International Journal of Cognitive Computing in Engineering 5 (2024) 279–296

Contents lists available at ScienceDirect

International Journal of Cognitive Computing in Engineering

journal homepage: www.keaipublishing.com/en/journals/international-journal-of-cognitive-computing-in-engineering/

Knowledge mapping analysis of situational awareness and aviation: A bibliometric study

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A R T I C L E I N F O

Keywords:
Situation awareness
Aviation
Bibliometric research
Knowledge mapping

A B S T R A C T

This study was motivated by the observed growth and increased significance of situation awareness (SA) in recent years. Despite its acknowledged importance, a notable gap exists in the literature regarding comprehensive systematic reviews of SA within the aviation sector. This gap spurred a meticulous analysis of 754 articles from the Web of Science (WoS) core database for bibliometric knowledge mapping. The primary aim was to fill this gap and acquire a holistic understanding of SA in aviation. This analysis highlighted the USA as the primary contributor to publications, with NASA leading among the institutions in paper contributions. Human Factors and the International Journal of Aerospace Psychology were the leading journals in this domain. This bibliometric study underscored the key focus on healthcare, aviation, performance, workload, and safety through co-occurrence and co-citation analyses. A chronological examination of keywords revealed a central research trajectory centered on patient and crew safety and the impact of automation on human performance in dynamic flight scenarios. Burst keyword analysis pinpointed leading-edge research in SA within healthcare, model, and system design, and the implications of human factors. This study explored the research landscape of SA in aviation using a bibliometric approach. The outcomes shed light on the present research landscape and expedite scholars' comprehension of advancements in this pivotal field. Finally, we derived a conceptual framework using the main components found in the literature. This framework will help researchers identify the main dimensions of SA.

1. Introduction

With 40 victories, Boelcke was Germany's first aviator ace during World War I. His innovative combat practices and experience allowed him to understand the importance of gaining awareness of his enemies (Endsley, 1988). Although the origin of the rule of awareness can be traced back to 1941, it was developed and defined by Endsley in 1988 as *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* (Endsley, 1988). Currently, situation awareness (SA) is a widely used cognitive construct in human factors and is often theorized to be a critical cause of human behavior in military, healthcare, and other safety-critical environments (Backdash et al., 2022; Feng et, al.,2022). SA has also been considered as a valuable construct for understanding and predicting human–system interaction performance in a dynamic complex system environment (Endsley et al., 1997; Parasuraman et al., 2000; Wickens et al., 2002). Improved SA training is considered to positively affect performance (Carretta et al., 1996; Endsley, 1995a; Endsley, 1995b, 1995; Endsley et al., 1996; Jones et al., 1996; Salas et al., 1995). Nevertheless, other authors argue the validity of SA in terms of performance (Bakdash et al., 2022; Sarter et al., 1991; Webber et al., 2017). Dekker et al. (2004) argued that SA does not have appropriate causal psychological mechanisms relevant to performance. A circularity issue was introduced to the literature by Flach (1995), who attempted to understand how SA is lost and the mechanism by which it is measured. However, Endsley (2015) argued this circularity problem by stating that SA research provides a foundation for improving SA with system design.

Undoubtedly, SA is a multidisciplinary domain that encompasses psychology (Fan et al., 2023; Hancock et al., 2022; Zhou et al., 2022), engineering (Moesl et al., 2023; Nie et al., 2022; Ramos et al., 2023), medicine (Olin et al., 2023; Renouard et al., 2023; Young et al., 2022), and aeronautical safety culture (Kale et al., 2023; Wang et al., 2023; Yu et al., 2023). The leading research in SA and aviation is on human–machine interactions, safety, and human error. From a human–machine interaction perspective, research is mainly concerned with designing automated systems that allow pilots to minimize their

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https://doi.org/10.1016/j.ijcce.2024.06.003
Received 27 October 2023; Received in revised form 15 June 2024; Accepted 15 June 2024
Available online 24 June 2024

List of abbreviations and acronyms

AI	Artificial Intelligence
ACI	Average Citation per Document
ASRS	Aviation Safety Reporting System
FMS	Flight Management System
HUD	Head-Up Display
NASA	National Aeronautics and Space Administration
SA	Situation Awareness
WoS	Web of Science

workload and increase crew awareness (Bolstad et al., 2010; Endsley, 2016; Potts et al., 2023). These systems enable the monitoring of nearby traffic (Kozovic et al., 2023), meteorological assessments (Kumar et al., 2023), flight conditions (Blundell et al., 2023; Kale et al., 2023; Papanikou et al., 2021), and air traffic control (Bongo et al., 2022; Langford et al., 2022; Reyes-Munoz et al., 2023). From a safety perspective, research focuses on aircraft maintenance (Jong et al., 2023), risk management analysis (Chionis et al., 2022; Tong et al., 2021), psychological factors associated with human behavior (Bendak et al., 2020; Hedayati et al., 2021; Wang et al., 2021), and crew resource management (CRM), in which the flight deck performance is analyzed based on crew competencies (Mansikka et al., 2019). From the perspective of human error, leading research has focused on accident data and the loss of pilot SA (Rupert et al., 2016). Despite the decrease in the number of events that threaten aviation safety, accidents owing to human error have not decreased because of new equipment and systems (Ayala et al., 2023; Yu et al., 2023). Moreover, 88 % of aviation accidents are due to limited pilot SA, with 76.3 % related to the failure of pilot perception of the situation (Yu et al., 2023).

There is a vast body of literature including narrative reviews and theoretical assumptions on SA (Adams et al., 1995; Al-Moteri, 2023; Gorman et al., 2000; Lopes et al., 2024; Lu et al., 2020; Pechacek et al., 1996; Dijk et al., 2011). However, quantitative approaches to the topic, meta-analyses, and a statistical perspective on the issue are still lacking (Bakdash, 2022).

To address these gaps, this study achieved the following:

- A knowledge-mapping analysis of aviation-related SA was conducted, employing intelligent tools such as CiteSpace, Scimago Graphica, Bibliometrix R package, and VOSviewer, along with effective research methods integrated with literature content.
- Utilizing a bibliometric methodology, statistical techniques were used to dissect all knowledge vectors quantitatively, unveiling prominent research hotspots within the subject area.
- To bridge these gaps, a thorough bibliometric analysis was conducted, thereby offering a comprehensive understanding of the current research landscape in SA within the aviation sector.
- Comprehensively grasps the knowledge structure at the intersection of SA and aviation.
- Knowledge was consolidated by discerning the main dimensions of SA in aviation, thus providing a well-structured knowledge base for future research.
- By identifying the research frontiers in the topic, we investigated the knowledge gaps in the field, contributing to the further study of the SA theoretical model involving new theories.
- Existing research gaps were identified, and the current state of ongoing research was revealed.
- This study offers insights into the future trajectory and trends within the field's evolution.
- The study's outcomes not only shed light on the present state of research, but also provide a helpful framework to guide future investigations in this critical field.

The following section presents the methodological approach to this topic. Sections II and III present the bibliometric study. Section IV covers the proposed conceptual framework. Section V elaborates on future study options using a new roadmap for SA. Finally, Section VI expounds the conclusions, limitations, and future work.

2. Records collection and methodology

The Web of Science (WoS) core database was selected for this study because of its prominent role in bibliometric analysis (Ji et al., 2023; Li et al., 2021). A comprehensive research query ("situation awareness" or "situational awareness" AND "aviation") was employed to collect bibliometric references within the WoS core database. The search spanned 1900–2023 and yielded 758 documents. These data were gathered in EndNote X9, which served as a reference and citation management tool. Records by type distribution are shown in Table 1, which includes 384 articles, with the most significant document type (Article) accounting for 50.7 % of all the literature. Proceedings were the next significant document type, accounting for 41.2 % of the literature, totaling 312 documents. The remaining documents were review articles (5.8 %), editorial notes (1.3 %), and others (1.1 %).

Given the extensive literature gathered through research queries, intelligent software tools were employed to generate quantitative and visual diagrams depicting SA within the aviation literature. This study used VOSviewer, CiteSpace, Bibliometrix R package, and Scimago Graphica software for knowledge mapping and bibliometric analysis. VOSviewer is a literature visualization software created by Van Eck et al. (2017) that can perform collaborative network, citation and co-citation, co-authorship, and co-occurrence analyses. The VOSviewer software facilitates the mapping of collaborative networks in academia, countries, universities, institutions, and journals. Scimago Graphica is a new visualization image-drawing tool that, combined with VOSviewer, allows for geographic visualization and literature image drawing (Li, 2023). Developed by Professor Chaomei Chen at Drexel University, CiteSpace provides various features, including bibliometric analysis, a keyword timeline view, and burst detection (Chen, 2006). The Bibliometrix R package can be used for comprehensive science-mapping analysis (Aria et al., 2017). This study conducted an evolutionary keyword path analysis and identified frontier research using CiteSpace. The amalgamation of these software tools revealed academic collaborations, citations, co-citations, co-occurrences, and geographical hotspot data for SA and aviation. Fig. 1. shows a visual representation of the research process.

From data extraction from the WoS through data treatment processes to utilizing tools such as VOSviewer, CiteSpace, R-studio, and SciMago Graphica for comprehensive data analysis and visualization, the methodology culminates in the synthesis of information, with insights derived through various techniques, including publication analysis, co-citation analyses, keyword timelines, keyword bursts, and geographical mapping.

3. Bibliometric outcome and analysis

3.1. Academic research over the years

Tracking article publications over time is vital for gauging trends in

Table 1
Documents by type distribution.

