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# A Bibliometric Analysis of Augmented Reality and Virtual Reality During 1993–2022

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***Abstract***

*Augmented reality (AR) and virtual reality (VR) have received much attention recently as innovative and valuable technology. With the growth of AR and VR research, a comprehensive examination is required. From the standpoint of bibliometrics, this study conducts a comprehensive analysis of AR and VR papers from 1993 to 2022. A total of 6,785 publications are obtained from the Web of Science (WoS) database and loaded into the professional science mapping tools VOSviewer and Cite Space through preprocessing. The publishing structures are examined using annual publications and the publications of the most productive countries/regions, institutions, and authors. Afterward, the co-citation networks of countries/regions, institutions, authors, and articles are visualized using VOSviewer. Their citation structure and the most influential examples are investigated further. Finally, VOSviewer depicts the collaboration networks of countries/regions, institutions, and writers. Cite Space utilizes timeline analysis and keyword citation burst detection to identify hotspots and research trends. Finally, this study explains a basic understanding of AR and VR for scholars and a detailed examination of AR and VR for future research in this area.*

***Keyword****: Augmented Reality, Virtual Reality, Analysis Bibliometric, Web of Science, Publication*

**Abstrak**

Augmented reality (AR) dan virtual reality (VR) mendapat banyak perhatian sebagai teknologi yang inovatif dan dapat dimanfaatkan ke dalam berbagai macam bidang kehidupan. Sehingga penelitian pada bidang ini juga ikut berkembang dari hari ke hari. Dengan pesatnya pertumbuhan penelitian AR dan VR, maka diperlukan sebuah studi komprehensif untuk melihat bagaimana tren penelitian pada bidang ini. Oleh karena itu,tujuan penelitian ini adalah untuk melakukan analisis tren penelitian pada jurnal AR dan VR dari tahun 1993 hingga 2022 dengan menggunakan pendekatan bibliometrics. Dengan menggunakan tools pemetaan jurnal VOSviewer dan Cite Space penelitian ini akan memetakan memetakan publikasi tahunan, publikasi negara, institusi, dan penulis paling produktif di antara jurnal-jurnal AR dan VR. Setelah itu, jaringan/network co-citation negara, institusi, penulis, dan artikel divisualisasikan menggunakan VOSviewer. Kemudian struktur kutipan dan kutipan yang paling berpengaruh juga akan dipetakan. Terakhir, VOSviewer akan digunakan untuk menggambarkan jaringan kolaborasi negara/wilayah, institusi, dan penulis dan sementara Cite Space digunakan untuk menganalisis tren waktu dan mengidentifikasi tren penelitian.

**Kata kunci**: Augmented Reality, Virtual Reality, Analisis Bibliometrik, Web of Science, Publikasi

## 1. Introduction

Over the last few decades, augmented reality (AR) and virtual reality (VR) have seen technological advancements that have improved immersion and the sense of telepresence. Several implementation instances can be found in gaming, education, retail, tourist locations, hotels, restaurants, architectural design, medical, military training, and tourism [1], [2]. In recent years, AR and VR have attracted the public's curiosity, especially when Mark Zuckerberg purchased Oculus technology for two billion dollars [3].

AR and VR are frequently utilized as positive technology for users. This is the structuring, enhancement, and replacement of personal experience using creative technology [4]. It improves the environment and supports people in new ways that better represent their needs when utilized to boost user engagement [5]. Positive technology functions include encouraging pleasant feelings, promoting participation and self-empowerment, and increasing social integration and connectivity [6]. Users can see virtual objects overlaid in the real world in AR by interacting with their smartphones using see-through displays [7].

Several AR and VR overviews have been studied because of the rapid progress and diverse applicability. Loureiro et al. (2020) created a survey of twenty years of research on VR and AR in the tourism context. The use of AR and VR in language learning [8], construction safety [9], the construction industry [10], education in science, technology, engineering, and mathematics [11], [12], health and well-being [13], and design and manufacturing [14], among other applications, has been investigated in depth. Most AR and VR overviews were based on a subset of their applications and looked at from a traditional standpoint. However, no bibliometric analyses of AR and VR have been conducted.

Bibliometrics is a quantitative analysis-based study that mixes several disciplines, including philology, information science, mathematics, and statistics [15]. It is an essential branch of intelligence science that can be utilized to examine the characteristics of research articles in a specific study area (Nayak, Prabhu, and Ligade, 2022). Also, a bibliometrics study can uncover publications' internal structures and relationships. The bibliometrics of a study direction were investigated utilizing bibliometric methodologies and scientific mapping for business intelligence and big data [17], solar cells [18], medicine [19], and information technology policies [20].

The two bibliometric evaluation methodologies are performance analysis and science mapping. Based on publications and citations, performance analysis evaluates the performance of various scientific actors [21]. Science mapping illustrates scientific research's organization, evaluation, and dynamic characteristics [20]. Several visualization techniques for science mapping were compared by Cobo et al. (2011). The most applied tools are VOSviewer and Cite Space, which are also used in this paper. VOSviewer can visualize co-citation networks, co-authorships, co-occurrence, citation, and bibliographic coupling [24]. Cite Space focuses on detecting hotspots and research trends through timeline examination [25].

This research aims to provide a comprehensive bibliometric analysis of AR and VR publications from 1993 to 2022, with an examination of publications, citations, and collaboration structures as well as a research trend. The following are the significant contributions of this paper:

- The publication structure is evaluated from the perspectives of countries/regions, institutions, and authors.
- The science mapping tool VOSviewer shows the co-citation structures of countries/regions, institutions, authors, and papers. The most cited ones are also examined.
- VOSviewer displays the cooperation networks of countries/regions, institutions, and authors, along with a list of the most substantial collaborative ties.
- Cite Space exports the timeline review and citation burst detection of keywords for an in-depth study of AR and VR hot places and research trends.

The rest of the paper starts with a description of the data. The following are the specific arrangements. The data source and preprocessing are described in Section 2. Section 3 explains the publication structure analysis. The citation structures of countries/regions, institutions, authors, and papers are examined in Section 4. Section 5 depicts the collaboration networks of countries/regions, organizations, and authors based on Cite Space. Section 6 contains further analysis, such as a chronology review and keyword citation burst detection. The paper ends in Section 7 with conclusions.

The rest of the paper starts with a description of the data. The following are the specific arrangements. The material and methods are described in Section 2. Section 3 explains the

publication structure analysis. The citation structures of countries/regions, institutions, authors, and papers are examined in section 3.1 and 3.2. Section 3.3 depicts the collaboration networks of countries/regions, organizations, and authors based on Cite Space. Section 3.4 contains further analysis, such as a timeline analysis and keyword citation burst detection. The paper ends in Section 4 with conclusions.

## 2. Research Method

The Web of Science (WoS) is a universal database that provides data on scientific content, influence, and collections from 1990 to the present. The WoS core collection, as one of the WoS databases, provides scholars with many authoritative journals and publications and adequate related information that can be exported and imported to the bibliometric analysis platform. The WoS includes six citation indices (the Science Citation Index Expanded (SCI-EXPANDED), the Social Sciences Citation Index (SSCI), the Arts and Humanities Citation Index (A&HCI), the Conference Proceedings Citation Index — Science (CPCI-S), the Conference Proceedings Citation Index — Social Science and Humanities (CPCI-SSH), and the Emerging Sources Citation Index (ESCI)) and two chemical indices (Current Chemical Reactions (CCR-EXPANDED) and Index Chemicus (IC)).

This study reviewed the above databases to confirm the data's accuracy and comprehensiveness and found that SCI-EXPANDED, SSCI, CPCI-S, and CPCI-SSH are the most precise indices. The search terms were "augmented reality" and "virtual reality," and 6,785 publications were found, the first of which was published in 1993. As a result, the search criteria were set as follows: topic "augmented reality" and "virtual reality," timeframe "1993–2022," and database "SCI-EXPANDED, SSCI, CPCI-S, and CPCI-SSH." Their related information (record content set to "full record and cited references") was exported from the WoS as plain text on May 25, 2022.

## 3. Results and Discussion

### 3.1. Examining the organization of publications

The publication structure is examined in this part from four perspectives: annual publication, productive countries/regions, productive institutions, and authors.

#### 3.1.1 Annual Publication

The annual publication situation of AR and VR from 1993 to 2022 is depicted in Figure 1 using data from the WoS. The first publication appeared in 1993, and there was a fluctuating trend of publications for eighteen years until 2011. The number of publications did not exceed 100 in the eighteen years between 1993 and 2011. The number of publications has increased since 2011, when it surpassed 100. The increased number of publications, particularly in the previous three years, reflects the rapid development of this field.

