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GLOBAL RESEARCH DYNAMICS, TRENDS, AND MAPS IN VIRTUAL REALITY SIMULATOR FOR AVIATOR EDUCATIONAL AND TRAINING: A BIBLIOMETRIC REVIEW

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ABSTRACT
The dynamics, trends, and global research maps related to the use of Virtual Reality (VR) simulators in aviator training are emerging areas of interest in educational and aviation technology research. The study aims to map research on the use of virtual reality across several countries, identify gaps and research trends, and inform further research. The study uses a quantitative research design and describes the analysis results in Biblioshiny. Forty-eight journal articles were analyzed using R, RStudio, and Biblioshiny. The R program used is version 4.5.1 (2025-06-13 ucrt), while the R Studio program used is version 2025.09.1 + 401. This research successfully mapped the dynamics and research trends of VR use in flight training worldwide. This study, covering 2015-2025, shows that 48 documents were generated from 26 sources; it demonstrates diversity in the literature on the use of virtual reality simulators in flight training. The 168 authors involved in the study demonstrated extensive collaboration, with 2,083% of authors involved in international co-authorship and an annual growth rate of 4.14%. The average of 8,542 citations per document indicates that the study had a significant impact on the scientific community. Overall, the analysis indicates that the use of virtual reality simulators in flight training is a dynamic and growing area of research, with strong collaboration among researchers.
Keywords: virtual reality, flight simulator, aviator, aviator training, bibliometric review.

1. INTRODUCTION

The dynamics, trends, and global research maps related to the use of VR simulators in flight training are emerging areas of interest in educational and aviation technology research. The emerging trend is the increasing interest in using VR flight simulators due to their advantages over conventional methods, such as cost-effectiveness and safety (1) (2). The latest study explores collaborative virtual environments for multi-crew training, which can complement traditional pilot training techniques(1,3). Meanwhile, the global research map notes that bibliometric analysis of the landscape of VR research in high-risk defence and training reveals exponential growth in publications and strong international collaborations, especially from the United States, China, and Germany (4).

VR is used across a wide range of high-risk fields, including aviation, emergency medicine, and disaster response, highlighting the broad flexibility and research interests (5). The dynamics of VR research indicate that VR simulators have shown promising results in terms of usability and user satisfaction, although eye strain remains a concern (6). VR can increase attendance and Engagement compared to desktop simulators, although flight performance remains similar. Combining VR with neurotechnology and haptics can further optimise training by providing real-time feedback and increasing Engagement (7,8). Eye tracking technology in VR simulators has also been used effectively to evaluate pilot performance. The growth of VR in training has led to a significant increase in aviation training publications over the past decade, reflecting advances in educational technology and methodology. The research also examined how immersive environments enhance aviators' learning experience. Continuous developments in VR technology, including improvements in graphics and haptic feedback, are anticipated to enhance training programs further (9).

Nevertheless, as research on VR grows, so do the drawbacks. Most studies do not systematically compare VR training with other emerging technologies (such as AR) or traditional methods. Available studies show that VR training can improve learning efficacy, Engagement, and skill transfer, but the best approach may involve integrating VR and AR with traditional methods to maximize the strengths of each (10,11). Research often lacks a comprehensive analysis of how factors such as age, gender, and cultural background affect the effectiveness of VR training (12). There is limited exploration of institutional barriers to implementing VR training in the aviation curriculum, including costs, infrastructure, and instructor training requirements. The long-term impact is so limited that research evaluating the effectiveness of VR training on aviator performance and skill retention is needed (7) (13). The limited analysis of empirical evidence hinders the widespread adoption of VR training to improve training effectiveness (3). The next challenge is the sickness simulator. Handling simulator sickness is essential for effective VR integration in flight training. Research shows that prior flying experience can reduce simulator sickness, so VR should be introduced after the first flight (14). Virtual reality-related research often intersects with fields such as psychological research (15), cognitive science, engineering, and education, highlighting the diverse benefits of VR (16).

This research is important because it aims to determine the extent of research on the use of virtual reality in aviation, especially in aviator training. The research analyzed journal articles using the R and RStudio programs to identify shortcomings in previous research for future research. The study aims to map research on the use of virtual reality across several countries, identify gaps and research trends, and inform further research.

VR simulators promise safer, cost-effective, and increasingly immersive flight training solutions (1). While individual experimental studies confirm benefits such as improved Engagement and reduced simulator sickness after acclimatisation (2), no comprehensive bibliometric mapping to date has quantified global research dynamics, collaboration patterns, or emerging themes in the domain. Addressing the gap, the present study answers:

How has scientific research on VR-based aviator training evolved since 2015?
Who are the most prolific authors, institutions, and countries?
What thematic clusters and research gaps characterize the field?

2. METHODOLOGY

The researcher conducted research from August to September 2025. The researcher obtained data from Scopus-indexed journal articles relevant to VR-based flight training. Article selection is conducted using the PRISMA flowchart. PRISMA is a guide for writers and helps them report why the review was conducted, what was done, and what was found (17–20). Articles are then analysed based on publication trends, collaboration networks, keywords, and major contributing institutions and countries.

2.1 Design: The study uses a bibliometric study. Bibliometric analysis has recently become a popular and rigorous technique for exploring and analyzing literature in business and management (21). Bibliometrics is a powerful technique for assessing the trajectory of scientific research (22). There is a statistical and quantitative method for analysing articles and other forms of scientific research using metrics such as impact factors, h-index, and citation counts (23). Bibliometric studies analyse the number of publications, citation trends, and the relationships between their articles (24,25). In addition, bibliometrics explores the impact factors of authors and institutions globally and maps collaborations among researchers, identifying leading contributors and institutions in the field (26). In bibliometric analysis, the research purpose must be determined first, such as identifying research trends, prominent authors, influential papers, and collaboration networks (27) (28). A quantitative bibliometric analysis was performed using the method described by Donthu et al.(2021). All reporting complies with PRISMA 2020 (29).

2.2 Database and Search Strategy

Bibliometric research uses reputable databases such as Scopus or the Web of Science to collect relevant publications (22,30). In the study, the researcher used a Scopus database. Search strategies are conducted comprehensively, using relevant keywords and time frames to ensure thorough data collection (30,31).

Scopus was searched on October 1, 2025, with the Boolean string:

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TITLE-ABS-KEY ("virtual reality" AND "flight training") AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "cr")) AND (LIMIT-TO (PUBSTAGE, "final") OR LIMIT-TO (PUBSTAGE, "aip")) AND (LIMIT-TO (SRCTYPE, "p") OR LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English"))

When using multiple databases, the datasets are combined to provide a broader view of the field of research. It is done through data cleaning and deduplication (30). However, in the study, no data cleaning was performed because the data were obtained solely from the Scopus database.

2.3 Screening and Eligibility

Inclusion criteria were used to ensure participants were eligible. The criterion is important for defining the study population and ensuring that the sample is representative of the target population (32). The inclusion criteria help researchers select participants who are most likely to provide relevant and reliable data for the research question (33). The selection of inclusion criteria can significantly impact the generalizability and validity of study findings. Strict criteria can

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yield highly selective samples that may not be representative of a broader population, limiting the applicability of the results to real-world settings (34). The inclusion criteria for the study are the years of research data, namely, 2015 to 2025.

In addition, the study uses exclusion criteria, specific conditions or characteristics that exclude prospective participants. The criterion is important to ensure the safety of participants, maintain the integrity of the research, and increase the internal validity of the research findings (35) (33). Broad exclusion criteria can significantly limit the generalisability of study findings to a broader population, as the study sample may not accurately reflect the diversity of the target population (36). The exclusion criteria in the study are document type, publication stage, source type, and language.