Number	Type	Documents	Percentage (%)
1	Article	384	50.7 %
2	Proceedings	312	41.2 %
3	Review article	44	5.8 %
4	Editorial	10	1.3 %
5	Other	8	1.1 %

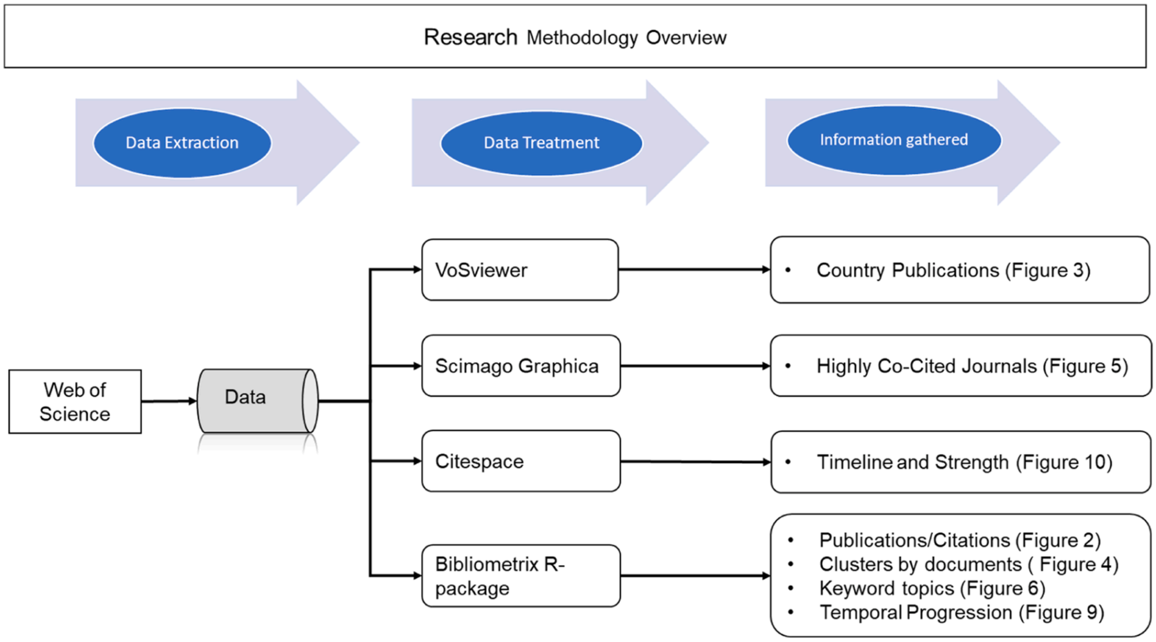

Fig. 1. Flowchart depicting the research methodology.

research field development. The pattern of paper publications reflects the evolving attention within a specific domain. The time distribution of publications from 1900 to 2023 is shown in Fig. 2. Publications were divided into three phases based on publication year and citation frequency. From the graph, we can observe the following trends:

- Publications: The number of articles (blue line) shows an increasing trend, indicating growing research interest or development in SA within aviation. Notable publication peaks occurred in specific years such as 2006 and 2017. These reflect the responses to industry needs, new technological advancements, and significant incidents, prompting increased research.

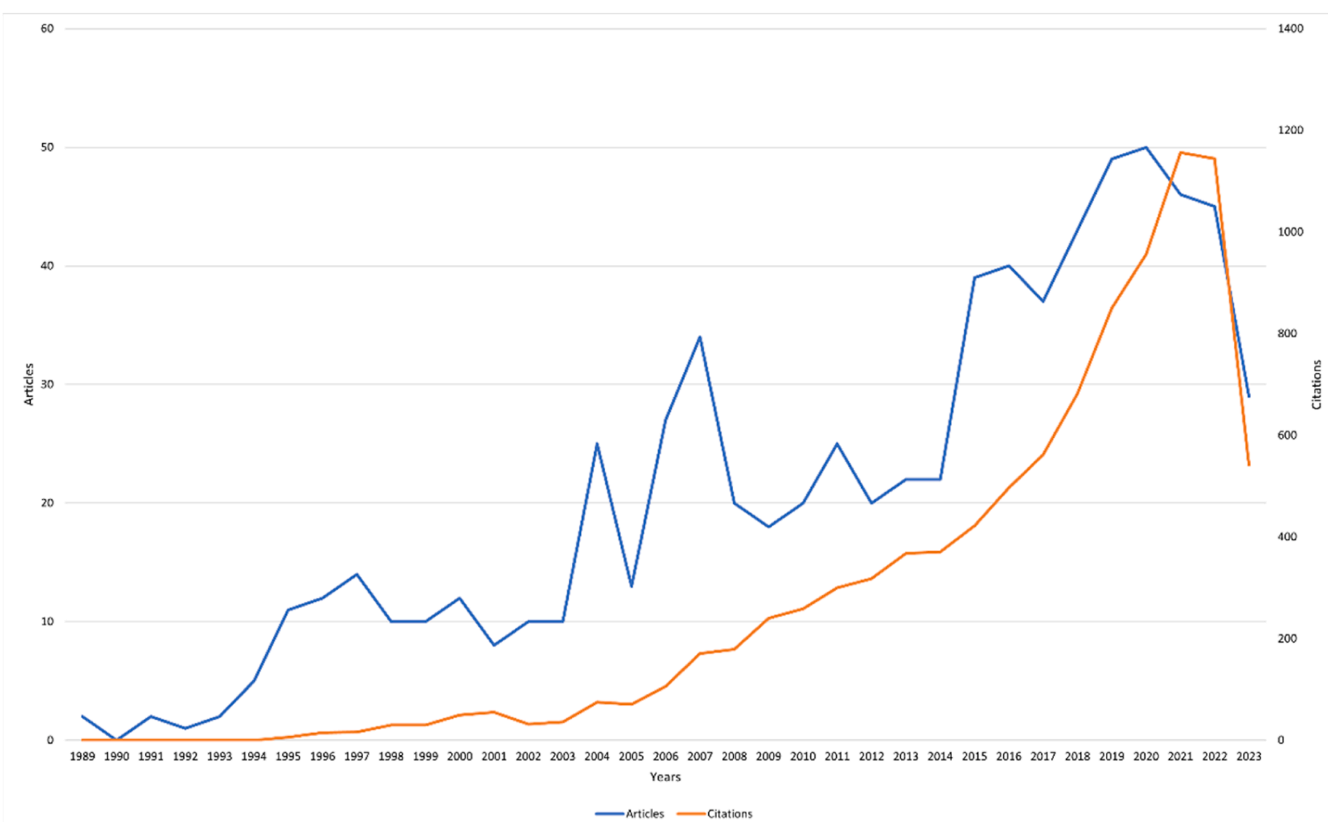

Fig. 2. Trends in academic output and impact (1989–2023).

- Citation Frequency: The citation frequency (orange line) also shows a general increase but has more pronounced fluctuations. This measure indicates how often the articles are referenced by other researchers, suggesting the impact or relevance of the research at different times. Peaks in citation frequency, such as those around 1991, 2003, and 2014–2016, correspond to seminal works and particularly influential shifts in research focus.
- Relationship Between Publications and Citations: There are periods in which an increase in article numbers is followed by a rise in citation frequency, suggesting that more recent research takes time to be recognized and integrated into the broader discourse. However, in some instances, such as the early 1990s and mid-2000s, the citation frequency peaked without a corresponding increase in publications, possibly indicating that fewer but highly influential articles were published during these times.
- Insights into the Field: The overall upward trends in both lines suggest that SA in aviation continues to be an essential and expanding field of study. The data also hint at the technological or regulatory changes driving research at various points, especially where sharp increases or peaks are observed.

This type of data visualization helps assess the impact and evolution of academic fields, highlighting how publication habits and dissemination of knowledge have evolved.

Fig. 2 illustrates the annual number of publications and citation frequency from 1989 to 2023. This highlights the consistent publication growth over the years, with a correlated increase in citations, reflecting the expanding influence and dissemination of academic research within the field. The data suggest an evolving landscape of scholarly activity, in which newer publications gradually gain recognition and impact, as reflected by citation trends.

The initial phase (1900–2005) signified the beginning of SA and aviation studies and was marked by significant foundational papers. This era witnessed the initial steps in this research domain, with a limited number of relevant documents signaling the field's inception. The peak publication year was 2004, with 25 articles. The citation frequency in this period was 0 during 1989–1994. The SA citation frequency increased in 1995, especially in Endsley's publications (1988, 1995a, 1995, 1995b). Professor Endsley's work has had an enormous impact on research in SA and aviation. Endsley (1988) provided the first definition of SA and the aircrew decision theoretical model, and the model of SA in dynamic decision-making was later renamed in 1995 (Endsley, 1995c).

In the second phase (2006–2018), the number of publications increased significantly. The three most cited articles during this period were (Li et al., 2018; Yu et al., 2014, 2016), with their work on visual scan patterns in flight operations and air traffic control management. This research content focused on the development of new technology related to aircraft crew workload (Fulton et al., 2011; Harding et al., 2015; Samuelson et al., 2006; Strybel et al., 2013), SA measurement (Endsley, 2015, 2017; Jipp et al., 2016; Jones et al., 2004; Kaber et al., 2006), and the psychological and human factor perspectives of SA in aviation (Craig, 2012; Cuevas et al., 2007; Pschierer et al., 2007; Stanton, 2016). In addition, during this period, the literature citation frequency increased rapidly, showing that this field of research was gradually developing, with improving theories and knowledge.

The third phase (2019–present) revealed increased publication growth, with the literature citation frequency growing significantly compared to the previous two stages. Scholars have proposed more in-depth research based on earlier studies, integrating existing frameworks into the research (Ceshi et al., 2019; Lounis et al., 2019; Parmar et al., 2020; Yusuf et al., 2022) and introducing developing fields such as artificial intelligence (AI) (Chaudhry et al., 2020; Jiang et al., 2022; Ramos et al., 2023). The maximum number of publications was in 2019 with 52 published papers, which was the most significant increase since 1900. This aspect underscores academia's earnest focus on SA in aviation, indicating a promising trajectory for further research in the upcoming years.

3.2. Analysis of literature distribution research by country

Mapping the publications and citations of various countries in the field of SA and aviation describes the most prolific publications in the involved research. An investigation of the higher volumes of publications and citations by country was conducted. Table 2 presents the ten leading countries ranked by document count, accompanied by their respective regions, citations, and average citation per document (ACI). Notably, the USA, United Kingdom, and China emerged as the foremost contributors, substantiating their prominence in paper production within this research domain. Nevertheless, China's ACI was only 3.98, placing it at a low level of literature citations. This statistic shows that despite the number of documents published by Chinese researchers (55), they have less influence on SA and aviation. Conversely, the United Kingdom was the most influential country with an ACI of 19.92, despite being the second most prolific country in documents. Table 2 also indicates that North America and Europe are the main continents on which SA and aviation have developed.

Fig. 3 illustrates the temporal evolution of a country's publications. Node size reflects a country's paper count, whereas line thickness indicates collaboration intensity. The node color corresponds to each country's average annual publication. Notably, the period from 2012 to 2020 saw heightened moderate publication activity. The USA, Sweden, and Germany exhibited notably earlier publication averages than England, France, Australia, and Canada.