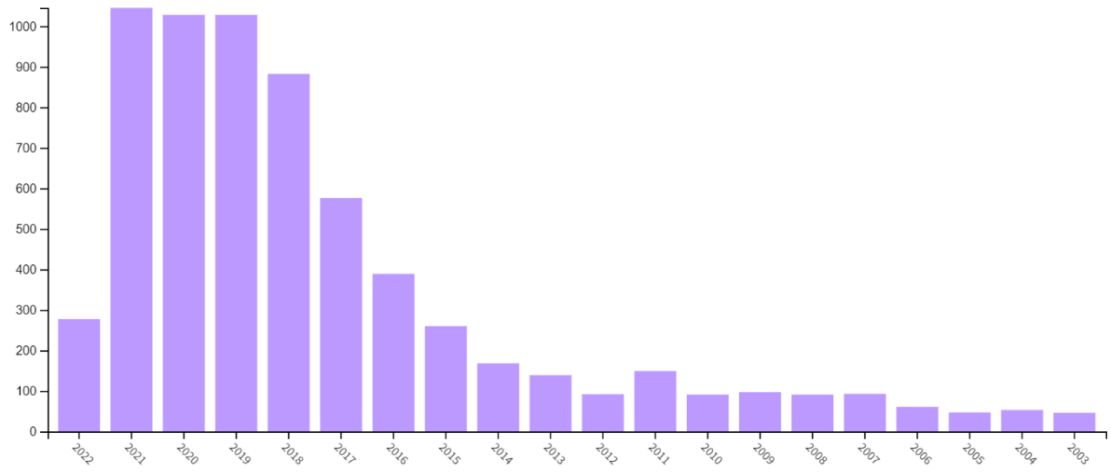


*Figure 1. Annual publication from 1993 to 2022.*

The primary types of these papers are assessed using the WoS, and the top ten types are depicted in Figure 2. The most common type of publication is proceeding papers, with 3,997 total publications, accounting for 58.909% of all 6,785 publications. Articles are the second most common type of publication, accounting for 2,449 papers and 36.094% of all publications. Also included are reviews (421), early access papers (152), book chapters (93), editorial material (70), meeting abstracts (5), letters (4), book reviews (3), and a data paper (1).


*Figure 2. The top ten types of the publications.*

The research directions of the papers are presented in Figure 3 based on WoS analysis. The two most common research directions, as seen in Figure 3, are computer science and engineering. Computer science has 4,125 publications, with a proportion of 60.796%, followed by engineering, which has 1,646 publications (24.259%). Imaging science photographic technology (972, 14.326%), educational research (532, 7.841%), telecommunications (298, 4.392%), optics (228, 3.360%), material science (206, 3.036%), business economics (184, 2.712%), physics (178, 2.623%), surgery (170, 2.506%), chemistry (165, 2.432%), science technology (and other topics) (158, 2.329%), and robotics (152, 2.240%) are among the most popular research directions. It is shown that AR and VR are well-developed in theory and methodology and extensive in applied research.


*Figure 3. The top ten research directions of the publications.*

### 3.1.2 Productive countries/regions

The top ten productive countries/regions and their annual publications are obtained and presented in Figure 4 to reflect the publications of such countries/regions. According to statistics, the top ten most productive countries/regions are the United States (1,517 publications), China (652 publications), Italy (476 publications), England (439 publications), Japan (392 publications), Spain (336 publications), South Korea (324 publications), Australia (300 publications), France (263 publications), Brazil (250 publications), Canada (229 publications), Taiwan (150 publications), and the Netherlands (139 publications), with a total of 6,785 publications.

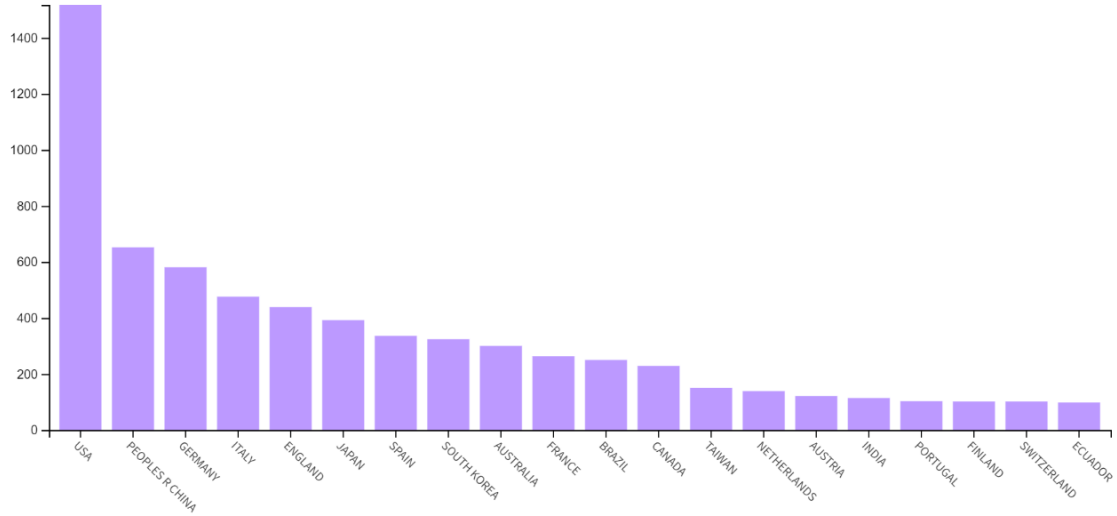


*Figure 4. The top ten productive countries/regions from 1993 to 2022.*

Most countries/regions have published papers since 1993. The annual publishing of the countries/regions is steadily increasing, and the top two countries/regions have more than 600 publications. The United States has become the first to publish over 1,400 articles, and its annual publication will continue to outnumber those of other countries/regions. The United States and China are the two most productive countries and have contributed the most to AR and VR research.

### 3.1.3. Productive institutions and authors

This part examines the publication from institutions and writers' perspectives. The top ten productive institutions and writers are given in Figure 5 and Table 1 accordingly. As shown in Figure 5, the top productive institutions are the League of European Research Universities (LERU) (Europe), the State University System of Florida (USA), the University of California (USA), Centre National de la Recherche Scientifique (CNRS) (France), the University of Central Florida (USA), Escuela Politecnica Superior Del Ejercito (Spain), the Technical University of Munich (Germany), the Udice French Research Universities (France), the University of South Australia (Australia), the University of London (England), the Chinese Academy of Sciences (China), Virginia Polytechnic Institute State University (USA), and the University of Tokyo (Japan).

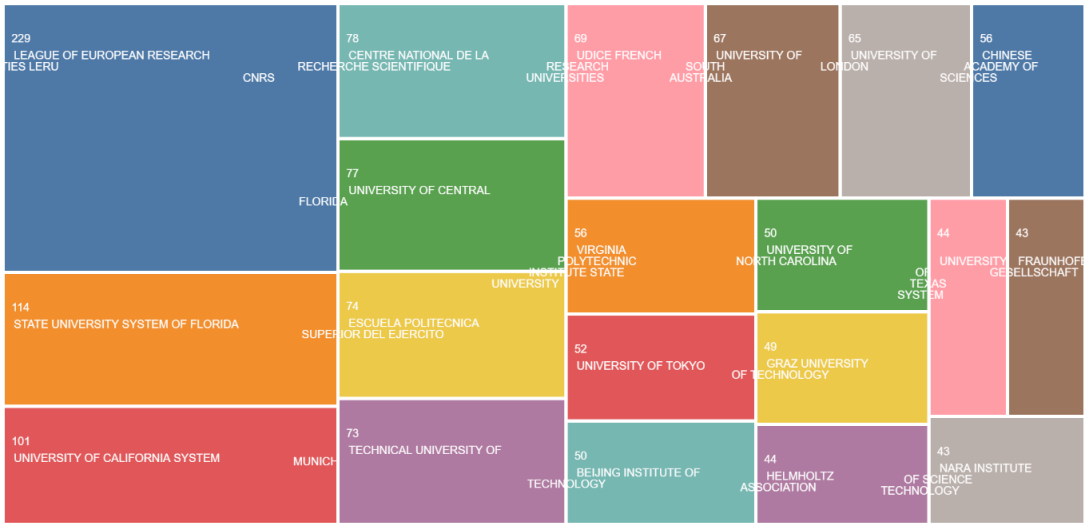


*Figure 5. The top ten productive institutions.*

Furthermore, LERU (299) has nearly double the number of articles compared to the rest of the institutions as they are a consortium of European research universities. The United States has four institutions, while France has two (2), and Spain and Germany have one each (1). With at least eight publications, the most productive writers and their countries/regions are given in Table 1. The letter P stands for the number of publications. Only three authors published more than forty publications in the field, with the most publications being fifty-nine. The United States (168), Australia (59), Ecuador (46), China (41), Austria (35), Germany (31), Taiwan (25), and South Korea (24), correspondingly, have the most productive fourteen authors.

