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Trends Analysis of Virtual Reality Research between 1987 and 2021

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Keywords

Betweenness centrality
Bibliometrics
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Virtual reality

Abstract.

The COVID-19 pandemic has dramatically altered the way how we communicate with others. From ZOOM to Metaverse, an increasing number of people are shifting to the virtual world for work and personal life. However, as a technology, virtual reality is still considered merely a device for immersive gaming for the young generation. Thus, despite its potential, virtual reality is hardly discussed as a core technology enabling Metaverse, which provides a virtual world for everyone. Therefore, it is necessary to examine prior studies for an understanding full spectrum of virtual reality research. There are three primary aims of this study: 1. To trace the history of virtual reality research for providing a holistic view of the research trajectory. 2. To discover prevalent topics during the last 34 years as well as highly cited papers and authors. 3. To find hub topics for identifying the direction of interdisciplinary research.

1. Introduction

On October 28, 2021, Facebook changed its name to Meta[1]. It strongly suggests that the corporate goal of social media giant has changed to exploiting Metaverse to stay competitive in pierce competition in the industry. Interestingly, Facebook is also a leading manufacturer of virtual reality devices (head-mounted displays) with a market share of 75% in Q1, 2021[2]. At the core of Metaverse, virtual reality technology plays a crucial role to provide a realistic and immersive environment where people can interact with others. It expands the coverage of the cyber world from enthusiastic video gamers to ordinary people we interact with daily. In other words, virtual reality needs to be defined more holistically than just a set of technologies (see Steuer [11]).

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[1]Dwoskin, Elizabeth (October 28, 2021). "Facebook is changing its name to Meta as it focuses on the virtual world". The Washington Post.
[2]Counterpoint, Global XR (VR & AR) Model Tracker, Q1 2021.

The film released in 2018 shows us one of example what the Metaverse looks like. In "Ready Player One[3]", people are attracted to enter a virtual world called "OASIS", meet new friends and participate in organized group events just like what we normally do in real life. Moreover, people buy items using a coin to decorate their avatar, which is a virtual character representing each player. Even though people are eager to be part of the virtual world to escape their unpleasant real life, bad things also happen there as well. At this point, Metaverse is not about technology anymore but about society co-existing with real life.

Additionally, 47 million people log in to a metaverse platform every day[4]. Originally, the "Roblox" started as an online game platform, but, it became more than just a game platform. The user is no longer a consumer but a creator in Roblox. They create computer games and sell them to other users. It is a virtual world where people work to make money and spend them to purchase items they want.

What is possible today only in real life would be possible in the virtual world in near future. Medical application is one of the potential candidates to be deployed in the virtual world. As of today, one of the three most researched themes in virtual reality research is rehabilitation. In particular, scholars and medical professionals pay tremendous attention to rehabilitation systems for helping stroke patients(see Krakauer [4]).

Therefore, it is crucial to investigate what is necessary to make the virtual world more applicable for everyone. In particular, understanding research trends would provide insights for young researchers to set future research directions precisely. Thus, we examined scholarly research articles published over 38 years to identify prevalent research topics.

2. Literature Review

By taxonomy, the concept of Metaverse is an extension of virtual reality (VR) and augmented reality (AR) (see Park and Kim [6]). In other words, VR is one of the primary pillars to implement a solid foundation for Metaverse.

As a novel technology, virtual reality has been applied in various areas. The impact of virtual reality on the level of user satisfaction was examined from a marketing perspective(see Alcaiz et al. [1]). VR is also frequently used in the research of spatial cognition. It investigates how people perceive the landscape differently in virtual reality(see Shi et al. [9]). The pattern of social interaction regarding geographical conditions has been examined in (see Schroeder et al. [8]). For the medical field, a VR-based system was proposed to facilitate the rehabilitation of neurological disorders (see Stanica et al. [10]).

Author keywords represent the primary theme of the research article. Their co-occurrence pattern reveals the semantic structure of research topics. Therefore, keyword co-occurrence analysis has been frequently applied to investigate knowledge structure and research trends. The keyword of 432 innovation-related articles was examined to generate

[3]Warner Bros. Entertainment Inc (2018), https://www.warnerbros.com/movies/ready-player-one.
[4]Statista (2021), https://www.statista.com/statistics/1192573/daily-active-users-global-roblox/

publication trends and knowledge evolution of the regional innovation system(see Lee and Su [5]). The research hotspot in librarian research was investigated using keyword co-occurrence analysis (see Cheng et al. [2]). Moreover, in the healthcare field, researchers applied the same technique for generating a map of research trends (see Saheb and Izadi [7]).

3. Methods

3.1. Data collecting

We collected the metadata of research articles indexed in the Web of Science database[5]. By searching "virtual reality" in title, abstract, and keyword, initially, 20,340 articles were selected as of January 2022. The download metadata includes authors, title, abstract, author keywords, publication year, etc. These were in plain text format and we imported them into R for pre-processing. Surprisingly, some articles had no information about the publication year. These articles turned out to be early access type. So, we used early access time data to substitute for publication year. After removing incomplete data from initial search results, finally, 20,256 publications remained for further analysis. The research framework in this study is presented in Figure 1.