Conversely, the remaining countries had a similar average number of publications. Strong collaboration was evident across all countries, with the USA demonstrating exceptional international cooperation. As evident from Table 2 and Fig. 3, Taiwan and Brazil held the second and third positions regarding publication count (Table 2). However, they displayed relatively low collaboration with other countries, which potentially explains the fewer citations of documents from Brazil and Taiwan.

This network diagram, created using VOSviewer, maps the interconnectivity and cooperative dynamics among various countries, based on their contributions to jointly authored articles. Key nodes such as the USA, Germany, and China act as central hubs, indicating their significant roles in international research partnerships. The timeline from 2012 to 2023, represented by the color gradient, illustrates the evolving nature of these collaborations.

3.3. Intellectual collaboration and significant research

Table 3 presents the ten leading authors with their respective universities/institutions, countries, publication counts, and citations. Among these authors, five were from the USA, two were from the United Kingdom, two were from China, and one was from Taiwan, revealing remarkable geographical diversity. Notably, the USA was at the

Table 2
Leading research countries.

Rank	Country/Region	World Zone	Records	Citations	ACI
1	USA	North America	324	4806	14.83
2	United Kingdom	Europe	85	1693	19.92
3	China	Asia	55	219	3.98
4	Germany	Europe	49	456	9.31
5	Australia	Oceania	43	544	12.65
6	Canada	North America	32	420	13.12
7	Netherlands	Europe	28	354	12.64
8	France	Europe	18	90	5.0
9	Sweden	Europe	15	123	8.20
10	Taiwan	Asia	14	166	11.86

Note: ACI: Average citation per document.

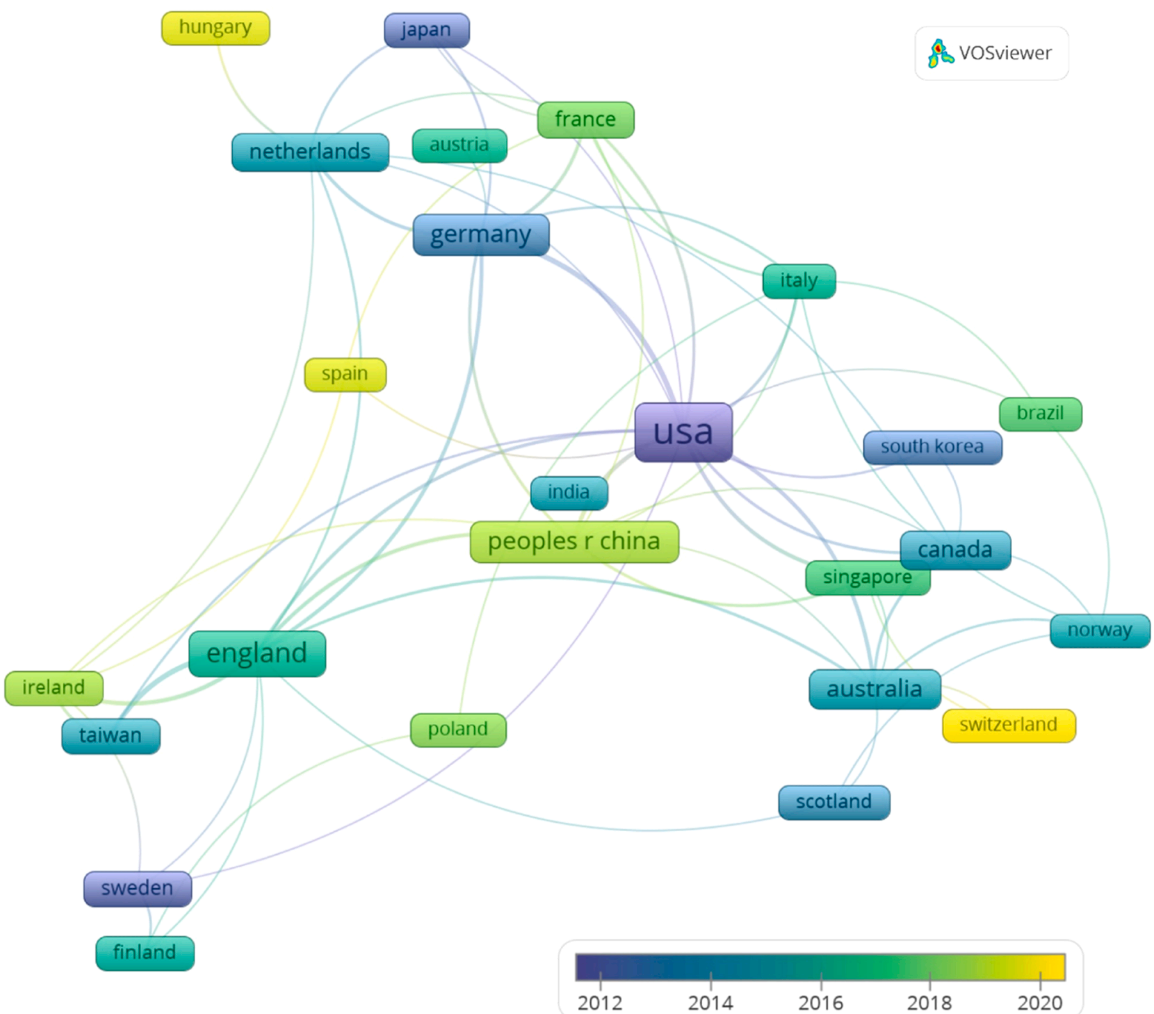

Fig. 3. Visual representation of global collaboration in publications from 2012 to 2023.

Table 3
Leading authors based on publications.

Rank	Author	Colleges	Country/ Region	Records	Citations
1	Li, Wen-Chi	National Taiwan University,	Taiwan	15	140
2	Braithwaite, Graham	Cranfield University	UK	12	107
3	Stanton, Neville	University of Southampton	UK	9	132
4	Endsley, Mica	SA Technologies	USA	8	435
5	Bailey, Randall	Langley Research Center	USA	7	35
6	Kramer, Lynda	Langley Research Center	USA	7	36
7	Liu, Shuang	School of Aeronautic Science and Engineering	China	7	10
8	Wanyan, Xiaoru	School of Aeronautic Science and Engineering	China	7	10
9	Vu, Kim-Phuong	University of Texas	USA	7	55
10	Prinzell, Lawrence	Old Dominion University	USA	7	100

forefront of SA and aviation research.

The five most prolific researchers in terms of publication volume were Li, Braithwaite, Stanton, Endsley, and Bailey. Prinzell, Bailey, and Kramer have also engaged in extensive collaboration since 2004. Their collective research focused on enhancing SA in aviation through synthetic vision displays for commercial airliner cockpits (Arthur et al., 2009; Kramer et al., 2017, 2007; Prinzell et al., 2004).

Li et al. (2019) investigated augmented visualization cues in flight displays to enhance pilot performance. Additionally, they explored pilot visual scan patterns and their impact on SA during flight operations (Li et al., 2020; Li et al., 2015a, 2015b; Yu et al., 2014, 2016). The purple cluster, composed solely of Chinese authors, is Xiarou, with seven essential documents published in co-authorship with other Asian authors. Their work involved a new method for SA measurement, pilot task performance analysis, and evaluation of SA from a flight simulator perspective (Chen et al., 2021; Chen et al., 2023, 2021; Feng et al., 2021, 2022, 2018; Min et al., 2022). Notably, Li, from Asia, was the only researcher with more publications (15) and citations, as shown in Table 3, and little academic cooperation with other scholars. This suggests that Li's articles are high impact or are currently a hotspot in the research area. Endsley, with the most citations (435), has had little collaboration with other authors, despite the high impact revealed in all the literature produced since 1988.

3.4. Key universities/institutions and collaboration analysis

In the research query from the WoS core database, 799 universities and institutions have published literature related to SA and aviation. The top ten universities and institutions are listed in Table 4. As shown in Table 4, five of the top ten universities were in the USA, meaning that 50 % of the related literature was published in North America with high research intensity. The United Kingdom had two universities in the top 10, and China had two universities. Despite ranking ninth, the Netherlands, with only one university, had a high citation ratio in the field.

As shown in Table 4, the top-ranked institution was the National Aeronautics and Space Administration (NASA), which explains its high ranking in publications. Scholars affiliated with NASA have studied SA at several levels in aviation and aerospace. The most cited article from this institution was Kaber et al. (2006), who studied the design of adaptive automation in aviation, particularly for information processing support in air traffic control tasks. The newest paper published by a NASA researcher was Mertens et al. (2023), who studied the Nowcast of Aerospace Ionizing Radiation System (NAIRAS) with a new feature that provides the global context and SA of the atmospheric ionizing radiation environment. Texas Tech University had the highest ACI among the top 10 universities and institutions as well as the second most citations. This was due to Endsley and Jones' work on SA, with the most cited article from this university (Jones et al., 1996). Using Aviation Safety Reporting System (ASRS) reports, they identified pilot error percentages at the three levels of Endsley's SA definition.

3.5. Journal publication and collaborative endeavors

Analyzing journal volumes based on document publications provides valuable insights into content distribution within the research field. Table 5 shows the top ten journals along with their citation indices, impact factors, links, and ACIs. The International Journal of Aviation Psychology, Human Factors, and Aviation Space and Environmental Medicine were the top three journals in terms of document publications. Their impact factors were 1.000 for the Journal of Aviation Psychology, known as the Journal of Aerospace Psychology since 2017, 3.598 for Human Factors, and 1.051 for Aviation Space and Environmental Medicine. It should be expected that the International Journal of Aerospace Psychology, with the highest number of documents, should have a more significant impact factor and a low ACI. The journal's primary focus beyond SA and aviation explains this. Human Factors had the most significant ACI in the top 10 journals, which can explain the journal's impact factor. The journals with the most significant impact factors in Table 5 were Safety Science (6.392), Applied Ergonomics (3.940), and Human Factors (3.598).

Table 4
Leading academic institutions based on publications.

Rank	University/ Organization	Country/ Region	Records	Citations	Links	ACI
1	NASA	USA	48	372	24	7.78
2	Cranfield University	UK	19	166	17	8.95
3	University of Central Florida	USA	13	305	5	22
4	Embry Riddle University	USA	13	36	6	2.85
5	University of Southampton	UK	11	164	4	12.3
6	Civil Aviation University of China	China	11	31	6	2.82
7	Nanyang Technological	Singapore	10	115	9	12.30
8	Delft University of Technology	Netherlands	10	139	6	14.2
9	Texas Tech University	USA	9	364	2	41.9
10	Purdue University	USA	9	79	3	9.11

Note: ACI: Average citation per document.