*Table 1. The fourteen most productive authors*

| No. | Author | Country/Region | P |
|---|---|---|---|
| 1 | Billinghurst, M. | Australia | 59 |
| 2 | Andaluz, V. H. | Ecuador | 46 |
| 3 | Liu, Y. | China | 41 |
| 4 | Schmalstieg, D. | Austria | 35 |
| 5 | Swan, J. E. | USA | 35 |
| 6 | Hollerer, T. | USA | 33 |
| 7 | Steinicke, F. | Germany | 31 |
| 8 | Interrante, V. | USA | 27 |
| 9 | Navab, N. | Germany | 26 |
| 10 | Rosenberg | USA | 25 |
| 11 | Wang, Y. T. | Taiwan | 25 |
| 12 | Gabbard, J. L. | USA | 24 |
| 13 | Kim, J | South Korea | 24 |
| 14 | Krum, D. M. | USA | 24 |

### 3.2. Citation structure analysis

The citation condition is depicted in this section from four different perspectives to emphasize the influence of the research articles. The top ten most referenced papers are listed, along with the citations of countries/regions, institutions, and authors. P, C, and AC denote the object's numbers of publications, citations, and average citations. The indicator link represents the number of the co-cited objects, and total link strength (TLS) reflects the frequency with which others reference the object.

#### 3.2.1. The most influential countries/regions

Currently, seventy-four countries/regions have published at least one paper in the field, with sixteen countries that have been mentioned more than 1,000 times. Some of the papers are mentioned multiple times.

The co-citation network of countries/regions that have published papers on AR and VR is depicted in Figure 6. The linked nodes are countries/regions that have been referenced jointly, and the node's size denotes the number of citations for that country/region. The more citations of countries/regions there are, the larger the node is. The thicker the link is, the more often the two countries/regions are mentioned in the same sentence. Table 2 shows the thirteen most cited countries/regions with more than 1,000 citations and their respective information for further analysis of the citation structure.

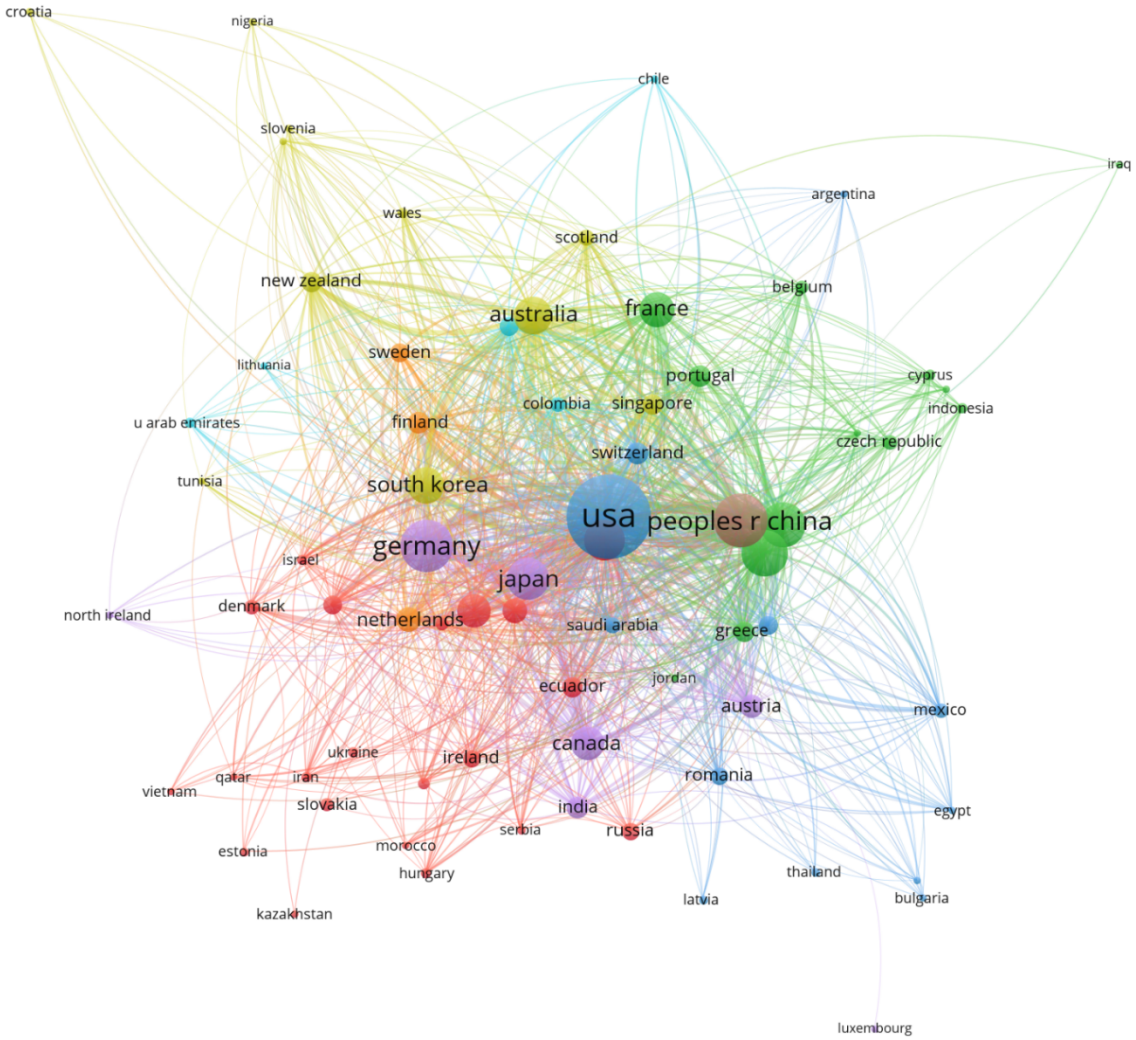


*Figure 6. The citation network of countries/regions.*

Table 2 lists the countries/regions in order of the TLS. The number of linkages indicates how many countries/regions are linked together. The United States, the most productive country, has the most citations, with an average citation of 12.76, implying that 12–13 publications are cited from the United States on average. Taiwan has only produced 133 papers in this field, yet it has the highest average citation count (15.72).

*Table 2. The thirteen most cited countries/regions*

| Rank | Country/Region | P | C | AC | Link | TLS |
|---|---|---|---|---|---|---|
| 1 | USA | 1,404 | 17,913 | 12.76 | 73 | 4,934 |
| 2 | China | 569 | 4,879 | 8.57 | 71 | 2,004 |
| 3 | England | 396 | 5,450 | 13.76 | 68 | 1,906 |
| 4 | Germany | 549 | 4,829 | 8.80 | 66 | 1,891 |
| 5 | Australia | 280 | 3,758 | 13.42 | 67 | 1,800 |
| 6 | Spain | 331 | 3,788 | 11.44 | 71 | 1,739 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | Italy | 440 | 3,610 | 8.20 | 68 | 1,627 |
| 8 | Canada | 221 | 3,113 | 14.09 | 58 | 1,123 |
| 9 | South Korea | 274 | 2,949 | 10.76 | 68 | 1,074 |
| 10 | Japan | 347 | 3,060 | 8.82 | 60 | 942 |
| 11 | Taiwan | 133 | 2,091 | **15.72** | 62 | 676 |
| 12 | France | 237 | 1,699 | 7.17 | 55 | 675 |
| 13 | New Zealand | 88 | 1,135 | 12.90 | 52 | 654 |

"A taxonomy of mixed reality visual displays" [26] (with 6,865 citations and published in 1994) and "Current status, opportunities, and challenges of augmented reality in education" [11] are the two publications with the highest citations (with 2,155 citations and published in 2013). Canada has the second-highest average citation of 14.09 and has been cited 3,113 times despite having just 221 publications. It is plausible to conclude from Table 2 that the number of citations does not always match the number of publications. A high citation does not always imply a high publishing count; a low citation can accompany a high number of publications.

### 3.2.2. The most influential institutions

This section examines the citation network at the organizational level. According to the data, 4,654 institutions have published in the field, with 478 publishing at least five papers. Furthermore, 183 universities have been cited more than 100 times, as seen in Figure 7. The 183 institutions are divided into 9 clusters and color-coded. The line between two nodes shows the associated institutions with publications mentioned together. The link thickness shows the strength of the co-cited relationship. The greater the node is, the more the institution's articles are cited. Table 3 lists the top twelve referenced institutions that have been cited more than 700 times and related information.