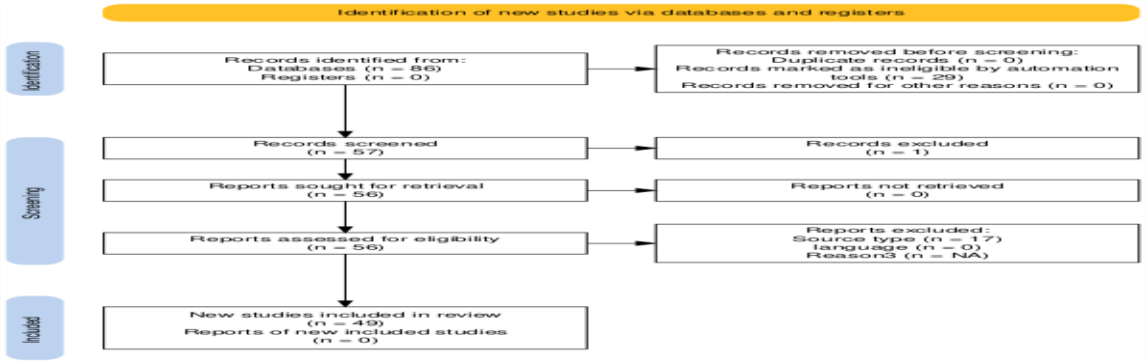

Figure 1. Flowchart PRISMA (37)

The PRISMA flowchart image above was generated using the R package and the Shiny application to produce the PRISMA 2020 flow diagram. From the Scopus database, 86 journal articles were filtered by year (2015-2025), document type, publication stage, source type, and language.

The study uses a quantitative research design and presents the analysis results in Biblioshiny. Forty-eight journal articles were analyzed using R, RStudio, and Biblioshiny. The R program used is version 4.5.1 (2025-06-13 ucrt), while the R Studio program used is version 2025.09.1 + 401. Biblioshiny is widely used for bibliometric analysis of various datasets. The tool is very effective in visualizing complex bibliographic data. It supports a wide range of visualization techniques, such as co-curation networks, thematic mapping, and citation analysis, that help identify key trends and influential works in a research area (38). Biblioshiny enables a thorough examination of bibliometric data, including performance metrics and citation analysis, and provides a holistic view of the study landscape (39).

2.4 Analytical Tools

Data were exported as BibTeX and processed in Biblioshiny (R package bibliometrix). Analyses comprised: Annual scientific production and growth rate; Author, institutional, and country productivity; Citation impact (total citations, h-index); Co-authorship and co-country networks; Keyword co-occurrence and thematic mapping.

Descriptive analysis is conducted by calculating basic metrics, such as the number of publications, citations, and the h-index, to understand productivity and overall impact (40). Thereafter, a performance analysis examines the identification of the most productive authors, institutions, and countries (41) (42).

3. Results and Discussion

3.1 Scientific Production Trends

Below are the results of data analysis using Biblioshiny, with the following information:

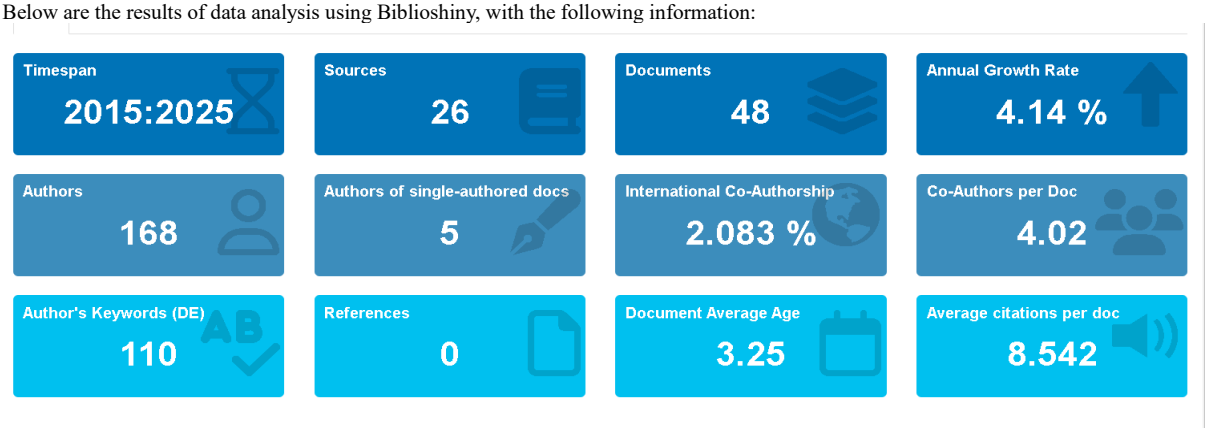

Figure 2. Main information

The bibliometric analysis conducted in the study provides in-depth insights into the development and dynamics of publications from 2015 to 2025. With 48 documents generated from 26 sources, the study demonstrates diversity in the literature on the use of virtual reality simulators in flight training. Diversity is important because it reflects the different perspectives and methodologies used in research and shows that various scientific communities raise the issue. In addition, the 168 authors involved in the study signify extensive collaboration among researchers, with only five papers written by a single author. This research suggests that most research is conducted collaboratively, which could improve the quality and depth of the analysis.

In terms of international collaboration, the data shows that 2,083% of authors are involved in international co-authorship, which, although relatively low, still indicates efforts to establish cross-border cooperation. They can enhance the exchange of ideas and best practices in the use of simulation technology for flight training. The average number of co-authors per document, 4.02, suggests that articles are generally written by large teams of researchers, reflecting the complexity of the topics discussed.

Furthermore, the author's keyword analysis identifies 110 keywords that help define the central themes and research focus in the area. The average age of the recorded documents was 3.25 years, indicating that many remain relevant and up to date. In contrast, the average citations per document of 8,542 indicate that the study had a significant impact on the scientific community, with many other researchers citing these works.

Overall, the analysis indicates that the use of virtual reality simulators in flight training is a dynamic and growing area of research, with strong collaboration among researchers. These findings not only provide insight into existing research trends and dynamics but also demonstrate the value of international and multidisciplinary collaboration in addressing challenges and capitalizing on opportunities in the field. In the future, more research is needed to explore the factors influencing growth and collaboration in this context, as well as to identify emerging trends.