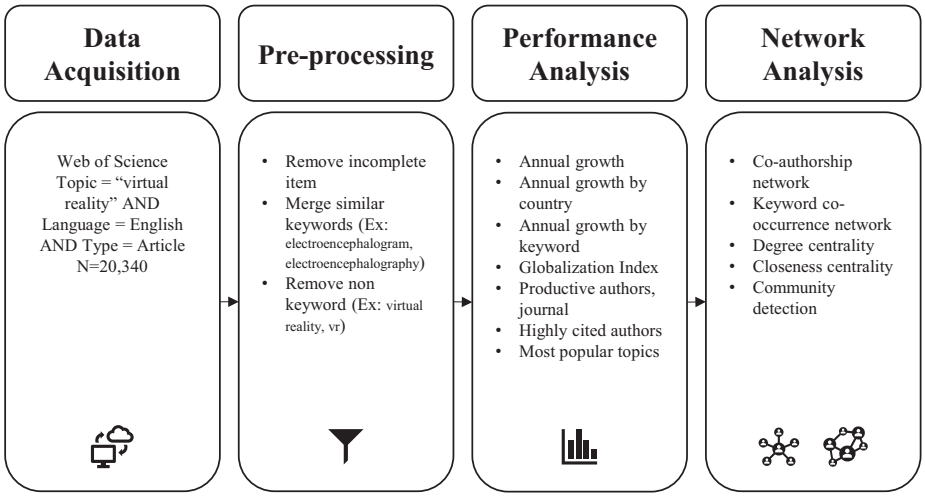

Figure 1: Research framework.

3.2. Performance analysis

For understanding the descriptive aspect of data, first, the distribution of articles over publication years between 1987 and 2021 was analyzed. Secondly, the top 20 ranking of most contributing countries, authors, and journals were created.

[5]Web of Science, https://www.webofscience.com/wos/woscc/basic-search.

3.3. Prevalent countries and hub topics

For understanding global collaboration patterns, we built a network structure using the co-occurrence of countries in authorship using the bibliometrix package for R. Then, network analysis was conducted to detect communities and influential actors in each community.

Regarding identifying influential topics, we first constructed a network of author keywords through co-occurrence analysis. Then, we applied network analysis to identify communities and influential keywords per community.

3.4. Measure of influence in community

To measure the strength of influential power of the country and keyword, we employed the concept of centrality which is frequently used for network analysis (see Freeman [3]). The degree centrality measures how many direct connections each node has in the network. A higher degree centrality indicates individual popularity in the network.

$$C_D(n_i) = \sum_j m_{ij}, \tag{3.1}$$

where $C_D(n_i)$ is the degree of node ni and $m_{ij} = 1$ if node i connect to node j.

The betweenness centrality measures how often the shortest path between two nodes goes through a given node in the network. Higher betweenness centrality indicates that it plays a strong role in connecting one community to another.

$$C_B(n_i) = \sum_{j<k} g_{jk}(n_i)/g_{jk}, \tag{3.2}$$

where $C_B(n_i)$ is the betweenness centrality of node n_i. g_{jk} is all geodesics between node j and k. $g_{jk}(n_i)$ is all geodesics[6] between node j and k that go through node i.

4. Results

4.1. Annual growth

The annual growth of the research community is presented in Figure 2. Since the first paper was published in 1987, it took 9 years to surpass 100 articles. However, from 100 to 200 articles, it took only less than two years.

Thereafter, the number of articles has been rapidly increasing. In the year 2021 alone, 3,446 articles were published which is as much as the number of articles from 1987 to 2007 combined. Particularly, since 2017, more than 1,000 articles are published each year. Nearly 50% of all articles were published in the recent 5 years. The number of publications per country during the last ten years (2011 2021) is presented in Figure 3. Additionally, Figure 4 shows keyword appearance distribution during the same period.

[6]Shortest path between two nodes in a graph.