*Table 3. The twelve most influential institutions*

| Rank | Institution | Country/Region | P | C | AC | Link | TLS |
|---|---|---|---|---|---|---|---|
| 1 | National University of Singapore | Singapore | 37 | 1,239 | 33.48 | 74 | 165 |
| 2 | National Taiwan University of Science and Technology | Taiwan | 8 | 1,057 | **132.12** | 66 | 109 |
| 3 | Curtin University | Australia | 16 | 1,002 | 62.62 | 59 | 124 |
| 4 | University of Illinois | USA | 29 | 979 | 33.75 | 69 | 130 |
| 5 | Tsinghua University | China | 21 | 904 | 43.04 | 56 | 73 |
| 6 | National Taiwan Normal University | Taiwan | 9 | 887 | 98.55 | 55 | 85 |
| 7 | Universitat Politècnica de València | Spain | 41 | 870 | 21.21 | 81 | 296 |
| 8 | University of Central Florida | USA | 73 | 865 | **288.33** | 81 | 177 |
| 9 | Graz University of Technology | Austria | 47 | 770 | 16.38 | 52 | 75 |
| 10 | Technical University of Munich | Germany | 66 | 731 | 11.07 | 88 | 202 |
| 11 | University of Washington | USA | 31 | 714 | 23.03 | 47 | 89 |
| 12 | University of Valencia | Spain | 35 | 712 | 20.34 | 77 | 351 |

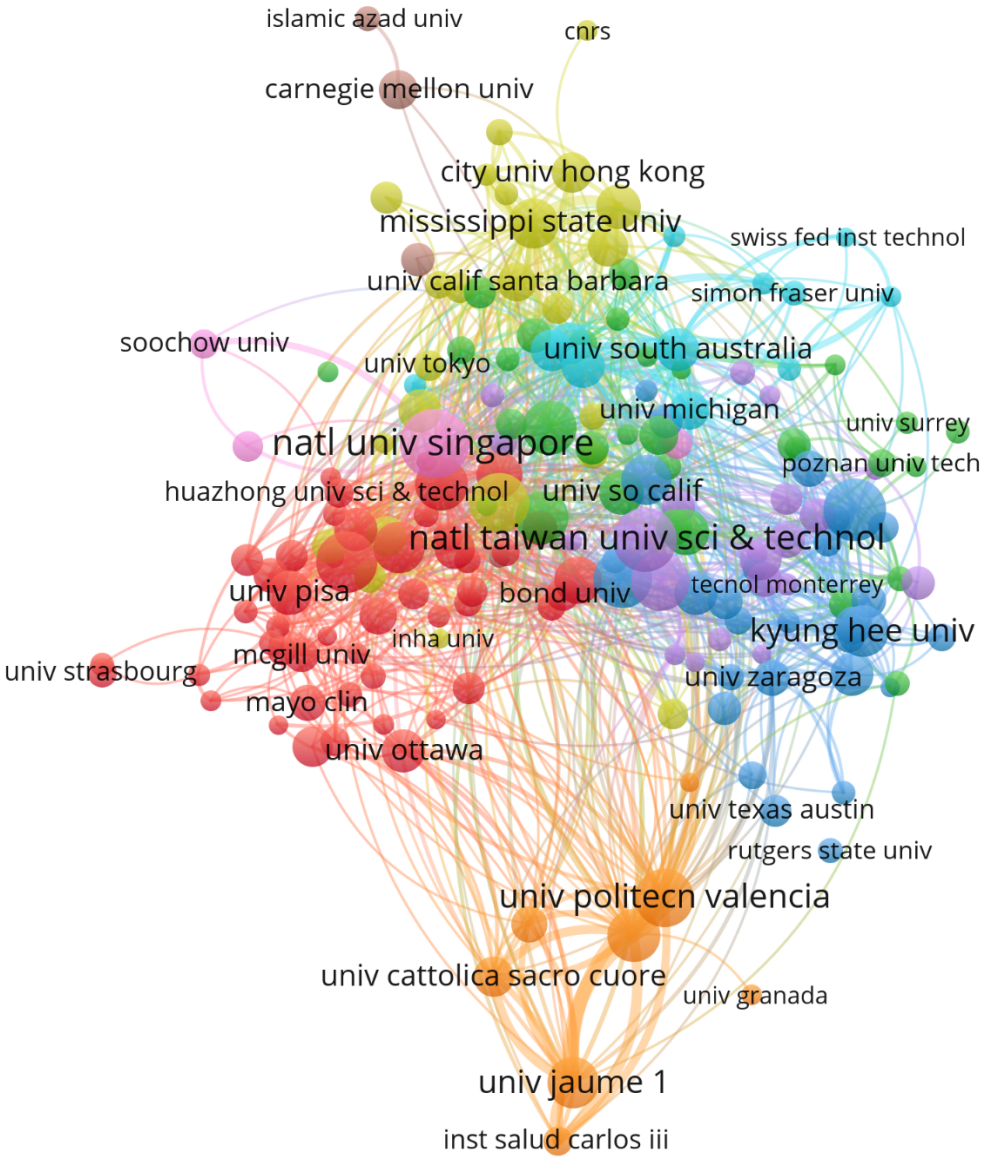


*Figure 7. The citation network of institutions.*

Table 3 shows that 3 of the 12 institutions are from the United States, 2 from Taiwan, and 2 from Spain. Singapore, Australia, China, Austria, and Germany have one institution each. The University of Central Florida and the National Taiwan University of Science and Technology have the highest average citations; they have produced 73 and 8 publications in the field, with 865 and 1,057 citations, respectively. The two institutions were also placed first and second regarding average citations. The TLS denotes the strength of the co-cited link, and the number of links represent the number of co-cited institutions. For example, the National Taiwan University of Science and Technology has collaborated with 66 institutions 109 times (using 88 links and 109 TLS).

### 3.2.3. The most influential authors

The following sections detail the author citations and their co-citation relationships. In total, 20,284 writers have written articles in the field, with 105 authors receiving more than 100 citations. The largest co-cited network consists of 376 among the 20,284 authors, as illustrated in Figure 8.

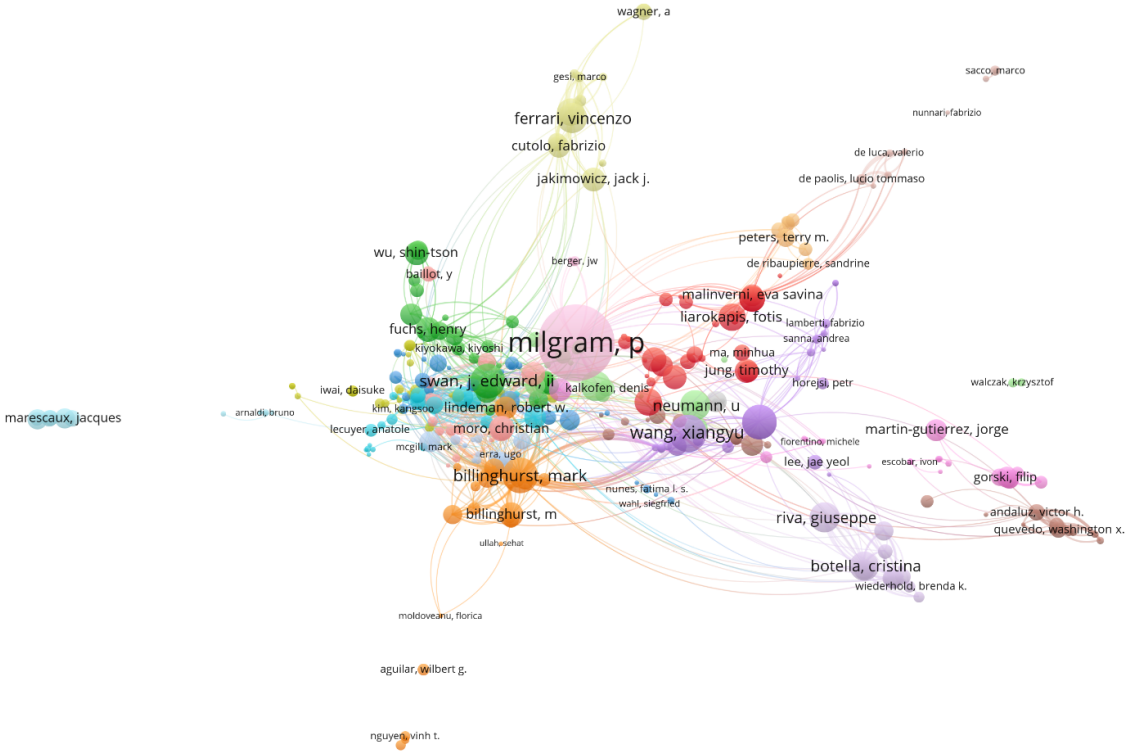


*Figure 8. The citation network of authors.*

Colors are used to group and distinguish the 376 authors. The node's size symbolizes the author's citations, and the line connects two authors whose works are referenced together. The more co-cited authors there are, the thicker the bond is. Table 4 displays the relative information of the top 17 writers with at least 100 citations. As can be seen, all the other 16 writers, except for Paul Milgram, received less than 700 citations. Paul Milgram received the most citations and highest TLS.