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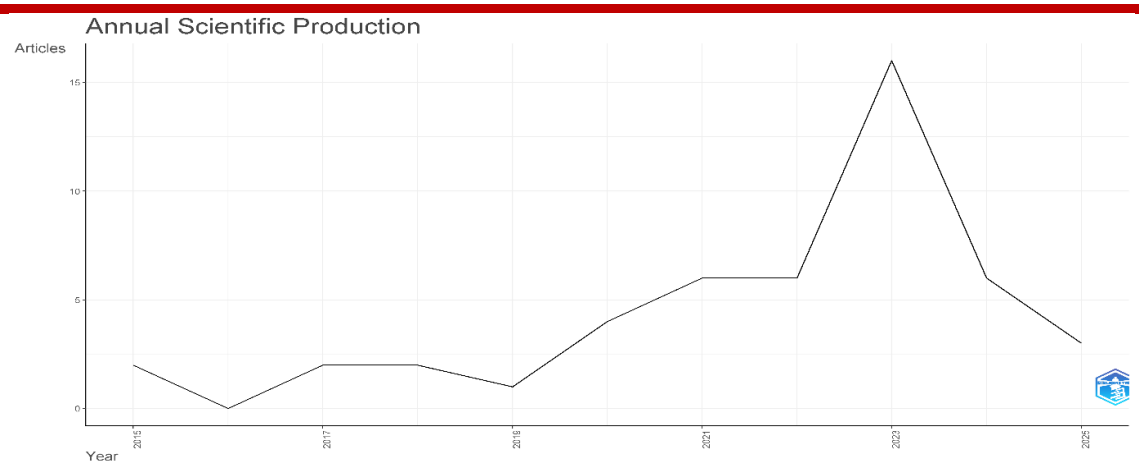

Figure 3. Annual Scientific Production

The analysis of the annual scientific production graph shown provides a precise figure of publication trends in the period under review. From 2015 to 2025, the production of scientific articles shows significant fluctuations, with a peak in 2023. The graph indicates that some years see a sharp increase in published articles, while others see the number stagnate or even decrease. The peak in 2023 may indicate increased focus on the research topic, or it may be due to a more accommodating publishing policy.

During the initial period, from 2015 to 2019, the graph shows a relatively low number of publications. It may be due to several factors, including a lack of attention or interest among researchers in the topic, as well as limited resources and research support. However, entering 2020, there has been a significant increase, which can be attributed to increased attention to globally relevant issues or to new initiatives in the scientific community.

After peaking in 2023, the number of publications appears to be declining. The decline may raise questions about the sustainability of the researcher's interest in the topic and about external factors that may affect publication dynamics. It is important to explore further factors that may be contributing to these fluctuations, such as changes in research funding, publishing policies, or even global conditions that may affect research priorities.

Overall, the graph offers valuable insights into the direction and dynamics of research on the use of virtual reality simulators in aviator training. By understanding these trends, researchers can identify areas that need further attention and consider collaborations with others to deepen the research. Subsequent steps may include exploring the factors driving the surge and fostering collaboration between academia and industry to encourage further innovation in flight training.

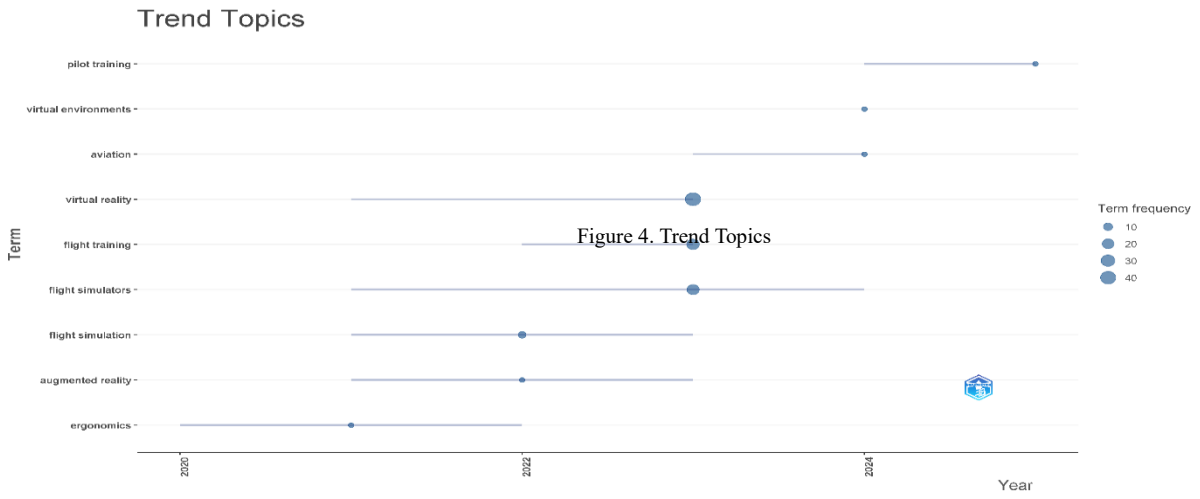

Figure 4. Trend Topics

The graph showing trending topics provides in-depth insight into the themes most discussed in publications on the use of virtual reality simulators in aviator training. The graph illustrates the frequency of key terms over time, enabling researchers to understand the primary focus of research in this area. From the graph, the terms "pilot training" and "virtual environments" show a significant increase in frequency, especially recently. It suggests that researchers are increasingly interested in developing more innovative and effective training methods for pilots using virtual reality technology. The increase in attention may be due to the need to improve pilots' skills in complex, urgent situations, which can be better trained through realistic simulations.

In addition, the terms "virtual reality" and "flight simulators" show positive trends, reflecting the popularity of these technologies in flight training. The increased Engagement in these two terms suggests that the researchers are not only focusing on the simulator itself but also on how virtual reality experiences can improve pilot learning and skills. More in-depth research in the area can lead to the development of more effective and efficient training methods. On the other hand, the terms "augmented reality" and "ergonomics" indicate lower frequencies, although they remain relevant. The study suggests that while research on augmented reality and ergonomics in aviator training exists, there may be room for further exploration in both areas. Additional research into ergonomic aspects can provide important insights into how interface design and interaction affect training effectiveness and how augmented reality technology can be better integrated into flight simulators.

Overall, the graph shows how the research focus on the use of virtual reality simulators for aviator training has evolved. By understanding these topic trends, researchers can identify areas that need further attention and take advantage of opportunities for collaboration and innovation in developing better training technologies for future aviators.

3.2 Author and Institutional Productivity

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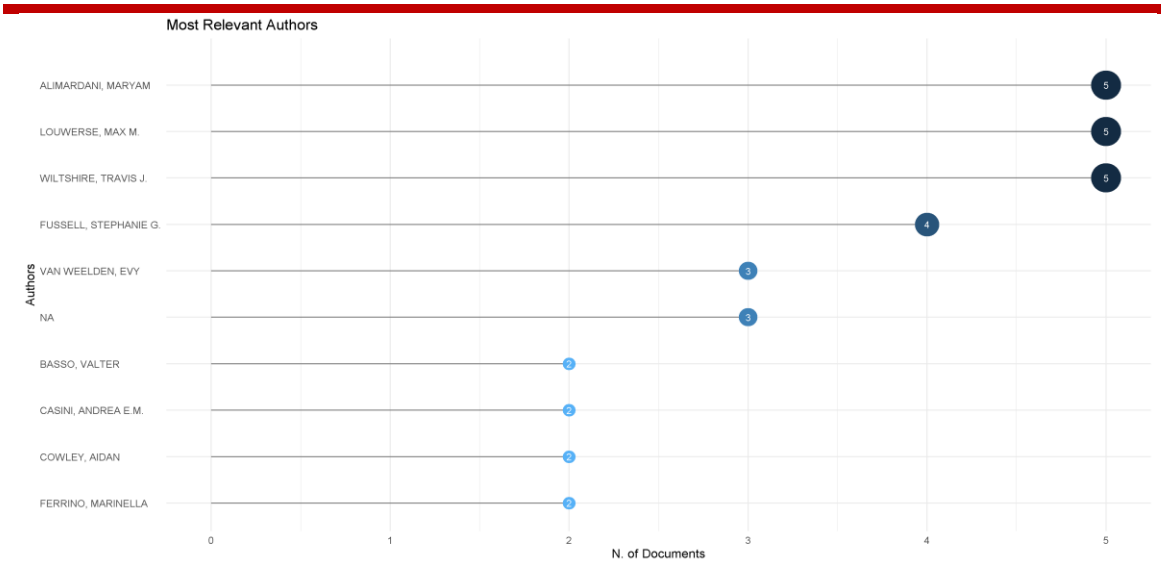

Figure 5. Most Relevant Authors

The graph of the most relevant authors provides an overview of the individual contributions of researchers in the literature on the use of virtual reality simulators in aviator training. The graph shows the number of papers published by leading authors in the field, an important indicator of influence and thought leadership in research. According to the graphs, several authors dominate the field, with Mariam Almandar, Max L. Wiltshe, and Stephane G. Fussell each having five documents. The dominance suggests that the authors may have contributed significantly to the development of knowledge and practice in the use of virtual reality technology for flight training. Their work is likely to include empirical research, literature reviews, or relevant case studies to strengthen the understanding of simulator applications in aviator training.