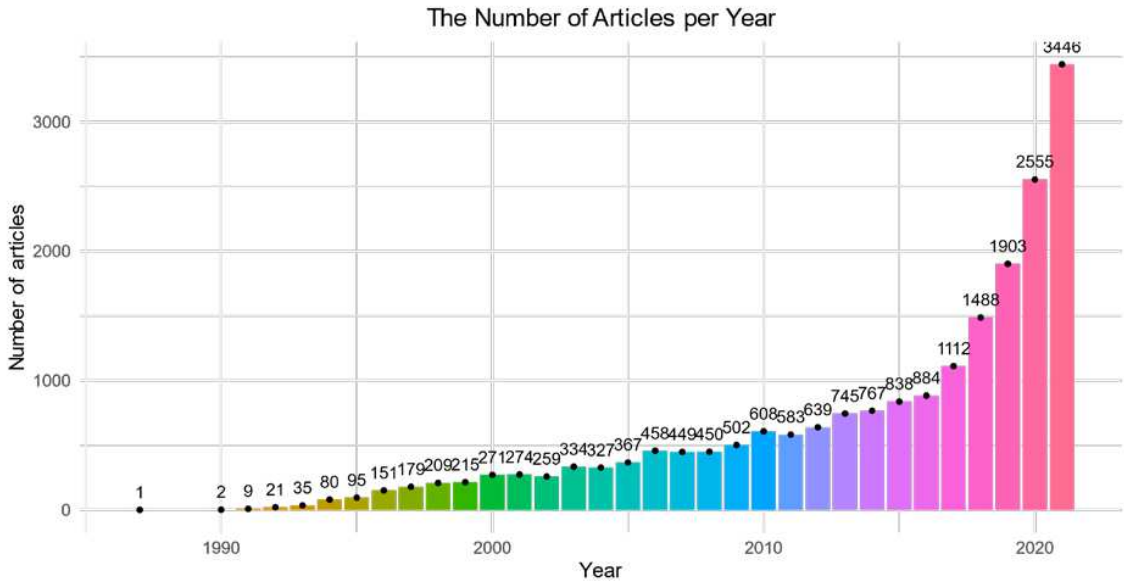

Figure 2: The number of articles per year.

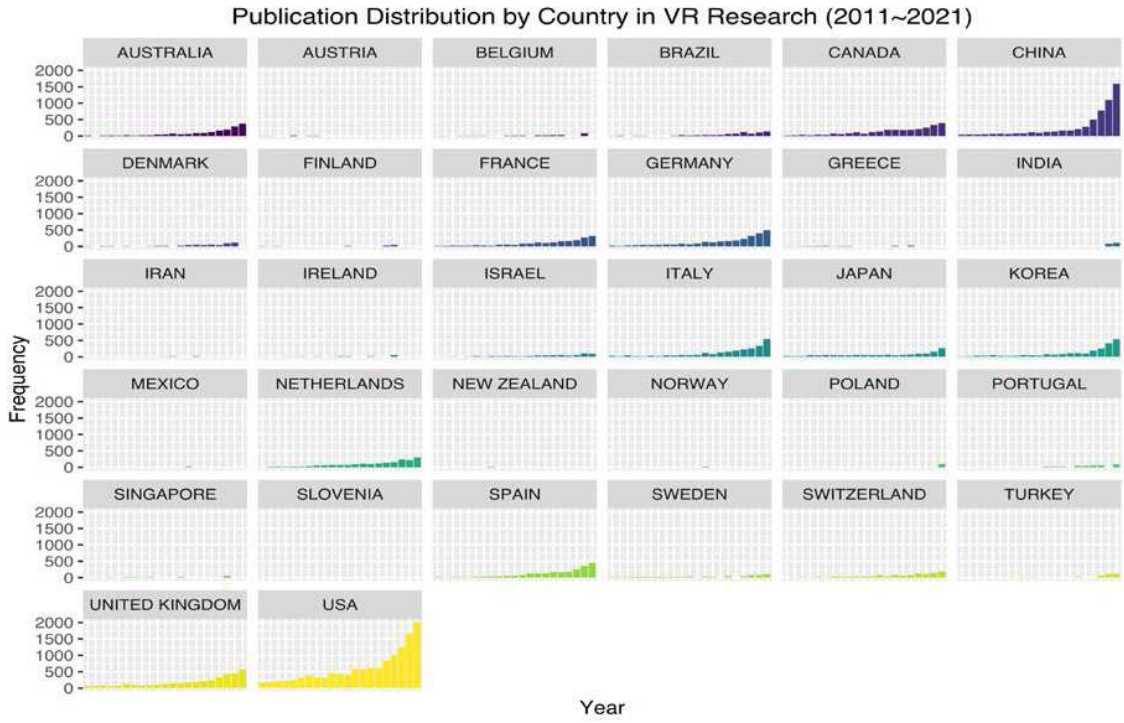

Figure 3: Publication by country.