*Table 4. The seventeen most influential authors*

| Rank | Author | Country/Region | P | C | AC | Link | TLS |
|---|---|---|---|---|---|---|---|
| 1 | Milgram, P. | Canada | 5 | 2,703 | 540.60 | 148 | 248 |
| 2 | Wang, X. | Australia | 16 | 661 | 41.31 | 23 | 47 |
| 3 | Billinghurst, M. | Australia | 52 | 601 | 11.56 | 97 | 423 |
| 4 | Sawn, J. E. | USA | 28 | 576 | 20.57 | 93 | 298 |
| 5 | Nee, A. Y. C | Singapore | 9 | 573 | 63.67 | 35 | 65 |
| 6 | Ong, S. K. | Singapore | 9 | 573 | 63.67 | 35 | 65 |
| 7 | Schmalstieg, D. | Austria | 25 | 435 | 17.40 | 45 | 80 |
| 8 | Ferrari, V. | Italy | 22 | 421 | 19.14 | 31 | 134 |
| 9 | Riva, G. | Italy | 7 | 420 | 60.00 | 19 | 89 |
| 10 | Neumann, U. | USA | 7 | 414 | 59.14 | 15 | 18 |
| 11 | Botella, C. | Spain | 16 | 401 | 25.06 | 20 | 166 |
| 12 | Tecchia, F. | Italy | 12 | 364 | 30.33 | 36 | 60 |
| 13 | Liarokapis, F. | Cyprus | 13 | 359 | 27.62 | 12 | 23 |
| 14 | Ferrari, M. | Italy | 12 | 356 | 29.67 | 20 | 94 |
| 15 | Pierdicca, R. | Italy | 19 | 307 | 16.16 | 27 | 108 |
| 16 | Frontoni, E. | Italy | 16 | 304 | 19.00 | 27 | 107 |
| 17 | Moro, C. | Australia | 7 | 282 | 40.29 | 18 | 66 |

### 3.2.4. The most influential papers

To investigate the features and content of the publications in depth, the following sections illustrate and prove the conditions of citation and co-citation. The co-citation relationship is depicted in Figure 9 as a matching network. Table 5 shows the ten most influential articles in terms of citations.

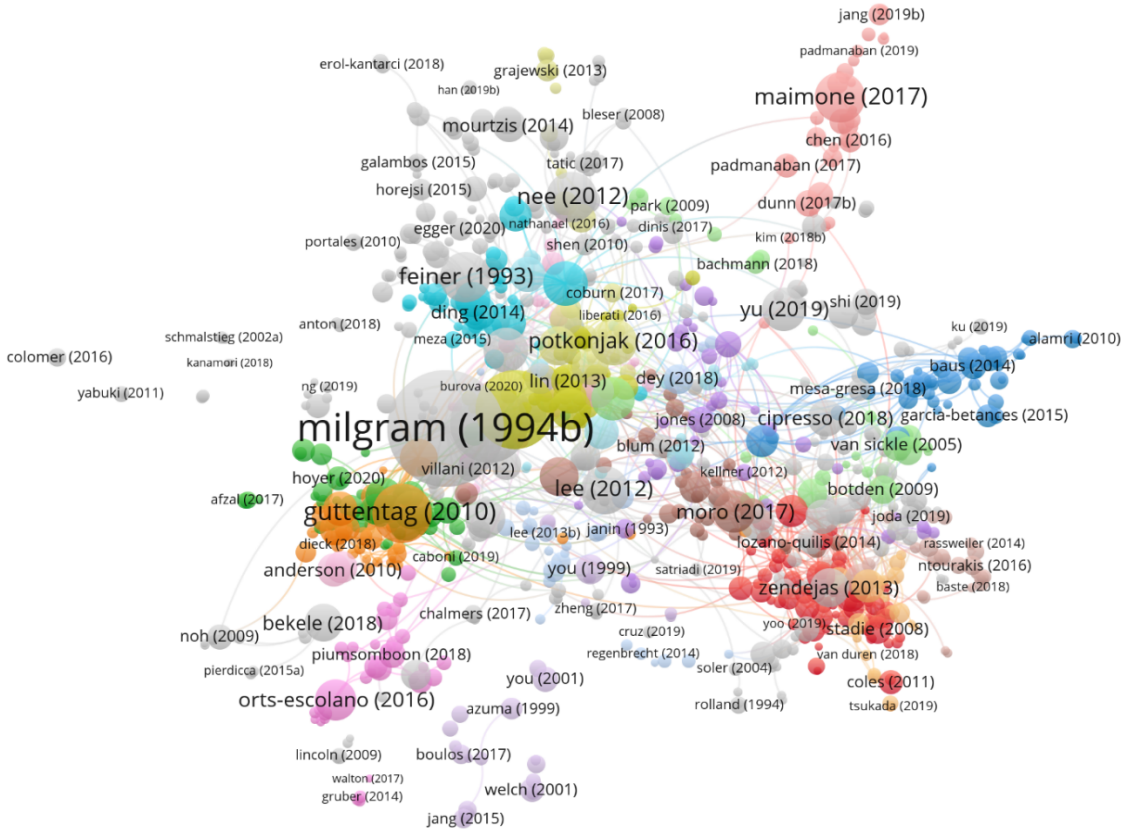


*Figure 9. The co-citation network of articles.*

Figure 9 shows the greatest connected network, with 71 papers mentioned more than 100 times. The linked papers have been co-cited, and the node size corresponds to the number of citations for each. They are divided into 44 groups and distinguished by several colors. The most influential papers have been highlighted, and Table 5 lists the ten most cited publications along with their relevant information. Except for the review, eight are collaborative publications. One author, Daniel A. Guttentag, wrote “Virtual reality: Applications and implications for tourism” [27], and Kangdon Lee wrote “Augmented reality in education and training.” Seven of the publications are reviews, and the remaining three are articles.

*Table 5. The ten most influential publications*

| Rank | Article | Authors | Types | Publication Year | Research Direction | C | Link |
|---|---|---|---|---|---|---|---|
| 1 | A taxonomy of mixed reality visual displays [26] | Paul Milgram, Fumio Kishino | Article | 1994 | Virtual Reality | 1,719 | 122 |
| 2 | Current status, opportunities, and challenges of augmented reality in education [11] | Hsin-Kai Wu, Silvia Wen-Yu Lee, Hsin-Yi Chang, Jyh-Chong Liang | Review | 2013 | Augmented Reality in Education | 795 | 60 |
| 3 | Augmented reality: A class of displays on the reality–virtuality continuum [28] | Paul Milgram, Haruo Takemura, Akira Utsumi, Fumio Kishino | Review | 1995 | Augmented Reality | 777 | 66 |
| 4 | Virtual reality: Applications and implications for tourism [27] | Daniel A. Guttentag | Review | 2010 | Virtual Reality in Tourism | 447 | 45 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | Knowledge-based augmented reality [29] | Steven Feiner, Blair Macintyre, Dorée Seligmann | Article | 1993 | Augmented Reality | 329 | 28 |
| 6 | Holographic near eye displays for virtual and augmented reality [30] | Andrew Maimone, Andreas Georgiou, Joel S. Kollin | Article | 2017 | Virtual and Augmented Reality | 327 | 17 |
| 7 | Augmented reality applications in design and manufacturing [14] | A. Y. C. Nee, S. K. Ong, G. Chryssolouris, D. Mourtzis | Review | 2012 | Augmented Reality in Design and Manufacturing | 326 | 30 |
| 8 | Augmented reality in education and training [31] | Kangdon Lee | Review | 2012 | Augmented Reality in Education and Training | 291 | 18 |
| 9 | Virtual laboratories for education in science, technology, and engineering: A review [12] | Veljko Potkonjak, Michael Gardner, Victor Callaghan, Pasi Mattila, Christian Guetl, Vladimir M. Petrović, Kosta Jovanović | Review | 2016 | Virtual Reality in Education | 287 | 6 |
| 10 | A critical review of virtual and augmented reality (VR/AR) applications in construction safety [9] | Xiao Li, Wen Yi, Hung-Lin Chi, Xiangyu Wang, Albert P. C. Chan | Review | 2018 | Virtual and Augmented Reality | 256 | 25 |

AR and VR are the most common research topics in the ten publications, but there are also studies on AR in education, VR in tourism, AR in design and manufacturing, and AR in education and training. All ten publications have been quoted more than 100 times, with the top three cited more than 700 times, while the remaining seven have been cited less than 400 times. The top ten publications were all published between 1993 and 2018.