Furthermore, other authors, such as Evy Van Weeleken and Valter Basso, make substantial contributions with four and three documents, respectively. It suggests that, while there may not be as many top writers, they still have a significant impact on the development of literature related to the topic. The research conducted by these authors can offer additional perspectives and innovative approaches to the application of virtual reality technology in training and enrich academic discourse in the field. Other authors, such as Andrea M. Casini, Aidan Cowley, and Mariella Ferrino, note a lower publication frequency, which may reflect an early stage in their research careers or a more focused topic. However, their presence in the graph suggests that a research community is committed to exploring new aspects of using virtual reality simulations in aviator training. Further research on these authors' contributions can offer new perspectives on the innovation and development of training technology in the modern era.

Overall, the graph not only highlights key authors in the field but also demonstrates the value of collaboration and diverse perspectives in research. Understanding each author's contributions can help new researchers forge productive partnerships, develop more comprehensive research in the future, and drive progress in the application of virtual reality technology to aviator training.

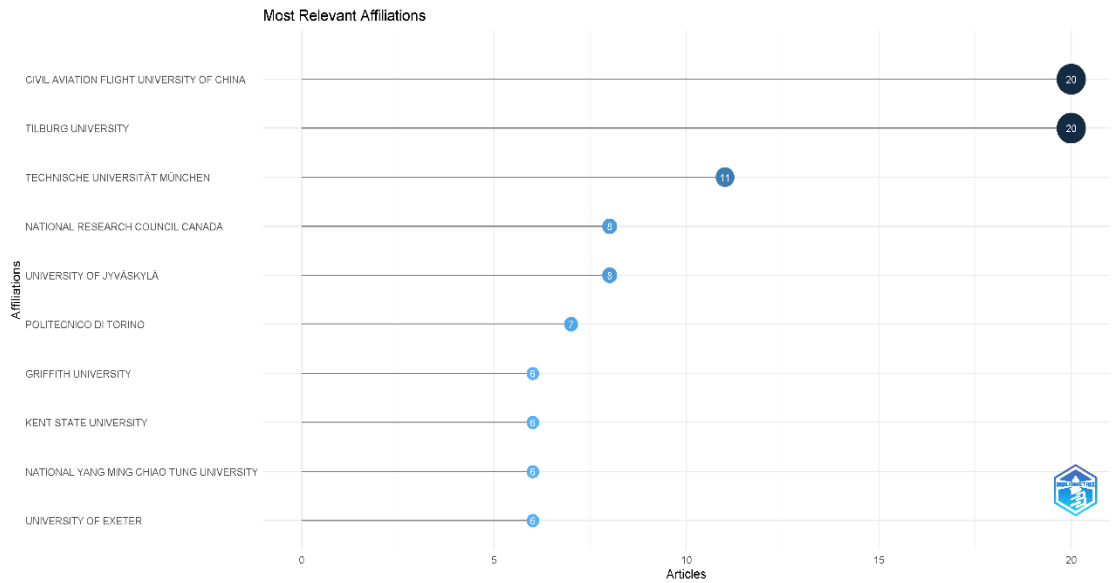

Figure 6. Most Relevant Affiliations

According to the graphs, Civil Aviation Flight University of China and Tilburg University each have 20 published articles. The dominance of these two institutions suggests they have invested in research on the use of virtual reality technology for aviator training and may have robust research programs and adequate facilities to support such studies. These institutions can make significant contributions to advancing the understanding and implementation of new technologies in flight training and serve as a reference for other researchers exploring similar topics.

Furthermore, the Technische Universität München and the National Research Council of Canada each contributed ten articles. The presence of these institutions in the graph highlights the importance of international and multidisciplinary cooperation in research. Research conducted by these institutions may include innovative approaches to the use of simulators to improve the effectiveness of pilot training, as well as contributions to the development of new methodologies and technologies for flight training.

Other institutions, such as the University of Yakutia, the Politecnico di Torino, Griffith University, Kent State University, and the University of Exeter, make lesser but still relevant contributions. Their presence in the analysis demonstrates the study's diversity of perspectives and approaches, even though their

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publications are fewer than those of the top two institutions. Research from these institutions can make a unique contribution to understanding and applying virtual reality technology in aviator training.
Overall, the graph not only highlights key institutions in the field of research but also underscores the importance of collaboration among institutions in driving innovation and advancing the use of virtual reality technologies for aviator training. Understanding the contributions of each institution can open opportunities for further cooperation and the development of more comprehensive research, thereby improving the quality of aviator training globally.

3.3 Citation Metrics

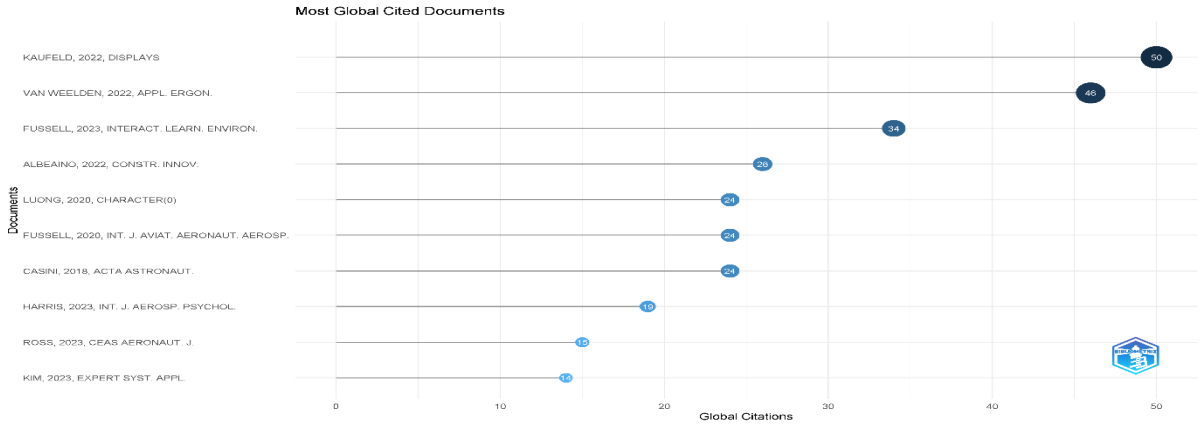

Figure 7 displays the most globally cited documents.
Based on the graph, the Kaufeld (2022) document titled “Displays” has the highest number of citations, with 50. The study may have made a significant contribution to understanding how displays in a training environment can affect pilots’ learning experience and performance. The high number of citations reflects the relevance and wide acceptance of the resulting findings, which may have served as a reference for other researchers exploring aspects of technology use in flight training.
Furthermore, a document by Van Weeleken (2022) titled “Interact Learn Environ” and a document by Fussell (2022) titled “Character” each have 40 citations. It indicates that the research conducted by these two authors also makes a significant contribution to the field’s literature. Their research may include themes related to interaction and learning in simulated environments, as well as characteristics that can improve the effectiveness of aviator training.
Other documents, such as those by Casini (2018) and Harris (2021), also show a valuable number of citations, although lower than those in previous documents. The suggestion is that, while such studies may be lagging in citation counts, they nonetheless make important contributions that could influence research and practice in the field of simulator use in flight training.
Overall, the graph not only highlights key documents that have contributed significantly to the field but also offers ideas for how research can connect and build collective knowledge on the use of virtual reality technologies for aviator training. By understanding the most cited documents, new researchers can more easily identify relevant and influential works and leverage those findings to develop future research.