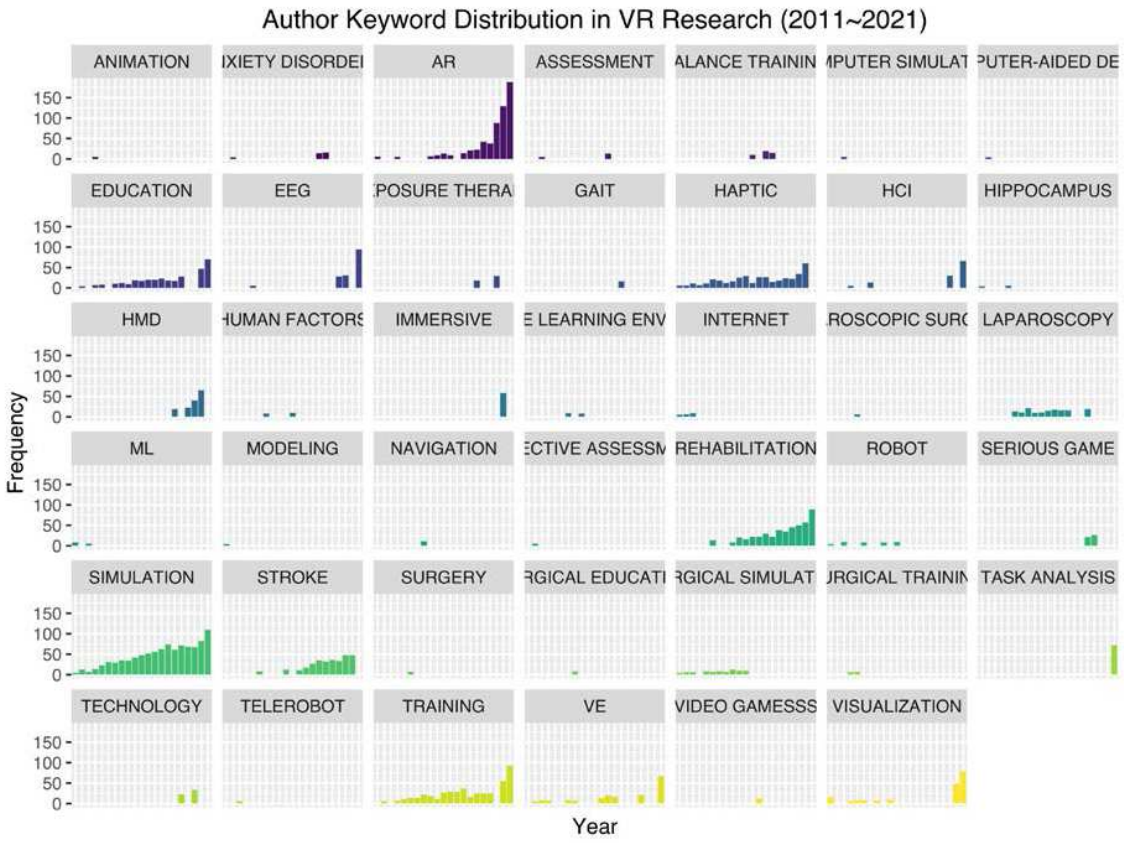

Figure 4: Keyword distribution.

4.2. Performance analysis

The most productive country is the USA as depicted in Table 1 with 4,762 articles which are almost double the second most productive country in the rank. Only five countries published more than 1,000 articles. Among those, one country is from North America, two from Asia, and two from Europe. In Asia, China is the most productive country with 2,469 articles which is more than double the number contributed by Korea which took the second position in that region.

Likewise, the UK took the top position in Europe with 1,533 articles, followed by Germany with 1,127 publications. Interestingly, the gap between the top two positions is relatively close compared to other regions.

Moreover, the globalization index (GI) is measured by calculating the proportion of multiple country publications in the total publications of each country. Higher GI implies a higher level of international collaboration. Surprisingly, 9 countries out of the top 10 list are from Europe. It strongly indicates research activities in the region involve researchers from multiple countries. More than half of all research articles from Belgium are generated by international collaboration. Switzerland ranked in second place with 0.36 and Denmark followed it with 0.33. The 10 countries with high globalization index are marked in Figure 5.

Table 1: Top country by the number of articles.

	Country	ALL	%	SCP	MCP	GI
1	USA	4762	0.238	4118	644	0.135
2	China	2469	0.124	1915	554	0.224
3	UK	1533	0.077	1101	432	0.282
4	Germany	1127	0.056	823	304	0.270
5	Korea	1011	0.051	868	143	0.141
6	Canada	924	0.046	702	222	0.240
7	Italy	878	0.044	632	246	0.280
8	Spain	818	0.041	626	192	0.235
9	France	676	0.034	492	184	0.272
10	Japan	649	0.032	569	80	0.123
11	Netherlands	620	0.031	468	152	0.245
12	Australia	588	0.029	419	169	0.287
13	Switzerland	383	0.019	245	138	0.360
14	Brazil	270	0.014	185	85	0.315
15	Israel	237	0.012	174	63	0.266
16	Denmark	234	0.012	156	78	0.333
17	Sweden	223	0.011	161	62	0.278
18	Turkey	183	0.009	165	18	0.098
19	Belgium	154	0.008	74	80	0.520
20	India	150	0.008	117	33	0.220

SCP: Single Country Publications, MCP: Multiple Country Publications, GI: MCP/ALL.