Table 5
Leading journals based on article count.

Rank	Journal	Records	Citation Impact	Impact Factor (2023)	Links	ACI
1	The International Journal of Aviation Psychology	45	SSCI	1.000	23	2.5
2	Human Factors	26	SCIE/ SSCI	3.598	21	66.46
3	Aviation Space and Environmental Medicine	39	SCIE	1.051	18	22.79
4	International Journal of Industrial Ergonomics	13	SCIE/ SSCI	2.884	12	27.31
5	Safety Science	12	SCIE	6.392	11	39.33
6	Ergonomics	11	SCIE/ SSCI	2.561	12	23.82
7	Aerospace Medicine and Human Performance	9	SCIE	1.051	8	5.89
8	Applied Ergonomics	7	SCIE/ SSCI	3.940	7	10.57
9	Human Factors and Ergonomics in Manufacturing	6	SCIE/ SSCI	1.699	10	4.8
10	Applied Sciences	5	SCIE	2.838	10	3.6

Note: ACI: Average citation per document.

Nonetheless, Applied Ergonomics had a comparatively lower ACI, potentially because of the expansive nature of the ergonomics field it encompasses. However, all three journals–Applied Ergonomics, International Journal of Aerospace Psychology, and Human Factors–contain SCIE and SSCI, indicating comprehensive and extensive research coverage. Other journals had a moderate impact factor, with the International Journal of Industrial Ergonomics and Ergonomics having notably high-quality publications with above-average ACIs. This underscores the researchers' inclination toward articles in journals related to SA and aviation.

Journal prominence is often correlated with publication volume. By assessing both publications and collaborations, we could identify standout journals in SA and aviation and articles that generate substantial research interest.

Using the Bibliometrix R package, we created Fig. 4 in Appendix A, which shows clustering by document coupling in SA related to aviation. The graph was plotted with axes labeled "Centrality" and "Impact," indicating the significance and influence of each cluster in the study. Clusters were labeled with various factors such as "skills," "aviation," "error," "automation," "performance," "situation awareness," "knowledge," "systems," and "attention." Each cluster had associated confidence percentages that indicated the strength or reliability of the connections within each cluster. The positioning of the clusters suggested varying degrees of centrality and impact.

- Clusters closer to the right had a higher centrality, indicating them as central or crucial to the study network.
- Clusters higher on the graph were considered to have a greater impact, indicating that they may have significant implications for the field or are derived from more influential studies. This analysis was

used to understand the interrelationships among different research areas, identify which themes were most central or impactful, and how they were interconnected (Fig. 4) . This can help identify trends, gaps, or core topics within a field and guide future research directions.

Fig. 4 shows the interrelationships and impacts of critical factors in aviation and human factors research. Each cluster was positioned based on its centrality and effects within the network, with confidence percentages indicating the strength of each cluster's connections. This analysis helped to identify core research themes and their influence on broader fields.

3.6. Contemporary research and knowledge assessment

Co-citation, introduced by Marshakova and Shaikevich (2005), has been widely used in bibliometric research to gauge similarities between cited references. This occurs when an article cites two previous papers together. The co-citation frequency reflects the significance of concepts and theories within a field (Small, 1973), and co-cited literature establishes a research foundation, with highly co-cited journals leading the field. Examining these works and journals reveals the underlying research base in the field. Similarly, the most-cited literature represents contemporary core research, offering insights into the current research landscape (Liang et al., 2023).

Table 6 presents the ten leading journals with significant co-citations ranked by co-citation frequency. This ranking provides citation indices, 2023 impact factors, and links. The top three highly co-cited journals were Human Factors, the International Journal of Aerospace Psychology (formerly the International Journal of Aviation Psychology), and Ergonomics.

Human Factors, established in 1958, is a prominent high-quality journal and the flagship publication of the Human Factors and Ergonomics Society. As shown in Table 5, it had the highest ACI. The journal focuses on human systems integration/ergonomics, aviation and aerospace, cognitive psychology and science, healthcare, and user-centered design.

Beyond ergonomics, the top ten highly co-cited journals encompass diverse subjects such as medicine, cognitive engineering, and decision-making. Accident Analysis and Prevention and the Journal of Cognitive Engineering and Decision Making were among the journals with the highest impact factors, as detailed in Table 6.

Table 6
Top 10 journals with high co-citation frequency.

Rank	Journal	Co-Citation	Citation Impact	Impact Fac-tor (2023)	Links
1	Human Factors	1126	SCIE/ SSCI	3.598	176
2	The International Journal of Aviation Psychology	490	SSCI	1.000	176
3	Ergonomics	434	SCIE/ SSCI	2.561	172
4	Aviation Space and Environmental Medicine	394	SCIE	1.051	167
5	Safety Science	243	SCIE	6.392	164
6	International Journal of Industrial Ergonomics	211	SCIE/ SSCI	2.884	159
7	Applied Ergonomics	181	SCIE/ SSCI	3.940	171
8	Theoretical Issues in Ergonomics Science	130	ESCI	0.647	159
9	Accident Analysis and Prevention	128	SSCI	6.376	155
10	Journal of Cognitive Engineering and Decision Making	114	ESCI	0.583	161

By applying VOSviewer, a minimum co-citation frequency of 20 was enforced, resulting in 123 nodes. The visual map shown in Fig. 5 was created using Scimago Graphica software. Node sizes reflect journal co-citation frequency, with larger nodes indicating a higher frequency. Thicker lines connecting nodes indicate stronger collaboration, emphasizing close relationships.

Fig. 5 shows six distinct clusters of journal co-citation dynamics. The principal green cluster (10 nodes) centered on Human Factors, whereas the other journals occupied a single node. Human Factors, the International Journal of Aerospace Psychology, Ergonomics, and Safety Science, emerged as the top co-citation frequency journals, affirming their stature as definitive SA and aviation literature sources. Noteworthy cross-cluster cooperation was evident, particularly among the ten journals within the green cluster.

This network graph illustrates the relationships between different journals based on the citation frequency in the literature.

The nodes (circles) represent individual journals, and the connecting lines indicate the frequency of citations between journals, with thicker lines denoting more frequent citations. Color-coded clusters represent different fields or specialties within broader academic or scientific disciplines. The graph also uses varying node sizes to indicate the prominence or citation volume of each journal. This type of visualization helps understand the influence and relationships between academic journals within a particular field of study.

Fig. 5 shows journal citation patterns within the ergonomics and human factor fields. The graph displays nodes representing various journals, with the thickness of the connecting lines indicating the co-citation frequency. Color-coded clusters highlight thematic or disciplinary alignments among the journals, with the node size reflecting the relative citation volume. This map provides insights into the interconnectivity and influence of scholarly publications in SA research.

Exploring extensively cited literature reveals the foundational components of the research field (Li et al., 2020). To identify the most frequently cited articles in the realms of SA and aviation, Table 7 was compiled using R-Studio and the Bibliometrix: Biblioshiny package (Aria et al., 2017) supplemented by the WoS citation analysis tool. This table shows the 16 most-cited articles, featuring titles, authors, publication years, journals, and citation counts. The arrangement is based on citation counts spanning the period 1900–2023.

The most cited work, "A North American Hourly Assimilation and Model Forecast Cycle: The Rapid Refresh" by Benjamin et al. (2016), was published in the Monthly Weather Review journal. Its broad applications include aviation, severe weather, and energy, bolstering SA and decision-making (Benjamin et al., 2016). The second entry was "Situation Awareness in Team Performance: Implications for Measurement and Training." Salas et al. (1995), featured in Human Factors, outlined and identified attributes of team SA. This article delved into the implications and research questions regarding measuring and training team SA (Salas et al., 1995).

Securing the third slot, "Teamwork and error in the operating room – Analysis of skills and roles" by Catchpole et al. (2008), published in the Annals of Surgery, scrutinized the impact of surgical, anesthetist, and nursing teamwork skills on operative duration and errors. This study highlighted the influence of leadership and awareness on surgical errors and operative time and advocated targeted training enhancements. Surgical and anesthetist leadership affect the operating time, whereas surgical awareness impacts surgical errors. Nursing leadership, on the other hand, influences errors beyond the operative field. Enhancing training in these domains may improve performance (Catchpole et al., 2008).

Further analysis was extended to the remaining highly cited papers. Among these, eight articles pertained to SA in aviation (Adams et al., 1995; Benjamin et al., 2016; Endsley, 2016; Jones et al.,1996; Salas et al., 1995; Schriver et al., 2008; Stanton et al., 2001; Wickens, 2002), addressing themes such as novel approaches for identifying unsafe behaviors among aviation crews. Five articles were related to medicine,