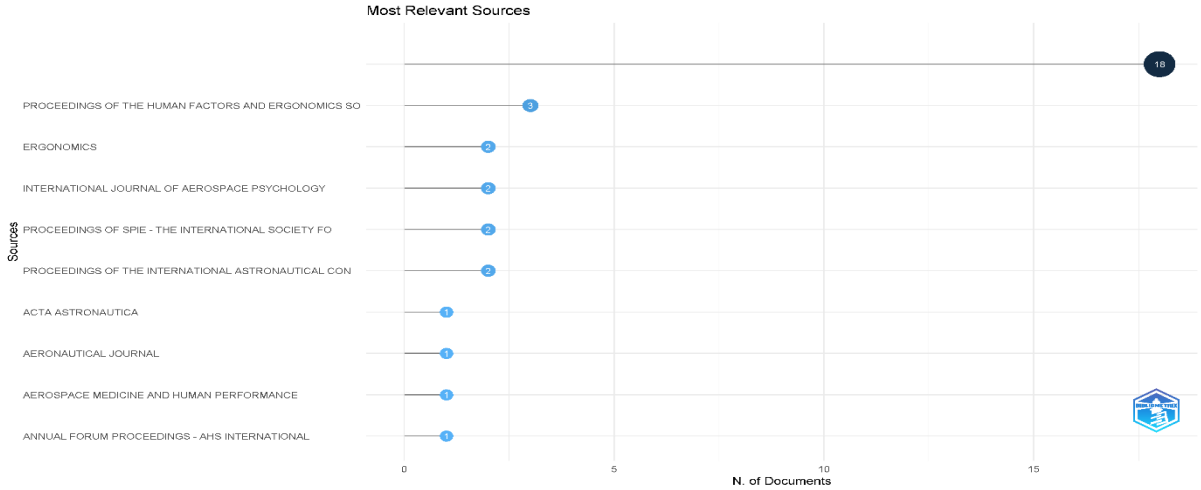

Figure 8. Most relevant sources

According to the graph, the Proceedings of the Human Factors and Ergonomics Society had the most documents, with 10 articles. The dominance of these sources suggests that much research on the use of technology and simulation in aviator training is published in The Forum, likely reflecting the relevance of ergonomics and human factors in flight training. By focusing on these aspects, the research published in The Source can provide valuable insights into how human design and interaction with technology can be optimized to improve training effectiveness.
The next source, Ergonomics, also makes a significant contribution, although with fewer documents. The journal’s involvement in aviator training research demonstrates the value of ergonomics in developing effective training systems. It shows that researchers are increasingly aware that good design and an understanding of human interaction with technology are key to improving training outcomes.
In addition, the International Journal of Aerospace Psychology and the Proceedings of SPIE—The International Society for Optical Engineering each show several relevant documents. It suggests that, while there may not be as many top sources, the forum still makes an important contribution to discussions of the psychology and technology aspects of flight training. The research published in these journals likely includes a range of approaches that could improve understanding of how aviation and training can be combined with modern technology.
Overall, the graph illustrates the importance of variation in the sources of publications on the use of virtual reality simulators in aviator training. By understanding the relevant primary sources, researchers can more easily explore the existing literature and identify trends and gaps in research that may be the focus of future studies. They also suggest that collaboration between different disciplines, such as psychology, ergonomics, and flight engineering, will increasingly be needed to drive innovation in aviator training.

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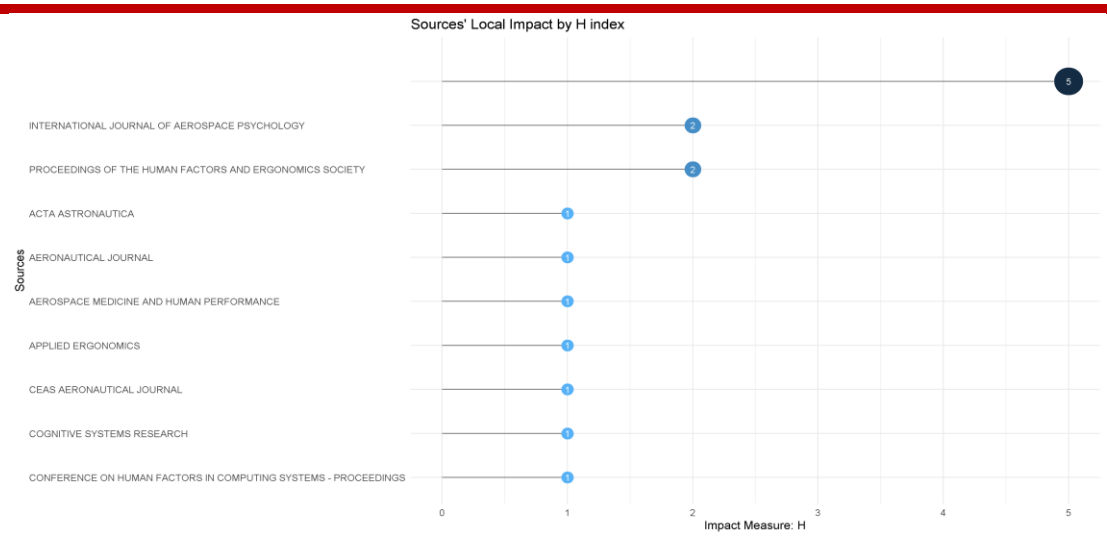

Figure 9 shows that most sources have a local impact, as indicated by their H-index.

According to the graph, the International Journal of Aerospace Psychology had the highest H index, 5. It indicates that the journal has significant recognition and impact in the academic community, particularly in aviation psychology and aviator training. The high H-index indicates that many articles published in the journal have received substantial citations, signalling a meaningful contribution to understanding human interaction and technology in aviation.

Furthermore, the Proceedings of the Human Factors and Ergonomics Society and Acta Astronautica have lower H indices of 3 and 2, respectively. Although not as high as the top journals, these two sources still show significant impact in related disciplines. It suggests that, although their number of publications or citations may not be as many as those in the top journals, they still contribute to the growing knowledge of human factors and technology in aviator training.

Other journals, such as Aerospace Medicine and Human Performance, Applied Ergonomics, and Cognitive Systems Research, show lower H indexes, ranging from 1 to 2. Nonetheless, their presence in the graph highlights the importance of diversity in the sources of publications that address the topic. These journals may offer different perspectives or focus on specific aspects of aviator training, thereby enriching academic discourse in the field.

Overall, the graph provides a precise figure of the local impact of various sources on research on the use of virtual reality simulators in aviator training. By understanding each source's H-index, researchers can more easily identify the most impactful and relevant literature for their study. Additionally, the understanding can help identify sources that may require more attention or research in the future, as well as encourage collaboration and innovation in these areas.