### 3.3. Cooperation analysis

VOSviewer is used to form collaboration networks of countries/regions, institutions, and writers to examine the cooperation relationship. P denotes the object's number of publications in this area. The TLS reflects how much the object collaborates with others, and the number of indicator links represent how much the object cooperates with others.

#### 3.3.1. Cooperation network of countries/regions

WoS data was retrieved and put into VOSviewer. They set the minimal number of papers for a country/region to 5, resulting in 74 of 105 countries/regions meeting the threshold and forming the collaborative networks depicted in Figure 10.

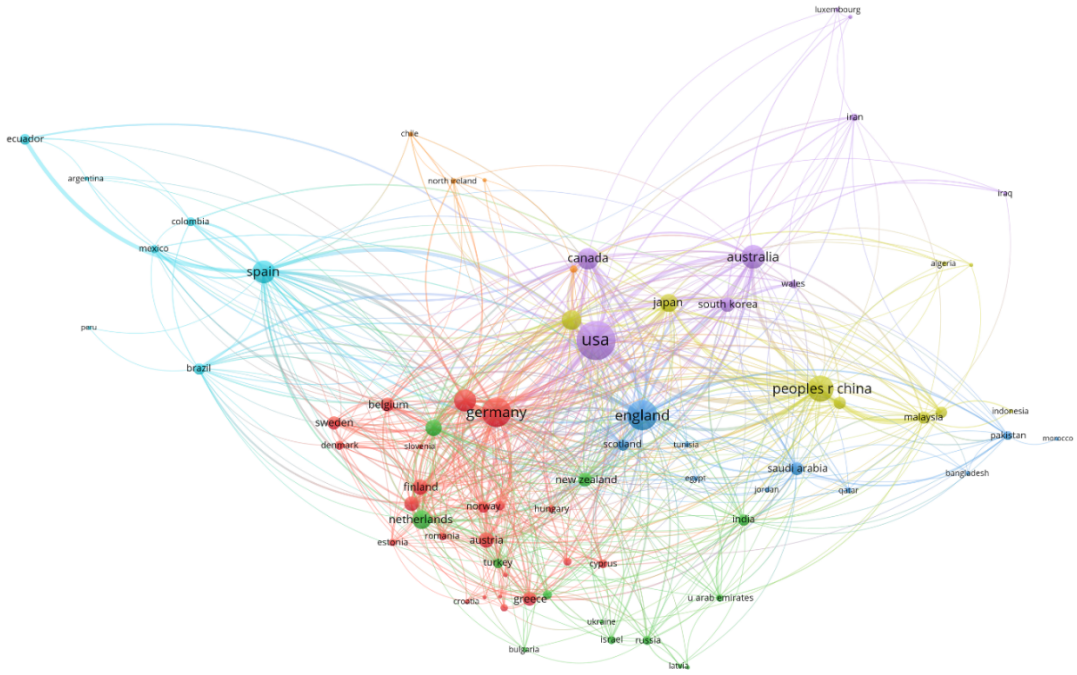


*Figure 10. The cooperation network of countries/regions.*

All 74 countries/regions are divided into seven clusters, each with its color scheme. The presence of a link between two nodes indicates that they are cooperating, and the width of the link indicates the link strength or the frequency of cooperation. The TLS of the node, which is the sum of all the node's link strengths, determines its size. The three countries with the highest TLS in Figure 10 are the United States, China, and England, with the strongest link among them. The six countries/regions with the most substantial cooperation relationships are displayed in Table 6 for further study of these countries/regions' collaboration relationships.

*Table 6. The top six countries/regions with the strongest cooperation relationship*

| Rank | Country/Region | P | Link | TLS | Total Cooperation Strength | Main Cooperators | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Country/Region | Link Strength | Cooperation Strength |
| 1 | USA | 1,404 | 73 | 450,563 | 320.91% | England | 32,764 | 72.72% |
| | | | | | | Germany | 34,314 | 76.16% |
| | | | | | | Italy | 29,407 | 65.27% |
| | | | | | | China | 29,257 | 64.93% |
| | | | | | | Spain | 23,825 | 52.88% |
| 2 | England | 396 | 73 | 189,498 | 478.53% | Germany | 12,587 | 66.42% |
| | | | | | | Italy | 10,580 | 55.83% |
| | | | | | | China | 10,514 | 55.48% |
| | | | | | | Spain | 8,700 | 45.91% |
| 3 | Germany | 549 | 73 | 187,968 | 342.38% | Italy | 11,045 | 58.76% |
| | | | | | | China | 10,311 | 54.86% |
| | | | | | | Spain | 9,680 | 51.50% |
| 4 | Italy | 440 | 73 | 172,687 | 392.47% | China | 9,251 | 53.57% |
| | | | | | | Spain | 10,730 | 62.14% |
| 5 | China | 569 | 73 | 166,655 | 292.89% | Spain | 8,765 | 52.59% |
| 6 | Spain | 331 | 73 | 150,852 | 455.75% | China | 8,765 | 58.10% |

Table 6 depicts the six collaborative country/region pairs with the strongest collaboration ties. Total cooperation strength derived by TLS/P represents the degree of collaboration. Cooperation strength is linking strength divided by TLS. The United States, the country with the greatest TLS and the most collaborative countries/regions, has worked with 73 countries/regions, with England, Germany, Italy, China, and Spain being the most collaborated. Mainly, all of the countries' total cooperation strength exceeds 100%, and this indicates that, on average, all the countries' publications collaborate with at least one country/region.

### 3.3.2. Cooperation network of institutions

According to the analysis, 4,654 institutions have produced papers in the area, with 470 institutions forming the greatest connected network (Figure 11). Cooperators are the related items, and the stronger the link, the better the cooperation relationship. The TLS of the node is determined by its size. Ten institutions have a TLS of more than 100, according to VOSviewer, and relative information for these institutions is shown in Table 7.

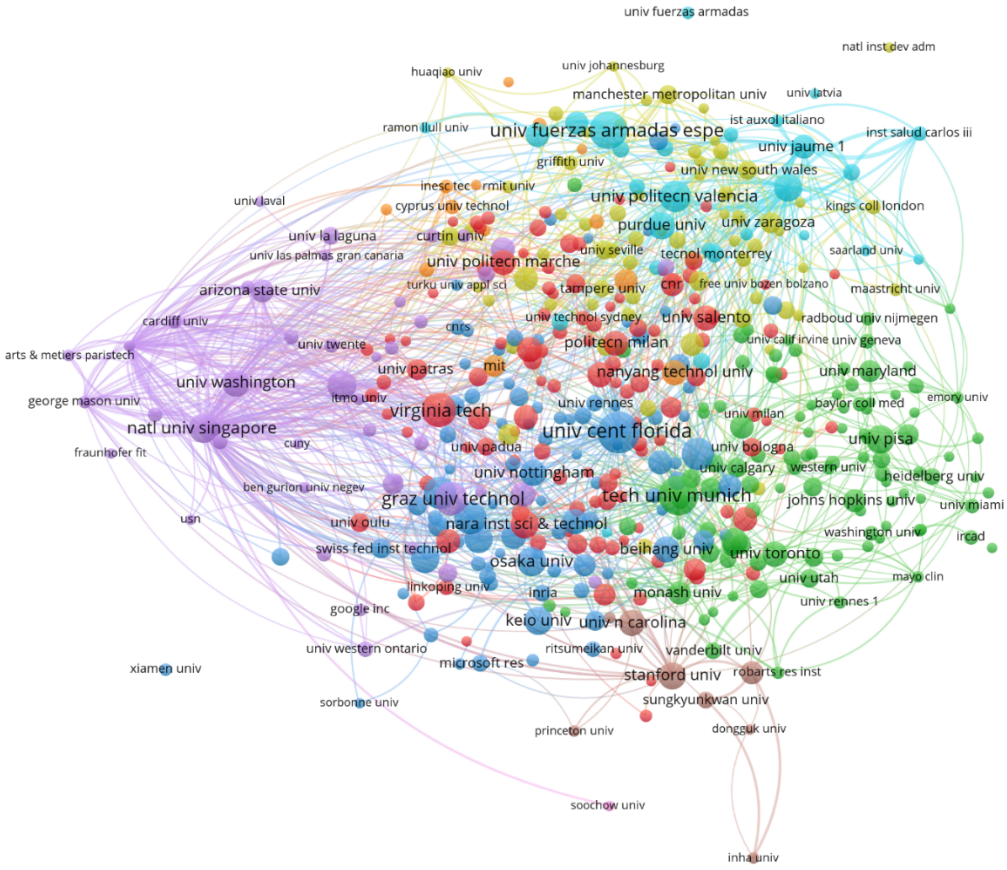


*Figure 11. The cooperation network of institutions.*

The number of connections represents the number of cooperative organizations. As the institution with the most publications, the National University of Singapore is also the institution with the most cooperators. It has collaborated with 452 institutions and has a TLS of 44,883, indicating that it has collaborated with certain institutions multiple times. The link is greater than the P for each institution, and the TLS is greater than the link, indicating that certain publications are collaborative works completed by more than two collaborators. Table 8 lists the six pairs of institutions with the strongest cooperation links and their respective information for further investigation of the collaboration.