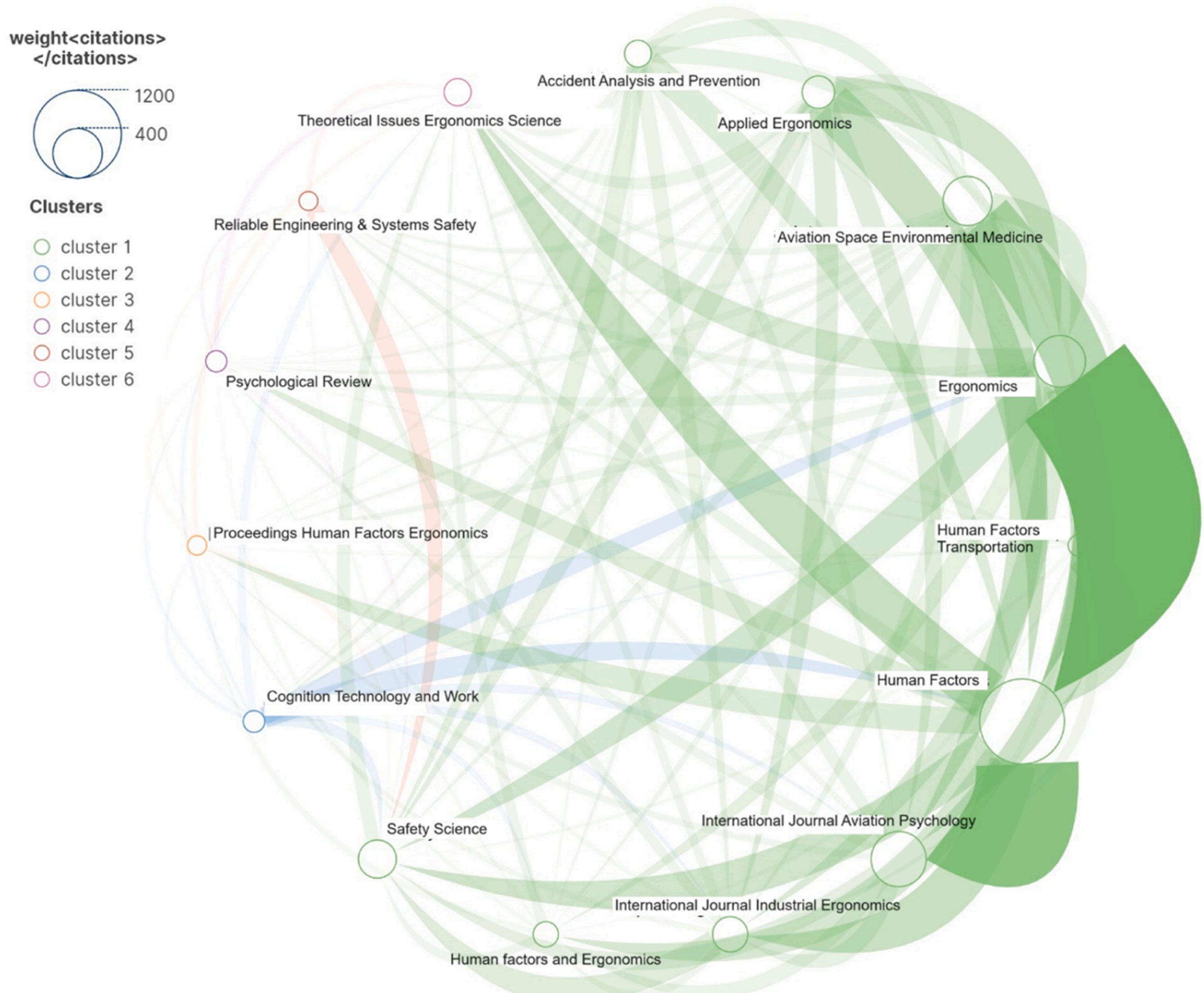

Fig. 5. Collaboration mapping of highly co-cited journals.

exploring SA within surgical settings (Catchpole et al., 2008; Gaba et al., 1995; Mishra et al., 2008; Reader et al., 2006; Singh et al., 2006), one addressed human–automation environments (Miller et al., 2007), and the other investigated SA within an industrial context (Sneddon et al., 2013).

Table 7 underscores the significance of SA across various domains, particularly in the aviation, medicine, and industrial environments. The concept of SA is crucial in dynamic and critical settings such as flying aircraft, surgical rooms, and complex industries such as drilling. Human Factors emerged as a leader in SA and aviation publications.

Valuable insights into foundational research have emerged from the significantly co-cited literature (Anwar et al., 2022). Table 8 lists the 15 most co-cited documents, including their titles, authors, journals, publication years, and co-citations.

Leading the co-citation frequency was “Toward a Theory of Situation Awareness in Dynamic Systems” by Endsley (1995c), which introduced a comprehensive model for SA in dynamic decision-making, a model still widely accepted and employed. This model is still being applied to understand the concept of SA. The second most frequently co-cited paper was “Measurement of Situation Awareness in Dynamic Systems” by Endsley (1995a), exploring empirical methods to gauge SA. This study meticulously examined the strengths, limitations, and practical aspects of each approach (Endsley, 1995a). Both influential papers were featured in Human Factors. The third most frequently co-cited paper, “Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research” by Hart et al. (1988), was published in Advances in Psychology. This paper presents findings from a comprehensive research initiative investigating factors related to subjective workload variations across various tasks. It encompasses data from 16 experiments that evaluate the subjective assessment of ten workload-related elements (Hart et al., 1988).

The other 13 papers were related to SA in the aviation environment. The literature encompassed SA in several aspects, namely, human errors due to the loss of SA (Jones et al.,1996; Reason, 1990), which are still one of the highest accident causal factors in aviation (Yu et al., 2023), workload and performance (Hart et al., 1988; Parasuraman et al., 2008), SA measurement and assessment (Endsley, 1988, 1995a; Salas et al., 1995; Salmon et al., 2009), and the impact of automation on human–machine performance (Parasuraman et al., 2000). In addition, six highly co-cited articles were published in Human Factors, indicating that this journal is highly impactful in SA and aviation research.

Table 7
Top 16 cited articles and journals.

Rank	Title	Article	Journal	Citations
1	*"A North American hourly assimilation and model forecast cycle: The Rapid Refresh."*	(Benjamin et al., 2016)	Monthly Weather Review	654
2	*"Situation awareness in team performance: Implications for measurement and training."*	(Salas et al., 1995)	Human Factors	320
3	*"Teamwork and error in the operating room – Analysis of skills and roles."*	(Catchpole et al., 2008)	Annals of Surgery	244
4	*"Sources of Situation Awareness Errors in Aviation."*	(Jones et al., 1996)	Aviation Space and Environmental Medicine	229
5	*"Situation Awareness and the Cognitive Management of Complex-Systems."*	(Adams et al., 1995)	Human Factors	226
6	*"From Here to Autonomy: Lessons Learned from Human–Automation Research."*	(Endsley, 2016)	Human Factors	225
7	*"Situational awareness and safety."*	(Stanton et al., 2001)	Safety Science	212
8	*"Situation Awareness in Anesthesiology."*	(Gaba et al., 1995)	Human Factors	195
9	*"Designing for Flexible Interaction Between Humans and Automation: Delegation Interfaces for Supervisory Control."*	(Miller et al., 2007)	Human Factors	194
10	*"The influence of non-technical performance on technical outcome in laparoscopic cholecystectomy."*	(Mishra et al., 2008)	Surgical endoscopy	179
11	*"Non-technical skills in the intensive care unit."*	(Reader et al., 2006)	British Journal of Anesthesia	179
12	*"Reliability of a revised NOTECHS scale for use in surgical teams."*	(Sevdalis et al., 2008)	The American Journal of Surgery	170
13	*"Stress, fatigue, situation awareness and safety in offshore drilling crews."*	(Sneddon et al.,2013)	Safety Science	124
14	*"Situation Awareness and Workload in Aviation."*	(Wickens, 2002)	Current directions in psychological science	122
15	*"Understanding diagnostic errors in medicine: a lesson from aviation."*	(Singh et al., 2006)	BMJ Quality & Safety	110
16	*"Expertise Differences in Attentional Strategies Related to Pilot Decision Making."*	(Schriver et al., 2008)	Human Factors	96

3.7. Keywords, hot spots, and citation keywords burst analysis

A keyword co-occurrence analysis captures current focal points, whereas a high-frequency keyword analysis identifies prevailing research themes. Table 9 highlights the three most frequently occurring keywords: SA (225 occurrences), aviation (109 occurrences), and performance (102 occurrences). The strength of the connections among the top ten keywords corresponds to their co-occurrence frequency, underlining the significance of safety and automation in contemporary SA research.

With a minimum five-time occurrence frequency, VOSviewer examined 2193 keywords to delve into SA and aviation research trends. This process yielded 124 nodes across four clusters. Fig. 6. in Appendix A, which was constructed with the Bibliometrix R package, visually presents the keyword co-occurrence network, where node size reflects keyword occurrence frequency and thicker node lines indicate higher co-occurrence frequency between keywords. The figure distinctly outlines seven clusters centered on healthcare, aviation, management, SA, workload, systems, and ergonomics.

This conceptual map illustrates the intricate network of topics related to SA in aviation. Central themes such as "performance," "aviation," and "human factors" are linked with various related concepts, emphasizing their roles in enhancing safety, efficiency, and effectiveness in aviation operations. This visualization aids in highlighting the interconnectedness of the multiple factors that influence SA in aviation. From the graph, we can observe the following trends:

- The most significant nodes in the network, such as "situation awareness" and "performance," represent central themes or primary concerns. These are the focus areas for understanding and improving SA in aviation.
- Smaller nodes, which are linked to the central nodes, such as "attention," "memory," and "decision-making," are essential components of SA. These concepts describe the cognitive processes or factors that contribute to or affect an individual's ability to maintain SA.
- The various colored nodes, such as those in red (for example, "aviation," "medicine," and "safety"), represent specific application areas or contexts where SA plays a crucial role. The red nodes indicate areas with distinct considerations or challenges related to SA.
- The lines between the nodes represent the relationships or associations between concepts. A dense cluster of lines indicates a complex interaction in which multiple factors significantly influence each other. For instance, the cluster around "performance" and "situational awareness" suggests that these elements are heavily interdependent and influenced by a variety of factors such as "task," "mental workload," and "systems."
- Scholars can target these areas to improve SA and overall safety by understanding the most interconnected factors. Moreover, this image serves as an effective educational or analytical tool for visualizing the complexity of SA, particularly how it relates to performance and safety in aviation and potentially in other fields, such as medicine.

3.7.1. Evolution of SA and aviation in the literature

In this study, timeline analysis was conducted using R-Studio software, as shown in Fig. 7 in Appendix A. The keyword timeline displays time on the horizontal axis and the keyword clusters on the vertical axis. Each node represents a keyword, and its size reflects the frequency of occurrence. The node color signifies the intensity of keyword evolution, with darker hues indicating higher intensity. Fig. 7 highlights the top five keywords in the left section: performance, human factors, SA, automation, and aviation. In this graph, the different lines connecting keywords suggest how various topics are related or how they have co-evolved over the years. This is a method commonly used in bibliometric analysis to visualize trends, relationships, and the development of concepts within specific academic or research fields. The first timeline began in 1999 and remains today, with keywords such as "automation," "mental workload," "air traffic control," and "interface design." The focal points of this timeline primarily revolve around the realm of aviation safety. In this context, SA has been extensively applied to prevent occupational injuries among pilots, passengers, and related professionals.

The visualization depicted in Fig. 7 traces the evolution and interconnectedness of critical concepts across various disciplines, as documented in the academic literature. Highlighting notable trends in fields such as aviation, patient safety, and human factors, the graph shows how thematic emphasis has shifted and expanded over the years, reflecting broader research and industrial developments.