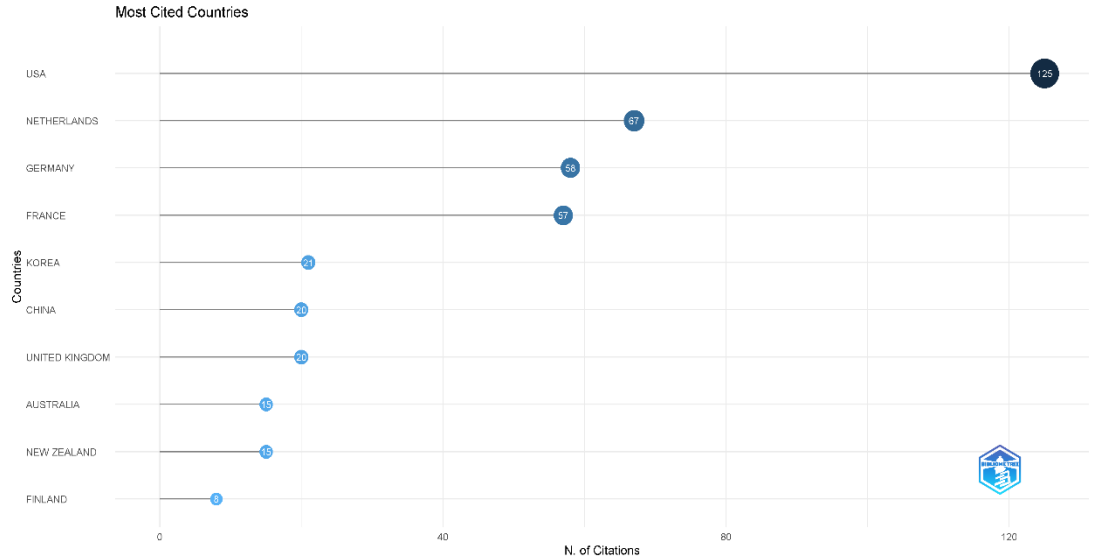

Figure 10. Most of the cited countries

According to the graph, the United States has the highest number of quotes, at 123. The dominance shows that research conducted in the U.S. has made a very significant contribution to the development of knowledge in the use of virtual reality technology for aviator training. The high number of citations reflects not only the high volume of research but also the quality and relevance of the findings produced by researchers in the country. It suggests that the U.S. may have adequate infrastructure and resources to support innovative research in the area.

The following countries, namely the Netherlands and Germany, recorded significant numbers of citations, namely 56 and 50, respectively. The involvement of these two countries in research on aviator training demonstrates that they also contribute substantially to the development of technology and methodology in the field. The resulting research from the Netherlands and Germany may include innovative approaches and relevant case studies that could enrich global understanding of the use of simulators in flight training.

Furthermore, France made a significant contribution with 36 citations, indicating that research conducted in the country remains relevant and influential. Meanwhile, other countries such as South Korea, China, the United Kingdom, Australia, New Zealand, and Finland show fewer citations but still signal an important research effort in the area. The presence of these countries in the graph reflects the diversity of perspectives and approaches that exist in research on the use of virtual reality simulators, as well as the importance of international collaboration in driving innovation.

Overall, the graph not only highlights the contributions of key countries in the study but also underscores the importance of international collaboration in developing knowledge and best practices for the use of virtual reality technologies in aviator training. Understanding the distribution of citations by country can help new researchers forge productive partnerships and identify global trends that may influence future research. They also emphasized that collective efforts across countries will increasingly be needed to drive progress in aviation training and the integration of modern technologies.

3.4 Keyword and Thematic Evolution

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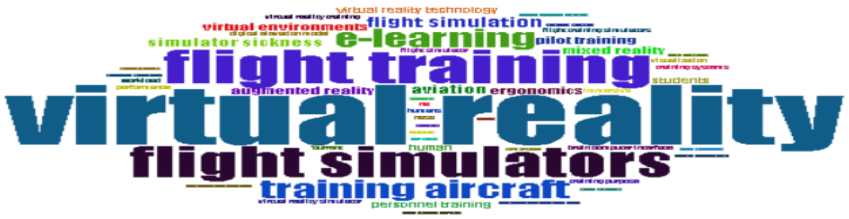

Figure 11. Work cloud

The word cloud analysis shows that "virtual reality" and "flight training" are the most dominant keywords, indicating that these two concepts are central to the research. The prominence of "virtual reality" as a keyword illustrates the value of technology in creating an immersive, interactive training environment. It suggests that researchers are increasingly recognizing the potential of virtual reality to improve the effectiveness of training, allowing aviators to practice in simulations that closely mimic real-world experiences without the risks of training on real aircraft.

In addition, keywords such as "flight simulators," "e-learning," and "simulator sickness" also appear with significant frequency. It indicates that great attention is paid to the various technical and pedagogical aspects of simulator use in flight training. For example, "flight simulators" refer to the various devices used for training, while "e-learning" refers to the integration of online learning methods into the aviator training process. In addition, attention to "simulator sickness" highlights the challenges faced by simulator users, which must be addressed to ensure the training experience remains practical and comfortable.

Other keywords, such as "training aircraft," "personal training," and "augmented reality," also indicate diversity in the approaches to aviator training. It reflects that the research is not only focused on the use of virtual simulators but also explores how additional technologies, such as augmented reality, can be integrated to enhance the learning experience. This diverse approach suggests that researchers seek to understand and address various aspects of flight training, including the need for personalization in training programs.

Overall, the word cloud analysis provides valuable insights into key themes, and research focuses on the use of virtual reality simulators for aviator training. By understanding the keywords that frequently appear, researchers can more easily identify areas that have been explored and those that may need further research. It also demonstrates the importance of interdisciplinary collaboration in finding innovative solutions to challenges in flight training using modern technology.

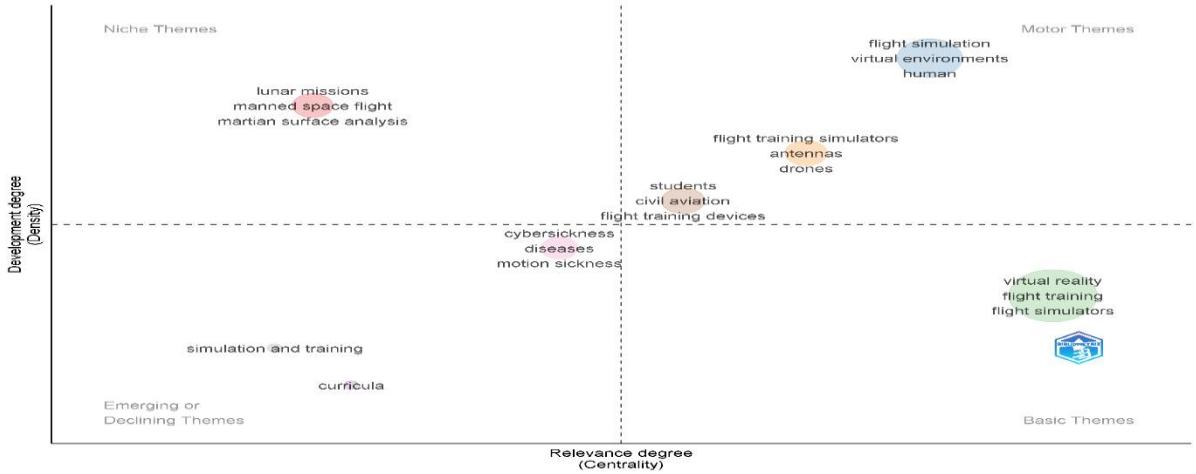

Figure 12. Thematic Map

In Figure 12, the development degree (density) indicates how internally developed or mature a theme is. Meanwhile, the relevance degree (centrality) indicates how important the theme is within the field of research. The motor theme (top right) is a quadrant with high centrality and high density, indicating that well-developed and important themes are driving the field. Niche themes (top left) are quadrants with low centrality and high density, indicating that niche and mature themes are developing well internally but are less connected to other themes. Emerging or declining themes (bottom left) are quadrants with low centrality and low density, indicating that themes are less developed and marginal and can appear but then disappear. While the basic themes (bottom right) are quadrants with high centrality and low density, the quadrants with fundamental and transversal themes are important for the field but have not been fully developed.