*Table 7. The top ten institutions with the highest total link strength (TLS)*

| Rank | Institution | Country/Region | P | Link | TLS |
|---|---|---|---|---|---|
| 1 | National University of Singapore | Singapore | 37 | 452 | 44,883 |
| 2 | University of Valencia | Spain | 35 | 447 | 26,649 |
| 3 | Carleton University | Canada | 6 | 421 | 26,479 |
| 4 | University of Central Florida | USA | 73 | 459 | 25,389 |
| 5 | Universitat Politècnica de València | Spain | 41 | 454 | 23,329 |
| 6 | Universitat Jaume I | Spain | 24 | 436 | 20,213 |
| 7 | Technical University of Munich | Germany | 66 | 461 | 19,396 |
| 8 | University of Washington | USA | 31 | 437 | 19,292 |
| 9 | Politecnico di Torino | Italy | 36 | 448 | 18,356 |
| 10 | Cardiff University | Wales | 8 | 406 | 16,445 |

As can be seen, the National University of Singapore and Carleton University have the strongest collaboration relationship, having collaborated 3,304 times. With a TLS of 44,883, Carleton University collaborated with the National University of Singapore 7.36% of the time, while the latter completed 12.48% of the former's cooperation works. The University of Valencia and Universitat Jaume I, as the duo with the second strongest collaborative partnership, collaborated and completed 2,093 publications together. With 35 articles, 447 collaborators, and 26,649 TLS, Universitat Jaume I collaborated with the University of Valencia 7.85% of the time. The University of Valencia completed 10.35% of its 26,649 cooperation projects with Universitat Jaume I. It has also only published 35 publications but has collaborated with 447 institutions 26,649 times, implying that it collaborates with the most institutions several times.

*Table 8. The top six couples of institutions with the strongest cooperation relationship*

| Rank | Institution | P | Link | TLS | Total Cooperation Strength | Main Cooperators | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Institution | Link Strength | Cooperation Strength |
| 1 | National University of Singapore | 37 | 452 | 44,883 | 1,213.05% | National University of Singapore | 3,304 | 7.36% |
| 2 | University of Valencia | 35 | 447 | 26,649 | 761.40% | University of Valencia | 2,093 | 7.85% |
| 3 | Carleton University | 6 | 421 | 26,479 | 4,413.17% | Carleton University | 3,304 | 12.48% |
| 4 | University of Central Florida | 73 | 459 | 25,389 | 347.79% | University of Central Florida | 297 | 1.17% |
| 5 | Universitat Politècnica de València | 41 | 454 | 23,329 | 569.00% | Universitat Politècnica de València | 239 | 1.02% |
| 6 | Universitat Jaume I | 24 | 436 | 20,213 | 842.21% | Universitat Jaume I | 2,093 | 10.35% |
| 7 | Technical University of Munich | 66 | 461 | 19,396 | 293.88% | Technical University of Munich | 297 | 1.53% |
| 8 | University of Washington | 31 | 437 | 19,292 | 622.32% | University of Washington | 239 | 1.24% |
| 9 | Politecnico di Torino | 36 | 448 | 18,356 | 509.89% | Politecnico di Torino | 459 | 2.50% |
| 10 | Cardiff University | 8 | 406 | 16,445 | 2,055.63% | Cardiff University | 459 | 2.79% |

The six authors with the highest TLS collaboration and the strongest collaboration relationships are illustrated in Table 9 and Figure 13. According to VOSviewer analysis, these six authors collaborated and kept one another as the strongest collaborators.

*Table 9. The top six authors with the largest total link strength (TLS)*

| Rank | Author | P | Link | TLS |
|---|---|---|---|---|
| 1 | Billinghurst, M. | 52 | 82 | 6,261 |
| 2 | Swan, J. E. | 28 | 81 | 3,350 |
| 3 | Dey, A. | 14 | 81 | 2,998 |
| 4 | Itoh, Y. | 14 | 76 | 2,800 |
| 5 | Navab, N. | 23 | 77 | 2,554 |
| 6 | Ferrari, V. | 22 | 69 | 2,528 |

### 3.3.3. Cooperation relationship of authors

VOSviewer is used to evaluate and present the cooperation network of authors to reflect the interactions among them. According to VOSviewer, 20,284 authors have written papers related to this topic, with 83 making up the greatest author cooperation network. In Figure 12, the cooperation network of the 83 writers is presented, with the node's size indicating the authors' TLS or frequency of cooperation with others. The connection between the two nodes indicates that the two authors collaborate. The network shown in Figure 12 has 2,823 links and 47,137 TLS, according to VOSviewer. Table 9 lists the six writers with the highest TLS and their related information. The strongest cooperative network is also shown in Figure 13.