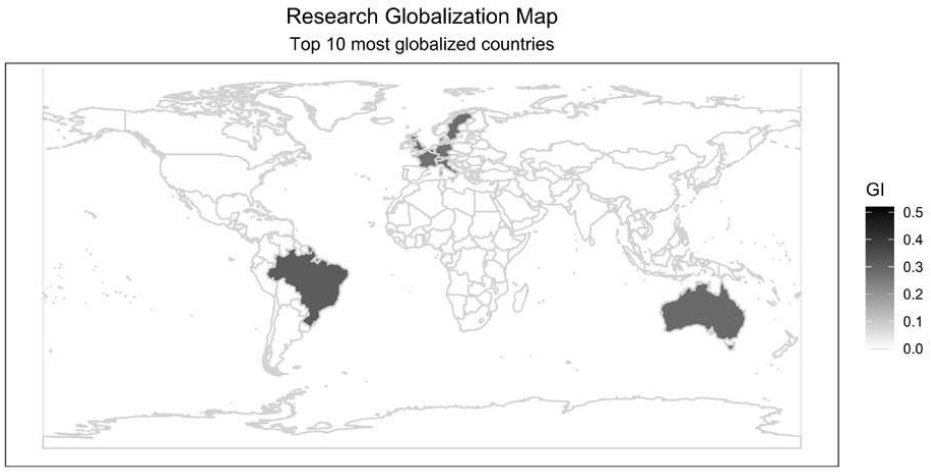

Figure 5: Globalization Map.

Table 2: Highly productive authors.

	Authors	Articles	Authors	Articles Fractionalized
1	Riva G	140	Riva G	37.2
2	Slater M	105	Kim J	26.8
3	Kim J	102	Slater M	25.6
4	Lee J	81	Lee J	20.6
5	Botella C	76	Lee S	18.6
6	Aggarwal R	72	[Anonymous]	18.0
7	Lee S	69	Satava Rm	16.3
8	Darzi A	68	Park J	14.5
9	Alcaniz M	66	Kim H	14.1
10	Konge L	66	Wiederhold Bk	13.4
11	Kim H	57	Darzi A	13.1
12	Hoffman Hg	56	Botella C	13.1
13	Park J	55	Kim S	12.6
14	Kim S	54	Aggarwal R	12.5
15	Wiederhold Bk	54	Zhang Y	12.5
16	Zhang Y	51	Konge L	12.4
17	Banos Rm	48	Alcaniz M	12.1
18	Koning Ahj	48	Hoffman Hg	11.5
19	Muhlberger A	48	Bulthoff Hh	10.2
20	Bouchard S	47	Bouchard S	10.1

The ranking of the highly productive author is presented in Table 2. Among the top five most contributing authors, one researcher is from Italy, two from Korea, and two from Spain. three authors published more than 100 papers. The number of articles is presented in two different ways. The second column in the table indicates the number of articles each author participated in regardless of the number of co-authors. But, the fourth column indicates a normalized number that is fractionalized by the number of co-authors. For example, in a single author's paper, the author gets 1 point, however, in a co-authored article, each author receives a partial point which is divided by the number of co-authors.

The ranking of the highly cited author is presented in Table 3. The most cited paper in the virtual reality research area is "Defining Virtual Reality: Dimensions Determining Telepresence" authored by Jonathan Steuer from Stanford University. "Features and uses of high-fidelity medical simulations that lead to effective learning: a BEME systematic review" is ranked in the second position. Overall, 7 articles have more than 1,000 citations. The article titled "UCSF ChimeraX: Meeting modern challenges in visualization and analysis" received more than 1,000 citations within three years after it was first published. This article presents a software called "ChimeraX" that is used to

Table 3: Highly cited authors.

	Paper	Total	Per Year
1	Steuer J, 1992, J Commun	2026	65.4
2	Issenberg Sb, 2005, Med Teach	1872	104.0
3	Seymour Ne, 2002, Ann Surg	1798	85.6
4	Milgram P, 1994, Ieice T Inf Syst	1615	55.7
5	Ericsson Ka, 2004, Acad Med	1498	78.8
6	Langhorne P, 2011, Lancet	1184	98.7
7	Goddard Td, 2018, Protein Sci	1072	214.4
8	Maguire Ea, 1998, Science	928	37.1
9	Grantcharov Tp, 2004, Brit J Surg	850	44.7
10	Shafi M, 2017, Ieee J Sel Area Comm	808	134.7
11	Ressler Kj, 2004, Arch Gen Psychiat	779	41.0
12	Wu Hk, 2013, Comput Educ	751	75.1
13	Zyda M, 2005, Computer	736	40.9
14	Lee Km, 2004, Commun Theor	704	37.1
15	Krakauer Jw, 2006, Curr Opin Neurol	664	39.1
16	Ramachandran Vs, 1996, P Roy Soc B-Biol Sci	657	24.3
17	Lambooij M, 2009, J Imaging Sci Techn	650	46.4
18	Lenggenhager B, 2007, Science	643	40.2
19	Gallagher Ag, 2005, Ann Surg	636	35.3
20	Slater M, 2009, Philos T R Soc B	613	43.8

visualize and analyze molecular structures developed by the University of California San Francisco. This paper also has the highest number of "citations per year" (214.4) in the ranking. The second highest per year citations goes to the article authored by Shifi M. et al. It covers 5G communication as a key technology to implement a connected world such as a virtual environment.