The graph showing the theme map provides in-depth insight into the grouping of research themes along two dimensions: degree of development and degree of relevance. The map not only shows the themes that appear in the literature but also indicates the extent to which each theme was developed and its relevance to aviator training using virtual reality technology.

The lower-right quadrant encompasses the basic themes of "virtual reality," "flight training," and "flight simulators." The existing literature has not fully developed or explored these themes, despite their relevance to research. The lower-right quadrant indicates that these themes are fundamental and may serve as a foundation for further research, but are not currently at the forefront of research or development. It indicates that, despite the importance, there is still significant room for exploration and innovation in the use of virtual reality technology in aviator training.

Overall, the theme map provides a precise figure of the research dynamics in the use of virtual reality simulators for aviator training. By understanding the grouping of themes by degree of development and relevance, researchers can identify areas that have been extensively researched and those that may need further attention. They also suggest that collaboration across disciplines and multidimensional approaches will be crucial for fully exploring the potential of virtual reality technologies in flight training in the future.

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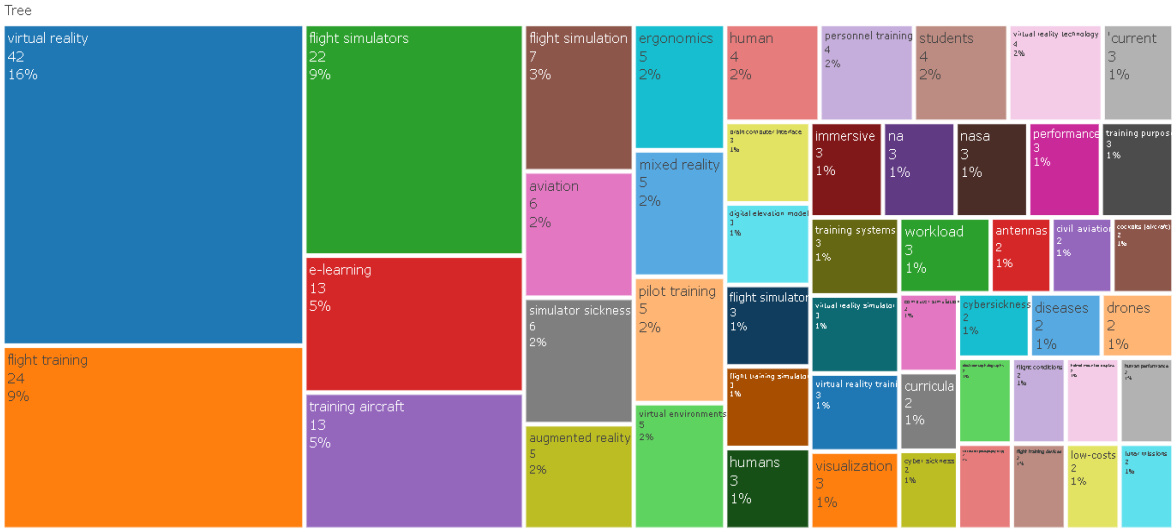

Figure 13 Tree Map

The graph shows that "virtual reality" is the most dominant theme, accounting for 16% of total publications, followed by "flight training" at 9%. The dominance of the theme reflects a significant research focus, indicating that virtual reality has become an important tool in the development of aviator training methods.

In addition, the themes of "flight simulators" and "e-learning" accounted for 2% and 5% of the total publications, respectively, indicating significant interest in the development and use of simulators in aviation education. Engagement with these themes shows that research revolves not only around the technology itself but also around its application in practical education and training.

Other themes that emerge, such as "ergonomics," "students," and "performance," suggest that research in this area also considers user experience and training outcomes. For example, attention to ergonomics highlights the importance of designing training tools that are comfortable and efficient, while a focus on performance and students suggests that research aims to improve learning outcomes.

Overall, the tree map analysis provides a comprehensive overview of the dynamics and trends in the use of virtual reality simulators for aviator training. By identifying the most frequently occurring themes and their frequencies, researchers can understand areas that have been extensively researched and direct attention to research gaps that may warrant further exploration. It will strengthen the existing knowledge base and encourage innovation in developing more effective and efficient flight training methods.

3.5 Collaboration Networks

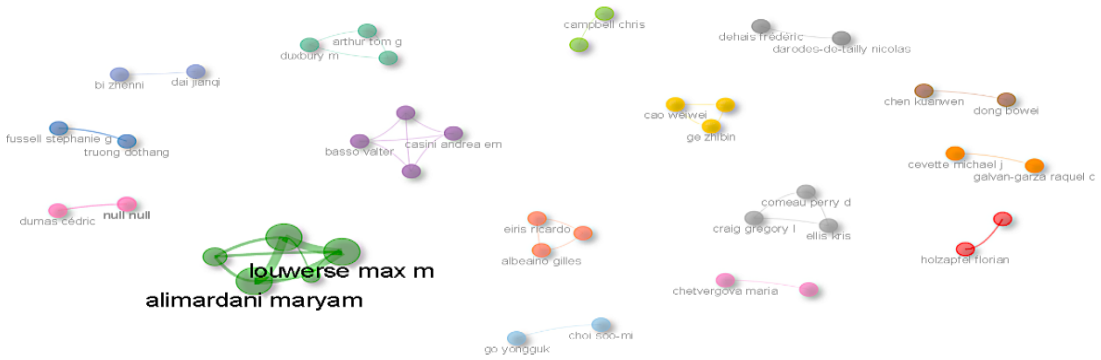

Figure 14. Author Collaboration Network

The authors' analysis of the collaboration networks shown in the graph provides important insights into the interactions and collaborations among researchers involved in studies of the use of virtual reality simulators in aviator training. The graph illustrates the connectivity among authors based on their publications and the patterns of collaboration in the literature.

Based on the graph analysis, Max M. Loluverse and Maryam Alimardani emerged as the network's central nodes. Both have extensive connections with other authors, suggesting they may have contributed significantly to the field's knowledge base. Their existence as a collaboration center may indicate that they have published widely cited or influential work on the use of virtual reality technology in flight training. It highlights the importance of their role in building strong research networks among academics.

In addition, other authors, such as Fussell, Dumarey, and Hatzopoulos, appear in the network, albeit with varying degrees of connection. Lower connectivity may indicate that they are more focused on individual research or more limited collaboration. However, despite not being at the center of the network, their contributions remain essential to understanding various aspects of aviator training using virtual reality simulators. It reflects the diversity of approaches and perspectives that exist in the study.

The network also shows that interdisciplinary collaboration can occur, where researchers from different backgrounds contribute to the same study. For example, the involvement of researchers from psychology, engineering, and education underscores that the use of virtual reality simulators in aviator training is a complex, multifaceted topic that requires synergy across disciplines to achieve optimal results. It emphasizes the importance of cooperation among researchers to explore and address challenges in flight training.