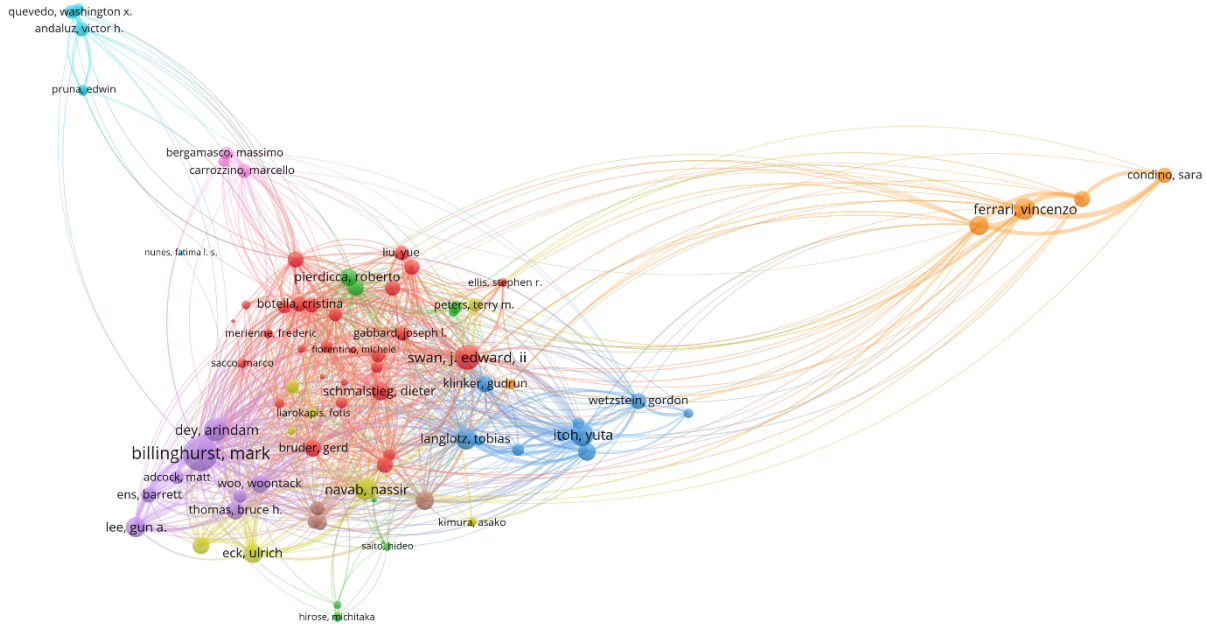


*Figure 12. The cooperation network of authors.*

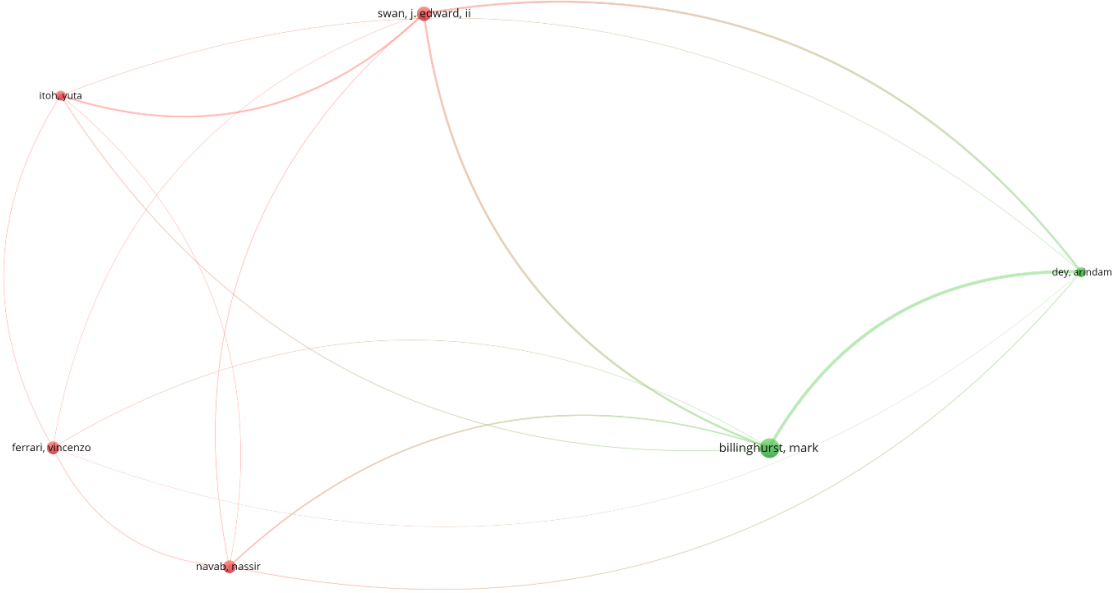


*Figure 13. The strongest cooperation network of authors.*

### 3.4. Timeline analysis and burst detection

The timeline review analysis of keywords is studied and illustrated for the further study of AR and VR. Also, this study identified the top 16 terms with the most citation bursts. Cite Space is used to display the results of the timeline review analysis to examine the research trend in this field. It represents different periods' study priorities, and the research trend has varied over time. Figure 14 depicts a keyword timeline review. Cite Space has identified 16 keywords with the highest citation bursts, which are displayed in Table 10.

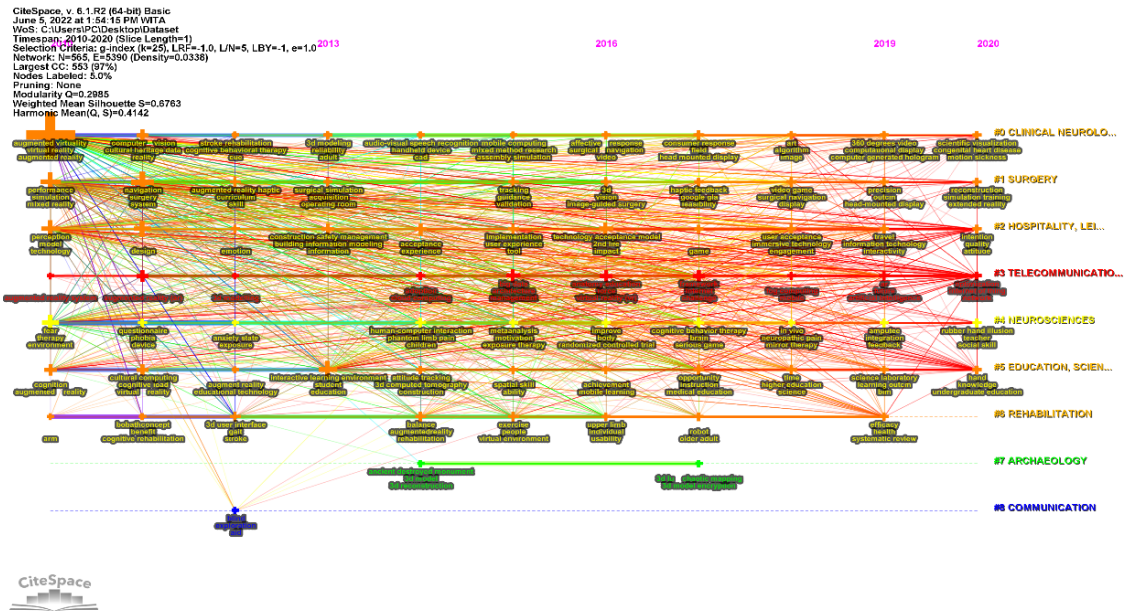


*Figure 14. The timeline review of keywords.*

Cite Space divides the keywords into eight clusters, seen in Figure 14, and labeled with numbers ranging from 0 to 8. Keywords and the log-likelihood ratio (LLR) technique are used to label the cluster. Clinical neurology, surgery, hospitality, telecommunication, neurosciences, education sciences, rehabilitation, archaeology, and communication are all examples of AR and

VR uses. In summary, the development of AR and VR has resulted in the creation of related applications.

*Table 10. The top twenty-four keywords with the strongest citation bursts*

| Rank | Keywords | Strength | Start | End | 2010–2020 |
|---|---|---|---|---|---|
| 1 | Fear | 4.4 | 2010 | 2015 | |
| 2 | Anxiety Disorder | 3.88 | 2010 | 2016 | |
| 3 | Therapy | 2.73 | 2010 | 2011 | |
| 4 | Virtual Reality | 2.77 | 2011 | 2014 | |
| 5 | Phobia | 2.53 | 2011 | 2015 | |
| 6 | Acquisition | 3 | 2013 | 2016 | |
| 7 | Operating Room | 2.85 | 2013 | 2016 | |
| 8 | Tracking | 3.92 | 2015 | 2018 | |
| 9 | Environment | 3.13 | 2015 | 2016 | |
| 10 | Validity | 3.08 | 2015 | 2017 | |
| 11 | Performance | 2.51 | 2015 | 2017 | |
| 12 | Randomized Controlled Trial | 3.48 | 2016 | 2018 | |
| 13 | Surgery | 4.85 | 2017 | 2018 | |
| 14 | Phantom Limb Pain | 3.39 | 2017 | 2018 | |
| 15 | Autism Spectrum Disorder | 2.62 | 2018 | 2018 | |
| 16 | Support | 3.25 | 2019 | 2020 | |

The keyword's citation bursts represent the citation situation and the period during which the keyword is cited the most. The timeline is the row with the title "2010–2020," and the red timeline reflects the keyword's citation burst era. "Surgery," "fear," "tracking," and "anxiety disorder" have received much attention since 2010. Surgery was mentioned often between 2017 and 2018, with a citation burst strength of 4.85. From 2010 to 2016, the keyword "anxiety disorder" saw a citation burst.

Surgery and fear burst citations increased from 2017 to 2018 and 2010 to 2015, respectively. Keywords such as "tracking," "randomized controlled trial," and "phantom limb pain" received more citations in 2015–2018 than in previous years. During 2015–2018, 5 of the 16 keywords had significantly more citations than during previous periods from 2010 to 2015. Since 2018, only six keywords have been quoted more frequently: "tracking," "randomized controlled trial," "surgery," "phantom limb pain," "autism spectrum disorder," and "support." The "support" citation bursts continued from 2019 to 2020, whereas the other keywords' bursts stopped in 2018.

AR and VR have several advantages and can be used in various studies. They may be utilized more in the future in decision-making environments, such as decision support, as the trend showed support keywords in 2019 and 2020.

## 5. Conclusion

This report provides a complete summary of AR and VR from 1993 to 2020. After preprocessing, 6,785 publications are chosen, and the related information is exported from the WoS. According to the WoS data, the publication structure is observed. VOSviewer examines the citation structure and collaboration networks of countries/regions, institutions, and authors. Cite Space displays additional analysis based on the timeline review analysis and citation burst detection of keywords.

1. Since 2012, the number of publications has increased, with over 1,000 publications in the last seven years, which is significantly higher than in previous years. The proceeding papers are the first and most common publication type, with 3,997 total publications, accounting for 58.909% of all 6,785 publications. Articles are the second most common type of publication, accounting for 2,449 copies and 36.094% of all publications. There are publications in the

area from 105 countries/regions, with the United States and China publishing 2,169 of them, accounting for 31.96%. The number of institutions and authors is spread out, with 4,654 institutions and 20,284 authors publishing throughout the area.

2. The citation structure analysis reveals that more publications do not necessarily imply high citations. The highest producing countries/regions, institutions, and authors are not necessarily the most influential. With more than 5,000 citations, the United States and England are the most cited countries. The National University of Singapore, the National Taiwan University of Science and Technology, and Curtin University have all published one paper each in the field, with the highest citations and average citations. Paul Milgram's papers received the most citations among all the 16 authors, with more than 2,000 citations, and others received publication papers lower than 700. The importance of the publication's quality over its number cannot be overstated.
3. The strongest cooperation relationship is between the United States and England, while the National University of Singapore and Carleton University maintain the strongest cooperation relationship for universities.
4. AR and VR have been researched extensively, particularly in medicine and education. The AR and VR hotspot changes with the seasons, and the study trend shifts with time.

This study presents a complete bibliometric analysis of AR and VR from 1993 to 2020, including an examination of publishing, citation, and collaboration patterns and the research trend. To summarize, while the conclusions in this work do not cover all the information, this paper is valuable and instructive to scholars interested in AR and VR. The development of AR and VR—particularly the creation, variants, and applications of several AR and VR models—will continue to receive attention in the future.

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