The highly contributing journals by all years and 2021 are ranked in Table 4. The most contributing journal is the journal of Virtual Reality. It is followed by Applied Science-Basel and IEEE Access. Interestingly, 7 out of the top 20 journals are related to the health and medical field in 2021.

4.3. Co-occurrence network analysis

In order to identify influential actors in the network, it is crucial to detect communities consisting of highly interactive peers. Our study focuses on two types of communities: Research community and keyword community.

First, the collaboration network of countries is presented in Figure 6. For detecting communities, the Louvain algorithm was applied to the network and three communities

Table 4: Highly contributing journals.

	All years		2021	
	Journal	Total	Journal	Total
1	Virtual Reality	323	Virtual Reality	139
2	IEEE Transactions On Visualization And Computer Graphics	318	Applied Sciences-Basel	108
3	IEEE Access	282	IEEE Access	89
4	Surgical Endoscopy And Other Interventional Techniques	262	Frontiers In Psychology*	76
5	Frontiers In Psychology	258	IEEE Transactions On Visualization And Computer Graphics	64
6	Plos One	246	Sensors	62
7	Applied Sciences-Basel	222	Scientific Reports	57
8	Cyberpsychology & Behavior	180	Sustainability	52
9	Sensors	177	International Journal Of Environmental Research And Public Health*	43
10	Presence-Teleoperators And Virtual Environments	171	Electronics	29
11	Scientific Reports	168	Interactive Learning Environments	28
12	Journal Of Neuroengineering And Rehabilitation	150	Multimedia Tools And Applications	26
13	Cyberpsychology Behavior And Social Networking	146	Journal Of Medical Internet Research*	25
14	Computers & Education	144	Brain Sciences*	23
15	Computers & Graphics-UK	143	Journal Of Healthcare Engineering*	23
16	Multimedia Tools And Applications	130	Plos One	23
17	Computers In Human Behavior	125	Journal Of Neuroengineering And Rehabilitation*	20
18	Frontiers In Human Neuroscience	120	Microprocessors And Microsystems	20
19	Journal Of Surgical Education	117	Mathematical Problems In Engineering	19
20	Sustainability	111	Frontiers In Neurology*	18

* indicates the journal belongs to the medical or health research field.

were identified. The size of a node indicates the number of appearances.

The top five countries in each community and their centrality are presented in Table 5. In community 1, the USA has the highest degree centrality which indicates it directly collaborated with 81 countries. However, Australia shows higher betweenness centrality than any other member country. Therefore, it shows that Australia plays a role as a bridge connecting communities. For community 2, the UK is identified as a central player with a degree centrality of 76. However, Netherland shows the highest betweenness centrality. For community 3, Portugal and Brazil are located in the central area of the

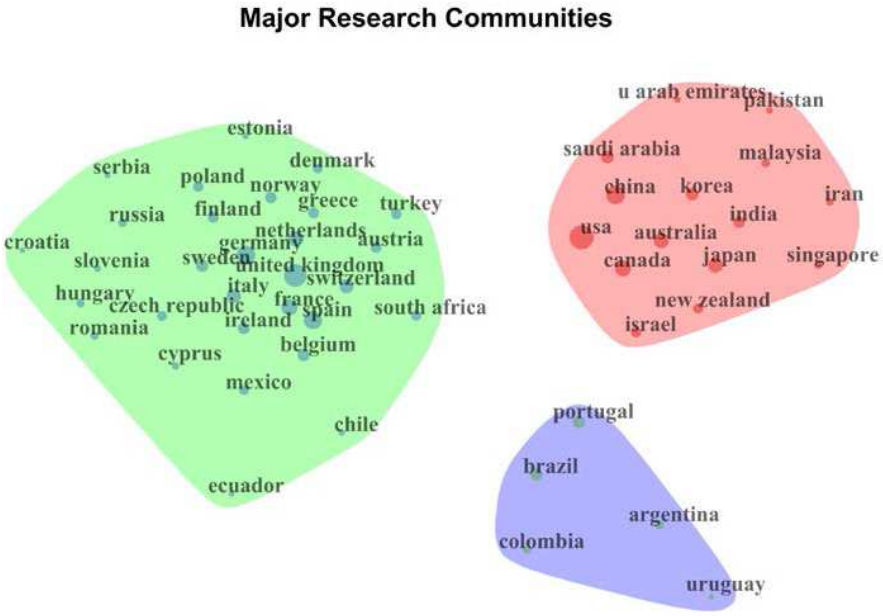

Figure 6: Collaboration pattern among countries.

community.