From 2000 to 2020, key terms such as "aviation," "crew resource

Table 8
Top 15 articles with high co-citations by citation count.

Rank	Title	Article	Journal	Year	Co-citations
1	*"Toward a Theory of Situation Awareness in Dynamic Systems"*	(Endsley, 1995b)	Human Factors	1995	164
2	*"Measurement of Situation Awareness in Dynamic Systems"*	(Endsley, 1995a)	Human Factors	1995	64
3	*"Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research."*	(Hart et al., 1988)	Advances in psychology	1988	49
4	*"Sources of situation awareness errors in aviation."*	(Jones et al., 1996)	Aviation, space, and environmental medicine	1996	47
5	*"Design and Evaluation for Situation Awareness Enhancement."*	(Endsley, 1988)	Human Factors	1988	40
6	*"Human Error."*	(Reason, 1990)	Cambridge University press	1990	32
7	*"The evolution of crew resource management training in commercial aviation."*	(Helmreich et al., 2017)	Human error in aviation	2017	28
8	*"Situation Awareness Is Adaptive, Externally Directed Consciousness*	(Smith et al., 1995)	Human Factors	1995	28
9	*The Out-of-the-Loop Performance" "Problem and Level of Control in Automation."*	(Endsley et al., 1995)	Human Factors	1995	26
10	*"A model for types and levels of human interaction with automation."*	(Parasuraman et al., 2000)	IEEE Transactions on systems, man, and cybernetics-Part A: Systems and Humans,	2000	26
11	*"Measuring Situation Awareness in complex systems: Comparison of measures study."*	(Salmon et al., 2009)	International Journal of Industrial Ergonomics	2009	25
12	*"Distributed situation awareness in dynamic systems: theoretical development and application of an ergonomics methodology"*	(Stanton et al., 2006)	Ergonomics	2006	24
13	*"Situation Awareness in Team Performance: Implications for Measurement and Training"*	(Salas et al., 1995)	Human Factors	1995	23
14	*"Situation Awareness, Mental Workload, and Trust in Automation: Viable, Empirically Supported Cognitive Engineering Constructs"*	(Parasuraman et al., 2008)	Journal of cognitive engineering and decision making	2008	22
15	*"Situation awareness: A critical but ill-defined phenomenon."*	(Sarter et al., 1991)	The International Journal of Aviation Psychology	1991	21

management," "human error," and "mental model" were highlighted. This timeline primarily focused on research on human error, in which SA plays a vital role. Notably, the loss of SA by pilots was responsible for almost 88 % of aviation accidents (Yu et al., 2023). Boyd et al. (2020) studied the spatial disorientation, SA lapses, and aerodynamic stalls that frequently underlie general aviation accidents, especially since 2002, when Cirrus Aircraft began taking substantial steps to mitigate such incidents. The manufacturer integrated advanced avionics into its piston aircraft (Cirrus SR20/22) and subjected them to stricter crashworthiness assessments than older aircraft that were cleared before these standards were formalized. Boyd et al. (2020) determined that promoting avionics upgrades among aircraft owners could help reduce human-factor-related incidents. Additionally, the installation of airbags can minimize the severity of injuries.

From 1995 to 2023, keywords such as "human factors," "operating room," "fatigue," and "patient safety" were highlighted. This timeline predominantly centered on healthcare and aviation safety research, focusing on the perspective of human factors. Young et al. (2022) observed that the healthcare field is progressively acknowledging the significance of human factors. Obstetric patients are especially vulnerable owing to insufficient SA, ineffective communication, and subpar leadership, which are often exacerbated by unfamiliar teams in rapidly worsening clinical scenarios (Young et al., 2022). Renouard et al. (2023) investigated human factors by examining the complications associated with periodontal and dental implant surgeries. These are commonly attributed to technical issues or inadequate biological responses, which often overshadow the role of human factors. Interestingly, experience does not always align with enhanced success, as evidence underscores the impact of clinical behavior on patient outcomes. This mirrors the errors observed in high-risk technical domains such as aviation (Renouard et al., 2023).

Kumar et al. (2023) studied the human factor facet when a pilot flies on an aircraft with limited visibility, demanding real-time precision and SA. A head-up display (HUD) addresses this complex task by projecting vital flight data onto a transparent screen within the pilot's forward view. This eliminates the need to divert attention between the head-down display (HDD) instruments and the windshield (Kumar et al., 2023). Their study determined that implementing a HUD improved SA and decreased pilot workload. Nonetheless, projecting extensive data onto a HUD can introduce human factor challenges, potentially impacting pilot performance and contributing to accidents under low-visibility conditions (Kumar et al., 2023).

From 1995 to 2022, keywords such as "situation awareness," "management," and "human autonomy" were highlighted. The publications focused on the environment in an aircraft cockpit and how pilots manage their behavior regarding SA, such as Schmid et al. (2020), who evaluated the concept of Single Pilot Operations (SPOs). SPOs envision further crew reduction by eliminating the copilot, while maintaining safety. Factors contributing to aviation safety include procedures, flight deck design, regulatory frameworks, training, certification, and redundancies provided by a second pilot. Redundancy adds crucial safety value, mainly by cross-verifying data entries into the flight management system (FMS) (Suppiah et al., 2020).

Keywords such as "performance," "decision-making," "trust," and "systems" center on performance research, emphasizing the human factors and system perspectives. The performance of pilots and their relationship with SA are still popular topics in the literature (Bakdash et al., 2022). Bakdash et al. (2022) examined the literature and found that SA is a cognitive concept frequently invoked in human factors, often theorized as a crucial driver or performance element. However, doubts exist regarding whether SA fully encompasses the psychological mechanisms that influence performance (Bakdash et al., 2022). Bakdash et al. (2022) aimed to reconcile these viewpoints through a meta-analysis and assess the associations between SA and performance. They analyzed ten distinct SA measures and their links to performance through a comprehensive literature review. The results revealed that, on average, the validity of SA in predicting performance was relatively weak, with substantial variation across effects. This suggests that enhancing SA may not necessarily translate into a meaningful performance enhancement. Consequently, it may be pertinent to re-evaluate the predominant SA theories.

3.7.2. Investigation frontline classification

CiteSpace's Burst Detection tool was employed to analyze the literature within the SA domain. The ten keywords with the highest burst intensity were combined with a previous analysis of the publication timeline in SA research. This facilitated the visualization of keyword trend evolution over time, as depicted in Fig. 8. For the analysis, we considered five years starting in 1998. The top six keywords in mutation intensity between 2018 and 2023, by keyword and strength, were

Table 9
Prominent co-occurring keywords.

Rank	Keywords	Co-occurrences	Total Strength
1	Situation Awareness	225	798
2	Aviation	109	430
3	Performance	102	493
4	Situational Awareness	49	130
5	Workload	46	211
6	Human Factors	44	196
7	Automation	40	183
8	Safety	40	205
9	Attention	31	136
10	Model	31	137

"safety" (1.31), "awareness" (1.44), "model" (2.37), "allocation" (1.2), "patient safety" (2.38), and "human factors" (1.9). The keyword "patient safety" had the highest value, with 2.38. These keywords will remain popular in future research because they appeared in 2023. Between 1998–2003, the top keywords were "moving map cockpit displays" (1.33), "horizontal-situation displays" (1.33), "electronic maps" (1.33), "coordination" (1.3), and "team performance" (1.26). Between 2003 and 2008, there were only four keyword bursts, with the highest-strength keyword being "human errors" (1.27). From 2008 to 2013, the keyword "dynamic systems" was the only one with a strength of 1.2. Between 2013 and 2018, keywords such as "management," "trust," "automation," "accidents," and "air traffic control" were used. This phase had more mutations in keywords, with an increase in SA research literature. The mutation keywords "safety," "awareness," "model,'' "allocation," "patient safety," and "human factors" from 2018 to 2023 still burst in 2023. Therefore, we may consider that the research frontier in SA and aviation focuses on the keywords with the most robust links, such as "patient safety," "model," and "awareness."

Fig. 8 visualizes the temporal relevance and importance of various keywords in aviation safety literature, measured by "strength" values. Each line represents a keyword, with its length denoting the duration of relevance from its "begin" to "end" year and the thickness indicating the strength of its significance during that period. This overview highlights the key themes and their shifts in focus over time, emphasizing the evolving nature of research and discussion in the field.

4. Proposed conceptual framework

After identifying the core elements of SA in aviation, we constructed a comprehensive framework. Through in-depth literature co-citation and co-occurrence analyses, we identified the following key concepts as central to this topic: healthcare, training, safety, assessment, risk management, automation, and machine learning. SA is a critical factor that encompasses human behavior in highly complex dynamic environments. Technological design, ergonomics, and patient safety are equally vital.

Disruptive technologies, such as AI and machine learning, can bring new insights, helping human cognitive processes, products, services, and the redefinition of value propositions, thus impacting SA theory.

In Fig. 9, we present our conceptual framework derived from the bibliometric analysis. Although we have not incorporated information system theories as dimensions within this framework, we acknowledge their pivotal roles in SA research. A thorough exploration of theories such as cognitive fit theory, self-efficacy, task-technology fit, and the unified theory of acceptance and use of technology is essential to validate this model. Each of these elements enhances SA in aviation, which is critical for effective decision making and operational safety. This framework suggests a comprehensive and holistic approach that integrates technology, training, and health management to improve and maintain SA in the aviation industry.

Healthcare focuses on the physical and psychological health of aviation personnel. Ensuring that pilots, air traffic controllers, and other critical staff members are in optimal health is crucial to maintain a high level of SA. Training programs are essential for developing and reinforcing the skills required for high SA. This includes simulations and drills that mimic real-world scenarios to prepare aviation staff for unexpected situations. Safety is the primary goal of SA in aviation. Enhancing safety protocols, emergency preparedness, and continuous monitoring of safety measures ensure the effective management of risks. Integrating advanced automation technologies can reduce the workload of human operators and help maintain high levels of SA by managing routine tasks or alerting humans to potential issues. Machine learning can analyze large amounts of data to detect patterns and predict potential problems before they become critical. This capability supports the proactive management of the aviation environment and involves identifying, assessing, and controlling risks. Effective risk management is crucial for pre-emptive planning and response, which are vital aspects of SA. The continuous assessment of processes, technologies, and human performance helps identify areas for improvement and ensures that all components of the SA framework function optimally. The interconnections among these components are depicted by the overlapping circles in Fig. 9, suggesting that each area is not isolated but influences and enhances the others. This interconnected approach ensures a comprehensive and systemic method for boosting SA, which is critical for making informed decisions and effectively responding to dynamic aviation situations.