Overall, the analysis of the collaborative network provides a clear picture of the dynamics of interaction between researchers in the field of using virtual reality simulators for aviator training. Understanding these patterns of collaboration can help new researchers identify potential partners and build a broader network for their research. In addition, the analysis highlights the importance of interdisciplinary collaboration in driving innovation and modernizing flight training.

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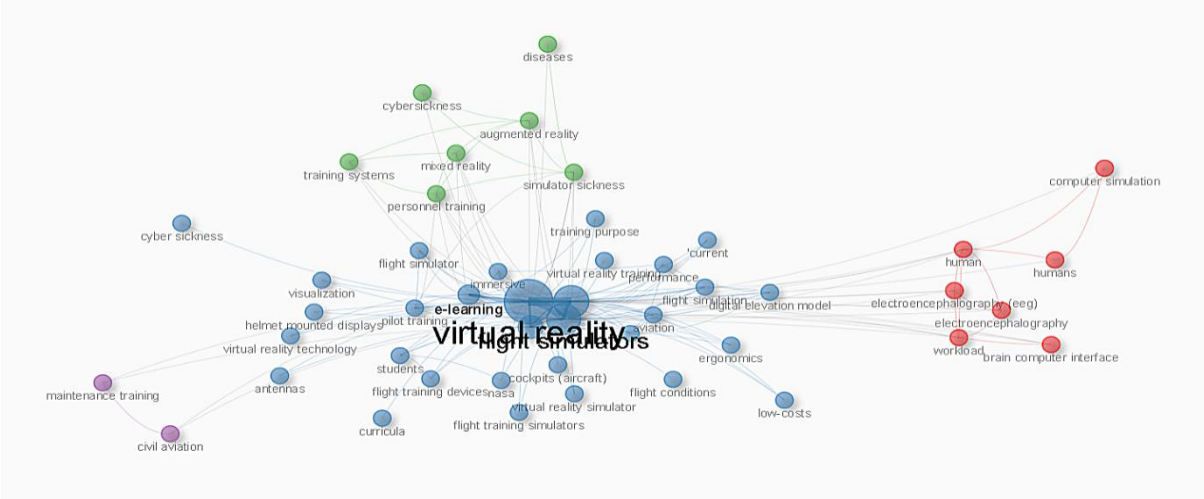

Figure 15. Network occurrence

From the network analysis, it can be seen that "virtual simulators" emerges as a central keyword with wide connections to various other themes. The literature suggests that virtual reality simulators are a significant focus, and that related concepts, such as "e-learning," "training purposes," and "cyber science," contribute to a deeper understanding of how these technologies are applied in flight training. This strong interconnectedness reflects the fact that research in this area is not only focused on the use of technology but also on its integration into the broader training curriculum.

Keywords such as "augmented reality," "human factors," and "maintenance training" also show attention to various elements that contribute to the effectiveness of training. For example, attention to the human factor highlights the importance of understanding the interaction between users and technology in the context of training. On the other hand, the concepts of "training systems" and "curricula" suggest that research also considers structural aspects in training, which can influence how technology is used and received by trainers and students.

Additionally, more specific themes, such as "cybersecurity," "diseases," and "computer simulation," appear at the edge of the network, suggesting that while these themes may not be the primary focus, they remain relevant and can influence the use of simulators in training. For example, cybersecurity issues become important in the context of training involving digital technology, while understanding "diseases" or other health challenges can affect simulation design and the overall training experience.

Overall, the keyword network analysis offers an in-depth assessment of the dynamics and complexity of research in the use of virtual reality simulators for aviator training. By understanding the relationships among themes and concepts, researchers can identify areas that have been extensively researched and those that may require further exploration. It also indicates that an interdisciplinary, collaborative approach is essential for addressing existing challenges and driving innovation in flight training through modern technologies.

4. CONCLUSION

With 48 documents generated from 26 sources, the study demonstrates diversity in the literature on the use of virtual reality simulators in flight training. The 168 authors involved in the study demonstrated extensive collaboration, with only five papers written by a single author. It suggests that most research is conducted collaboratively, which could improve the quality and depth of analysis. 2,083% of authors are involved in international co-authorship, which, although relatively low, still shows an effort to establish cross-border cooperation. They can enhance the exchange of ideas and best practices in the use of simulation technology for flight training. The average number of co-authors per document, 4.02, suggests that articles are generally written by large teams of researchers, reflecting the complexity of the topics discussed. There are 110 keywords used to identify the central themes and research in the area. The average age of the recorded documents was 3.25 years, indicating that many documents are still relevant and up to date, while the average citations per document of 8,542 indicate that the study has had a significant impact on the scientific community.

From 2015 to 2019, the graph shows relatively low publication numbers. Entering 2020, there was a significant increase. After reaching a peak in 2023, the number of publications seems to have declined again. The decline may raise questions about the sustainability of the researcher's interest in the topic and about external factors that may affect publication dynamics.

There are several dominant authors in the field; Mariam Almandar, Max L. Wiltshe, and Stephane G. Fussell each have five documents. The dominance suggests that the authors may have contributed significantly to the development of knowledge and practice in the use of virtual reality technology for flight training. Furthermore, other authors, such as Evy Van Weeleken and Valter Basso, make substantial contributions with four and three documents, respectively. Other authors, such as Andrea M. Casini, Aidan Cowley, and Mariella Ferrino, note a lower publication frequency.

The Civil Aviation Flight institutions of the University of China and Tilburg University each have twenty published articles. The dominance of these two institutions shows that they have invested in research on the use of virtual reality technology for aviator training. Furthermore, the Technische Universität München and the National Research Council of Canada have also made significant contributions, each with 10 articles.

The United States has the highest number of citations, with 123. The dominance shows that research conducted in the U.S. has made a very significant contribution to the development of knowledge in the use of virtual reality technology for aviator training. The following countries, namely the Netherlands and Germany, recorded significant numbers of citations, namely 56 and 50, respectively. Furthermore, France made a significant contribution with 36 citations, indicating that research conducted in the country remains relevant and influential. Meanwhile, other countries such as South Korea, China, the United Kingdom, Australia, New Zealand, and Finland show lower numbers of quotes. The presence of these countries in the graph reflects the diversity of perspectives and approaches that exist in research on the use of virtual reality simulators, as well as the importance of international collaboration in driving innovation.

The keywords "virtual reality" and "flight training" were the most dominant, indicating that these two concepts were central to the research.

The lower-right quadrant encompasses the basic themes of "virtual reality," "flight training," and "flight simulators." The existing literature has not fully developed or explored these themes, despite their relevance to research. The lower-right quadrant indicates that these themes are fundamental and may serve as a foundation for further research but are not currently at the forefront of research or development. It indicates that, despite the importance, there is still significant room for exploration and innovation in the use of virtual reality technology in aviator training.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript with any individuals or organizations.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that this manuscript was prepared without the use of ChatGPT or any OpenAI technology.

Author Contributions

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Stefanus Timonora Wahyu Ariyanto: conceptualization and writing original draft, Achmad Ridwan: review for final manuscript, Riyan Arthur: methodology and editing for the content

Ethics Approval

Not applicable

Data Availability

The data used in this manuscript were obtained through analysis of articles published in several Scopus-indexed journals classified as Q1. All relevant sources are journal articles included in the review dataset used for this study.

Abbreviation

VR for Virtual Reality

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