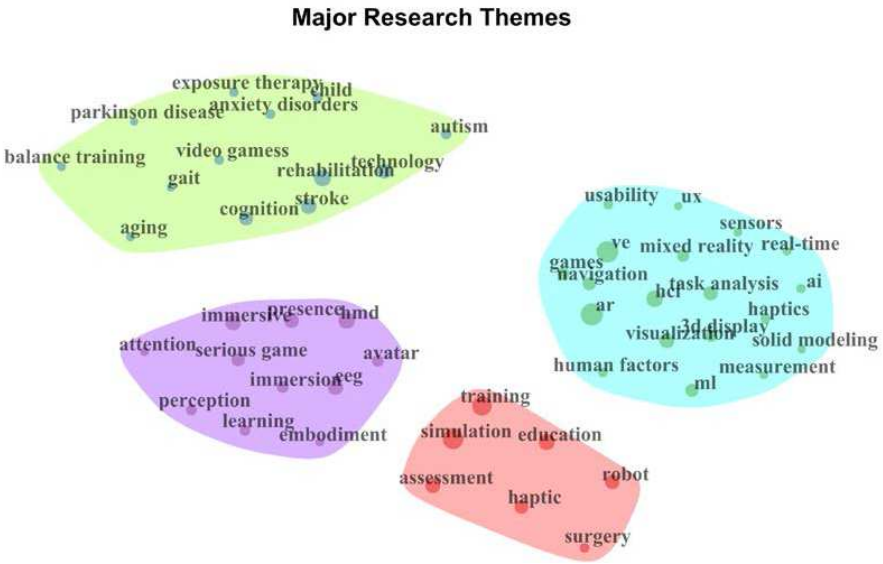

Figure 7: Co-occurrence network of author keywords.

Secondly, the keyword co-occurrence network is presented in Figure 7. Overall, 4 communities are detected and keywords in each community are summarized in Table 6.

The term *simulation* has the highest degree centrality in community 1. Overall, 173 articles share the term *simulation* as the author keyword. Based on the keyword

Table 5: Country's centrality in communities.

Community	Keyword	Degree Centrality	Betweenness Centrality	Closeness Centrality	Pagerank Centrality
1	USA	81	0.19444	0.00719	0.12751
	China	62	6.37937	0.00926	0.05232
	Canada	53	7.10287	0.00952	0.04168
	Australia	51	13.88547	0.00943	0.03646
	Korea	42	6.63027	0.00862	0.02163
2	UK	76	1.21212	0.00746	0.09063
	Germany	63	0.04762	0.00676	0.06176
	Spain	61	8.82770	0.00909	0.04393
	Netherlands	52	13.11937	0.00935	0.03928
	Italy	48	1.76821	0.00800	0.04960
3	Portugal	41	74.48322	0.01075	0.01085
	Brazil	41	43.58993	0.00980	0.01467
	Argentina	30	30.24359	0.00952	0.00603
	Colombia	29	34.31193	0.01000	0.00626
	Uruguay	19	35.07679	0.00952	0.00402

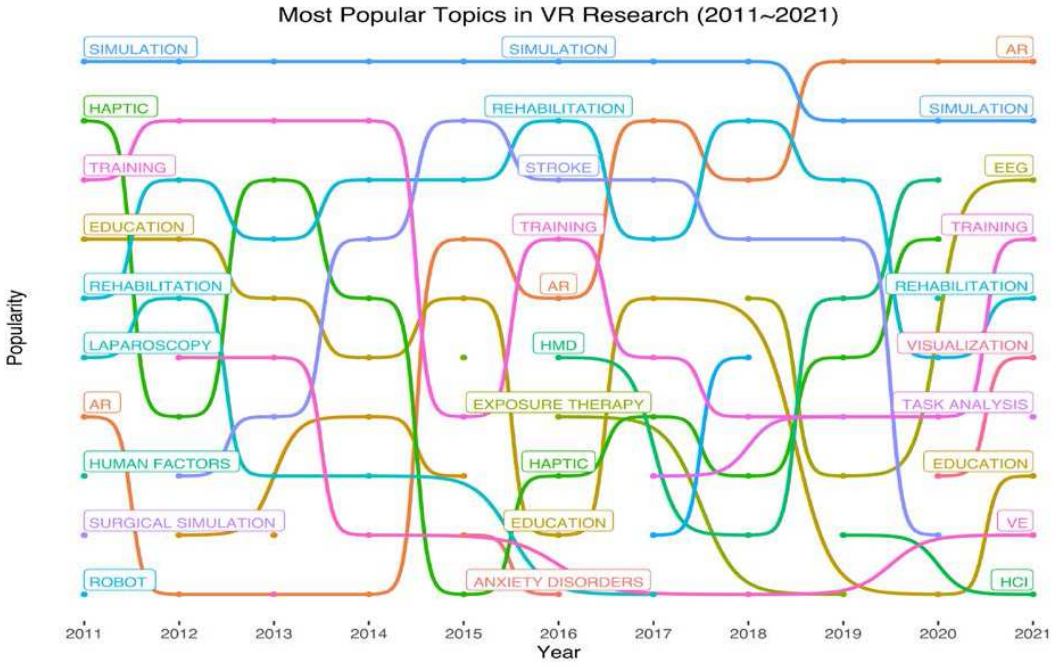

Figure 8: Research Trend Dynamic.