5. Future study options, and a new roadmap for SA

Ensuring optimal SA poses multifaceted challenges for the future in an increasingly complex and interconnected world. Technological advancements, while enhancing information access, also lead to data overload and potential distractions, thus hindering focused attention. Furthermore, rapid societal changes and evolving threat landscapes require adaptive awareness across diverse domains. Balancing these dynamics and fostering robust cognitive processes amidst constant information flux are pivotal challenges in cultivating effective SA. Addressing these challenges is essential for advancing SA systems, tools, and training methods to ensure that individuals and teams maintain high levels of awareness in complex and dynamic environments. Here, we enumerate these challenges with reference to the academic literature and research studies.

1. **Complexity of Defining and Measuring Situational Awareness:** SA involves understanding elements in the environment within a volume of time and space, comprehending their meaning, and projecting their status into the near future. However, defining and measuring SA precisely is challenging because of its subjective nature. Different contexts require different SA elements, making universal measurements difficult (Endsley, 1995b).
2. **Dynamic and Rapidly Changing Environments:** Many environments requiring high SA are characterized by rapid changes and high levels of uncertainty. Keeping up with these changes and updating SA are significant challenges (Stanton et al., 2001).
3. **Information Overload:** Operators often face overwhelming information that can hinder, rather than help, SA. Determining the relevance and priority of the information is a critical challenge (Hima et al., 2024).
4. **Integration of Technologies:** Integrating advanced technologies (for example, AI, IoT, and big data analytics) into existing systems to enhance SA presents compatibility and usability challenges. Ensuring that these technologies improve rather than complicate SA is a key concern (Kaber et al., 2004; Noel et al., 2024).
5. **Human Factors and Cognitive Limitations:** Human factors, such as workload, stress, fatigue, and cognitive limitations, can significantly impact SA. Understanding and mitigating these effects to maintain high SA levels are ongoing research challenges (Van et al., 2024).

6. **Training and Education:** Developing effective training programmes to improve SA skills, particularly the ability to anticipate and project future states, is challenging. Traditional training methods may not adequately prepare individuals for the complexities of real-world SA (Türkistanli, 2024).
7. **Team and Collaborative Situational Awareness:** Maintaining SA in a team context involves challenges related to communication, coordination, and shared understanding among team members. Research is required to develop methods and tools that enhance team SA (Xu et al., 2024).
8. **Cross-Domain Applications:** SA concepts and measures developed in one domain may not be directly applied to another, posing challenges for cross-domain SA research and applications. Tailoring SA research to specific domains while identifying commonalities across domains is complex (Banbury et al., 2017).

Addressing these challenges requires a multidisciplinary approach that combines insights from psychology, human factors, computer science, and domain-specific knowledge. Advancements in SA research can contribute significantly to the design of systems and training programs that enhance the ability of individuals and teams to make informed decisions in complex and dynamic environments. Recently, several studies have focused on evaluating deep learning algorithms such as on image classification, planning, and SA (Kaur et al., 2024; Krishnamoorthy et al., 2024; Mittal et al., 2022; Ramachandran et al., 2021). Other studies have focused on behavioral decision-making (Bai et al., 2024; Zhang et al., 2024) and decision support (Balasubramani et al., 2024) in intelligent transport systems.

6. Conclusions, limitations, and future work

The objective of this study was to explore the research landscape of SA in aviation. We used intelligent mapping tools such as VOSviewer, Scimago Graphica, and CiteSpace as visualization tools for the bibliometric analysis of SA and aviation literature. This study covered the period 1990–2023 using the WoS core database, examining the spatial-temporal distribution, collaborations, research foundations, focus areas, and emerging trends. We aimed to identify the key research areas, prominent countries, and highly cited papers in this domain. Our findings revealed that most publications focused on healthcare, safety, training, assessment, risk management, automation, and AI. The key findings are as follows.

The evolution of SA and aviation literature has progressed through three phases: the initial phase (1900–2005), the second phase (2006–2018), and the third phase (2018–2023). Regarding geographical distribution, the USA leads in publications, as illustrated in Table 2, among the top ten research countries. The primary contributors to the academic landscape are NASA, Cranfield University, the University of

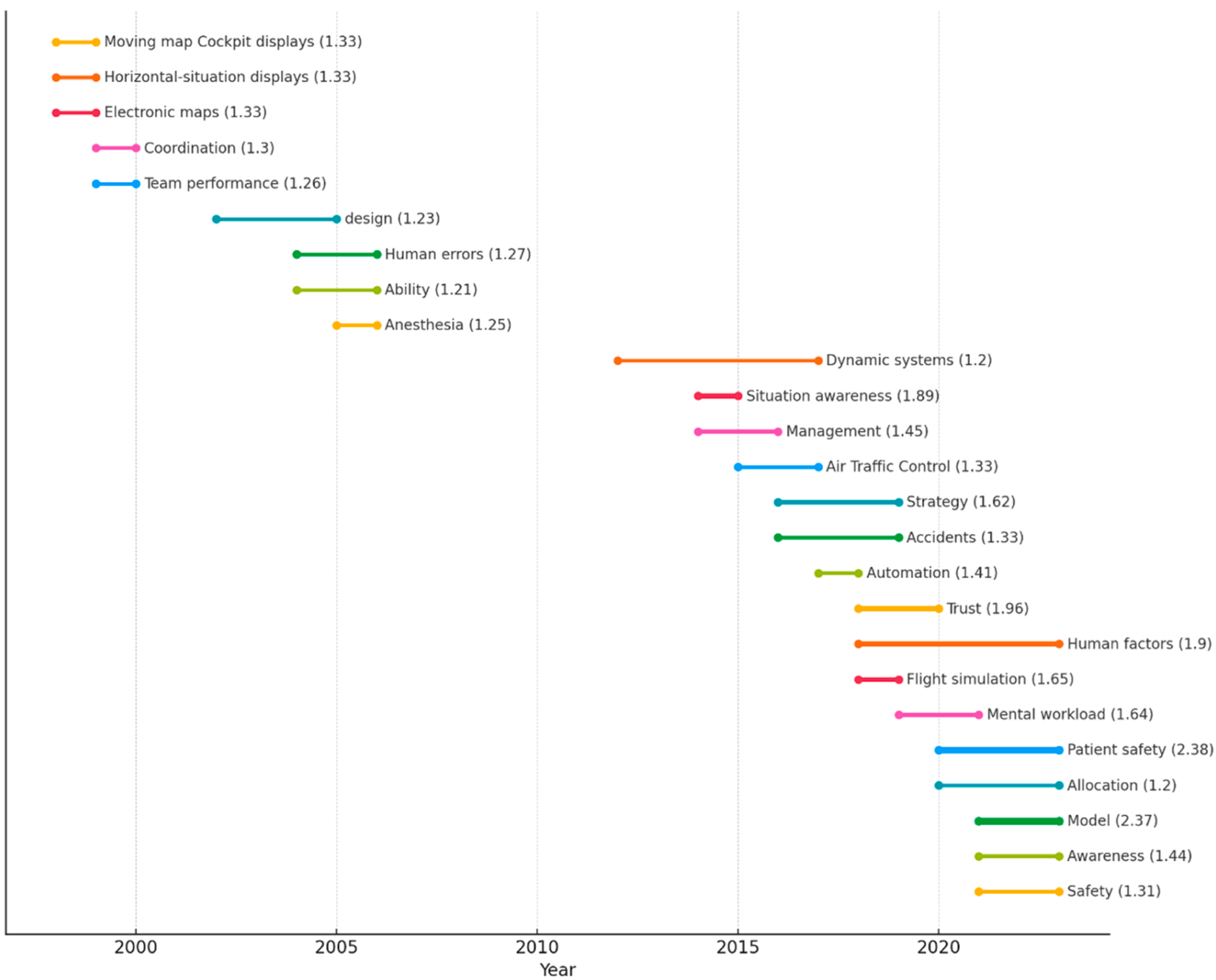

Fig. 8. Timeline and strength of keywords in aviation literature (1998–2023).

Fig. 9. Exploring the multifaceted approach to situation awareness in aviation.

Central Florida, and Embry Riddle University, as shown in Table 4. Notably, Li Wen-Chi from the National Taiwan University in Taiwan is a prolific academic in terms of publications. The key journals in the SA and aviation domain include the International Journal of Aerospace Psychology, Human Factors, and Aviation Space and Environmental Medicine, as listed in Table 5.

SA and aviation research primarily revolves around the concept and definition of aircraft crew workload and performance, patient safety, and advancing AI frameworks. The most prominent focus areas encompass the applications in these domains. Among the top journals, Human Factors, the International Journal of Aerospace Psychology, Ergonomics, Aviation Space and Environmental Medicine, and Safety Science stand out because of their high co-citation frequencies. When considering article counts, citations, and co-citations together, Human Factors, the International Journal of Aerospace Psychology, and Ergonomics emerge as the foremost journals in the field of SA and aviation.

SA investigation is propelled by critical areas such as information systems and ergonomic design, patient and crew safety, modeling techniques, and human–computer interface exploration. The field's evolution is marked by two core trajectories: occupational health and safety investigations and ergonomic system design. Studies focusing on aircrew safety, in terms of management, model design, and system architecture, are leading. The outcomes illuminate the focal points of the present development and offer insights into future trends. These insights guide scholars and encourage the exploration of diverse research themes and emergence of innovative ideas.

Finally, we proposed a new conceptual framework with the seven dimensions found in the bibliometric research. Within the cited papers, these dimensions were identified and aggregated into categories, allowing for the visualization of the main dimensions of SA and the aviation field of research. In addition, using a timeline keyword analysis, we explored this topic's main concepts and research frontier. This allows for new ground-based studies by further expanding SA theory, especially with the impact of AI and machine learning in aviation.

