.20	183.00
	Positive Ranks	13 <sup>e</sup>	17.15	223.00
	Ties	0 <sup>f</sup>		
	Total	28		
Video - VR	Negative Ranks	3 <sup>g</sup>	4.67	14.00
	Positive Ranks	26 <sup>h</sup>	16.19	421.00
	Ties	0 <sup>i</sup>		
	Total	29		

a. AerialImagery < VR

b. AerialImagery > VR

c. AerialImagery = VR

d. StreetView < VR

e. StreetView > VR

f. StreetView = VR

g. Video < VR

h. Video > VR

i. Video = VR

Local Damage Identification

Access Point