Table 6: Keyword's Centrality in Communities.

Community	Keyword	Degree Centrality	Betweenness Centrality	Closeness Centrality	Pagerank Centrality
1 App	Simulation	173	43.37314	0.00990	0.05828
	Training	164	10.54296	0.00917	0.05648
	Education	133	16.13964	0.00893	0.03772
	Robot	120	2.86220	0.00885	0.02374
	Haptic	116	23.20633	0.01031	0.02215
2 Medical	Rehabilitation	141	4.65213	0.00901	0.05021
	Stroke	131	28.55312	0.01000	0.04231
	Technology	121	3.63311	0.00909	0.01626
	Cognition	118	26.98563	0.00980	0.01549
	Balance training	175	1.09937	0.00833	0.01614
3 Concept	ARAugmented Reality	186	1.02870	0.00855	0.04349
	VEVirtual Environment	181	7.16544	0.00862	0.03279
	Visualization	125	3.30859	0.00862	0.03076
	Task analysis	120	7.87833	0.00893	0.02819
	3D display	101	27.43004	0.00980	0.02271
4 Technology	HMDHead-Mounted Display	137	9.57994	0.00917	0.02435
	EEG ElectroEncephaloGram	128	10.71644	0.00971	0.01894
	Presence	122	4.69356	0.00847	0.02851
	Serious game	112	25.85456	0.00926	0.01711
	Immersion	199	19.57362	0.00909	0.01833

belonging to it, this community is related to the application of virtual reality. For community 2, most of the keywords are highly related to health or medical fields, which indicates it is strongly related to medical usage of virtual reality. For community 3, AR and VE represent a conceptual aspect of virtual reality. Regarding community 4, HMD and EEG represent technologies related to core parts of virtual reality.

The evolution of the prevalent research topic is presented in Figure 8. Among the top 10 topics in 2011, only 5 of them manage to survive on the list in 2021; *AR, simulation, training, rehabilitation*, and *education*. Compared with those of 2016, 5 topics still belong to the top 10 list. The simulation maintains its status as one of the most popular topics until 2018. From 2019, the top spot was replaced by AR. Particularly, it is worth mentioning that *EEG, task analysis, visualization*, and *HCI* started to appear in the top 10 list since 2019.

5. Discussion and Conclusion

The main aim of this study is to construct of knowledge map of virtual reality research by analyzing 20,256 research articles between 1987 and 2021. Regarding the

growth rate of research publications, there are two significant results. First, approximately 50% of all articles were published in the recent 5 years. Secondly, the number of articles published in 2021 is as much as those of all publications from 1987 to 2007 combined. The annual growth rate stays as high as 34% from 2019. In terms of academic performance, the results show that only five countries ever have published more than 1,000 articles; one from North America, two from Asia, and two from Europe. It implicates key actors are distributed across different regions. However, based on the geographic characteristic of countries conducting international collaboration frequently, it is clear that European countries are far more globalized than those of any other region. For example, half of Belgiums research outputs are co-authored by researchers from multiple countries. The article that attempted to define "what virtual reality is" turned out be to the most cited one. It seems to be quite natural that most research articles tend to define their research target first. The paper presenting a software tool for analyzing molecular structure has received the highest "per year citation" in the citation ranking. It implies that this tool is considered to be a de facto standard for the given research domain. Particularly, in the top 20 ranking of the most contributing journal, seven journals are related to either medical or health research. It implies that virtual reality technology is heavily discussed in those research communities.

Regarding collaboration pattern analysis, three research communities are detected from the authorship co-occurrence network. Based on the results, each community consists of countries that are located closely. It strongly indicates that there is a relationship between the geographic location and the research partner selection process.

For prevalent topics, four communities are detected. Based on the significant keywords in each community, we labeled them as follows; *Application, Medical, Concept, Technology*. The application community covers topics such as simulation, training, education, robot, and haptic. Particularly, simulation has high betweenness centrality implying that it acts as a hub topic situated between different communities. The medical community mainly deals with rehabilitation, stroke, technology, cognition, and balance training. It indicates stroke-related rehabilitation training is the most researched topic as a medical application of virtual reality technology.

Overall, among the top 10 most frequently researched topics in 2011, only a halt of them survived in the ranking of 2021. In other words, half of the topics disappeared within the last 10 years and newer topics appeared during the same period. Particularly, EEG, task analysis, visualization, and HCI have drawn tremendous attention recently. Thus, these topics would be considered to be potential candidates for young scholars in the area of virtual reality research.

However, these findings are limited in several ways. Firstly, the raw data of this study are from a single source, the Web of Science (WOS). The results from other sources such as Scopus would generate different results. Secondly, the information about the topic of the given research article would spread over the title, abstract, and keyword. So, there is a possibility that all topics would not be covered by the keyword-based analysis. Therefore, to develop a full picture of the topic-based knowledge structure, it is recommended to include the title and abstract for future studies.

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