The conclusions drawn from this bibliometric analysis offer valuable insights into the current landscape and focal points of SAs, including journals, scholars, and institutions. These insights and theoretical implications will aid newcomers in swiftly understanding the essence of the field. Concurrently, this study is pivotal in promoting the subject's growth. Uncovering new research trends and directions will foster a profound and encompassing evolution in SA and aviation. Furthermore, the corpus of literature reviewed in this investigation was limited and focused exclusively on articles in the SA domain. This analysis was conducted from a macroscopic perspective and encompassed various disciplinary perspectives. Despite efforts to remain objective, scientific knowledge mapping of a subject can be influenced by the reviewer's bias in selecting, interpreting, and analyzing studies. Although this analysis focuses exclusively on the SA and aviation literature across diverse disciplines, it remains a foundational resource. Future endeavors could employ meta-analyses to systematically review SA and aviation within specific subjects, adhering to the PRISMA guidelines. Analyzing human performance in a dynamic, complex environment, such as flying an aircraft, also requires further study with the emergence of new AI trends. Other enhancements may involve expanding databases to offer a more detailed understanding of the discipline's knowledge structure.

Funding

This research was funded by FCT—Fundação para a Ciência e Tecnologia, I.P. (Portugal), under research grant UIDB/04152/2020—Centro de Investigação em Gestão de Informação (MagIC).

CRediT authorship contribution statement

Nuno Moura Lopes: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Manuela Aparicio:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Fátima Trindade Neves:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijcce.2024.06.003.

Appendix A. Clusters by document coupling analysis, keyword topics, and temporal evolution of research topics

Figs. 4, 6 and 7

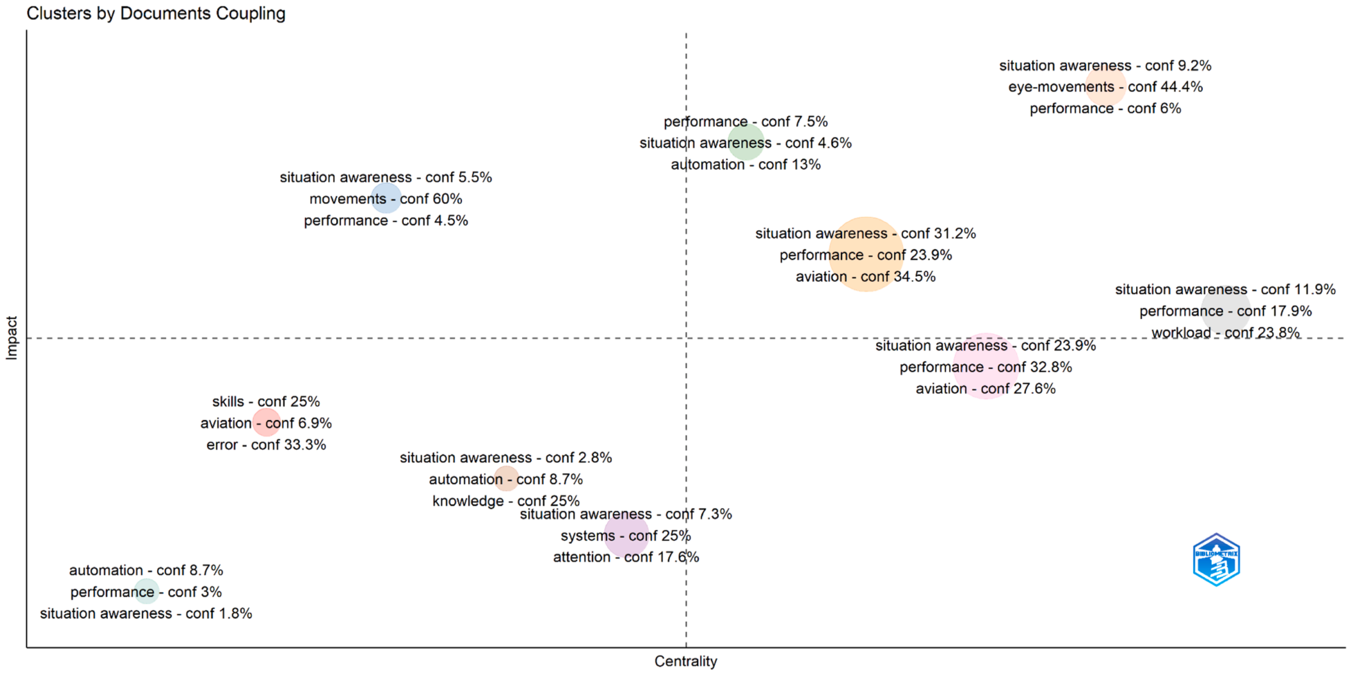

Fig. 4. Clusters by document coupling analysis.

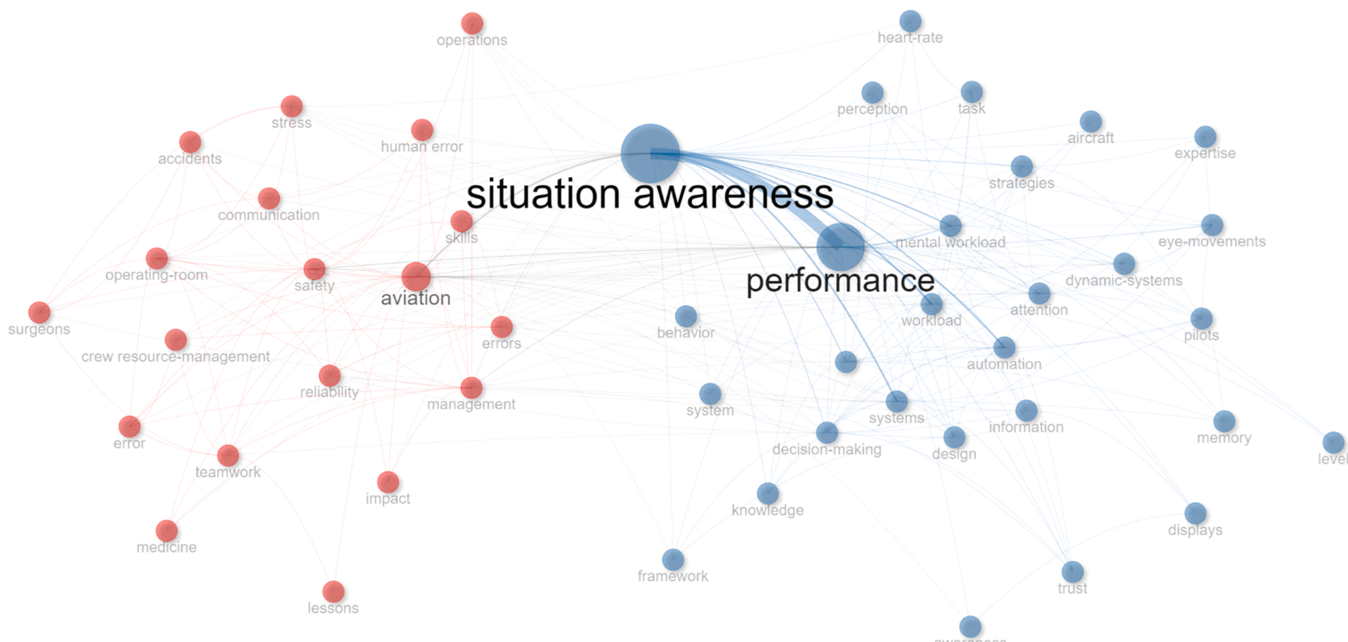

Fig. 6. Keyword topics in SA and aviation.

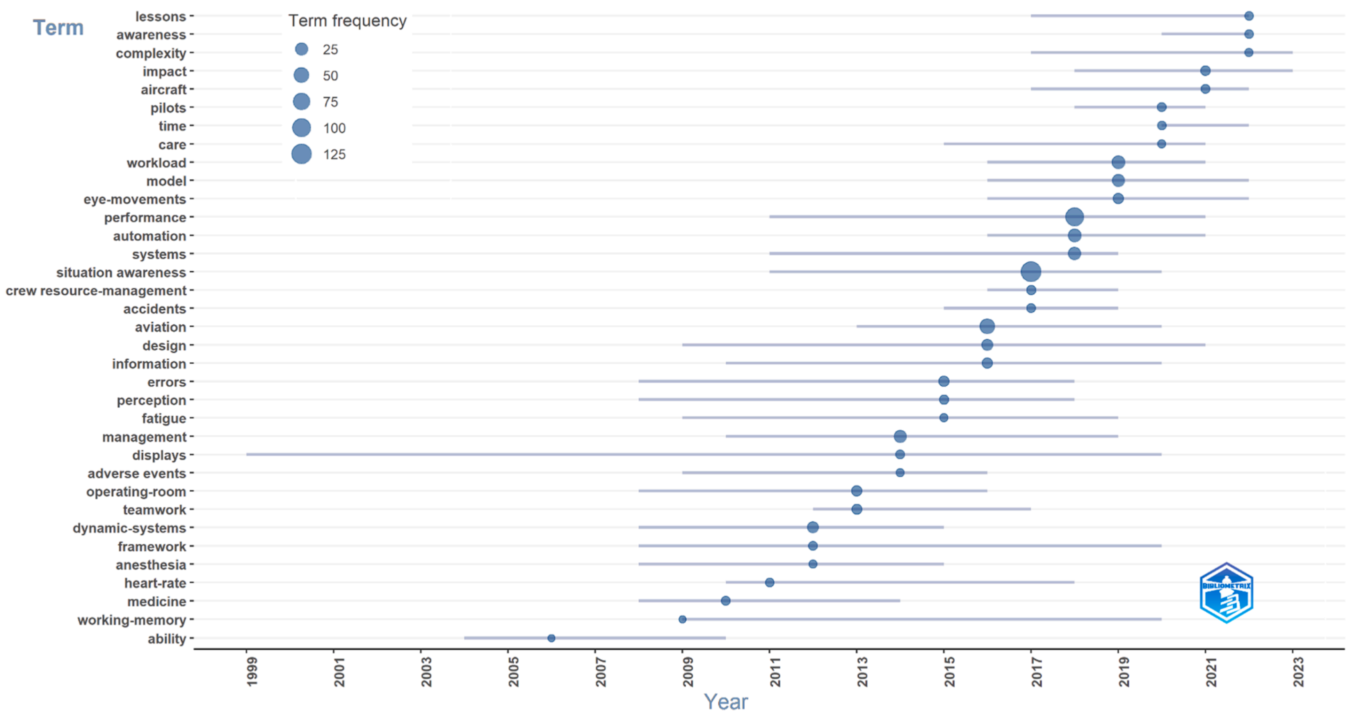

Fig. 7. Temporal evolution and interrelation of crucial research topics in the period 1998–2023.

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