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The past and present of thought experiments' research at Glancy: bibliometric review and analysis

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Abstract
In the development of physical theories, thought experiments play a crucial role. Research on this topic began in 1976 and has continued to the present. This study aims to provide a more complete picture of the progress of thought experiments over the past two decades. To achieve this, this study employs bibliometric mapping methods. A total of 679 published papers were analyzed, including articles (504), conference papers (92), and book chapters (83). This data was retrieved from the Scopus database. The study's findings reveal that research and publications on thought experiments are highly valued and have received significant attention over the past eight years. According to the findings, 90% of the top 20 source titles contributing to thought experiments are from journals in the first and second quartiles (Q1 and Q2). This quartile ranking shows the quality and significant influence of a journal. The geographical distribution indicates that the United States contributes the most to thought experiments research, with 213 documents, 2592 citations, and 47 links. We also identified several prospective keywords that could be the focus of future research, including artificial intelligence, physics education, fiction, God, theology, productive imagination, technology, speculative design, and critical design. Therefore, this study provides a thorough picture of thought experiment research trends and future directions of potential topics that can be the focus of future researchers.

Keywords Bibliometrics · Physics · Science · Thought experiments

1 Introduction

Thought experiments (TEs) have a long history in science. Since Ernst Mach, the term TEs, a direct translation of the phrase *Gedankenexperimente*, has been widely discussed in the philosophy of science [18]. Thought and experiments are two components of TEs [4, 18, 29]. The thought element involves visualizing an imaginary world based on theory and experience, whereas the experimental aspect entails practical tasks in a physical laboratory, such as manipulating items and related variables. While some authors consider TEs to be mere arguments [24], others believe TEs are a form of fiction since their function is comparable to literary fiction in that both have a narrative framework by creating scenarios of occurrences from beginning to end [13, 22]. However, unlike fiction, which frequently provides contradictory discourses, we believe that TEs should be logically and conceptually cohesive. TEs are structured imaginative actions based on the theory and experience of thought experimenters to achieve certain goals.

The contributions of TEs to the growth of scientific theories, particularly in physics, are essential. Physicists have employed TEs several times throughout history to either come up with new hypotheses or disprove previous ones.

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As the most representative examples, Newton used the TEs of cannonballs to support his hypothesis that the force of gravity is universal and the principal force of planetary motion, or Galileo used the TEs of free-falling bodies to disprove Aristotle's theory of gravity, which stated that the speed of falling objects is proportional to their weight. Galileo's falling body, Newton's bucket and cannon, Maxwell's demon, and Schrodinger's cat are just a few of the well-known TEs in physics [4]. These are only a few examples of the significant role TEs played in the development of scientific theories.

In the past 10 years, several works have studied TEs from the perspectives of history and philosophy of science [7, 8, 10, 30, 33]. Because most existing historical work on TEs focuses on individual TEs or individual accounts of TEs, reassessing the history of the philosophical debate on TEs becomes essential [33]. In the philosophy of science, historical debates regarding interactions between various philosophers or philosophical explanations across time in developed TEs are sometimes disregarded. Several studies have also used TEs as an imaginative tool in the classroom to teach science subjects. Velentzas and Halkia [37], for example, used TEs from Newton's Cannon to teach satellite physics. They then assert that TEs, as a teaching tool, can assist students in strengthening their syllogistic abilities and help them conceive scenarios beyond their everyday experience [37]. El Skaf and Palacios [12] have also systematically analyzed the epistemic role of TEs from Wheeler's demon and Geroch's engine, which gave rise to black hole thermodynamics. Recently, Bancong et al. [2] reported that physics teachers in Indonesia have a high awareness of the importance of TEs in learning physics, especially atomic theory and relativity, even though they lack skills in the pedagogic aspects of TEs. Therefore, Indonesian physics teachers also suggest using technology such as virtual reality to help visualize an imaginary world when performing TEs.

Although a number of studies on TEs from various perspectives have been conducted, no study has yet completely examined this field to look at the trend of this topic in recent years. Therefore, it becomes essential to conduct a bibliometric study of TEs over time based on authoritative databases like Scopus. Because of Scopus's comprehensive coverage of scholarly articles in the field of education [23, 27, 34], it was chosen as the database for this study. Scopus is also a popular resource for bibliometric research [23, 28]. For this reason, we use data sources from the Scopus database to carry out the bibliometric method. Our study covers journal articles, conference papers, and book chapters from the last 20 years to provide a more complete view.

To highlight the significance of TEs research, we compare its growth to other scientific topics. While many scientific fields have seen growth over the past two decades, TEs research has also shown a unique and sustained increase in interest and publications. This trend contrasts sharply with the decline in research focus on traditional physics experiments [41]. Similarly, other topics in physics education, such as methodological issues, textbook analysis, and pre-service physics teachers, are also experiencing reduced research interest [25]. Additionally, the integration of TEs with emerging technologies, such as artificial intelligence, underscores their evolving relevance and potential for future research [21].

Therefore, this study aims to provide an up-to-date overview of trends in TEs research. The research questions in this study are as follows:

a. How is the growth of research output on the topic of TEs over the last 20 years?
b. Which source titles have contributed the most to the publication of papers on TEs in the last 20 years?
c. Who are the most prominent authors on the topic of TEs in the last 20 years?
d. Which countries have published the most articles on TEs over the past 20 years?
e. What are the most relevant keywords that can be found in the studies of TEs over the last 20 years?

2 Methods

2.1 Research design

This study aims to analyze the trends in TEs research over the past 20 years by using a bibliometric mapping method. To ensure a thorough analysis of recent trends and developments, this study focused on studies published between 2003 and 2022. This period was chosen because of significant advancements in research methodologies and bibliometric analysis tools in the early 2000s, as well as the consistent growth and comprehensive coverage of the Scopus database since that time. Bibliometric analysis is a well-known statistical method for examining and analyzing a large amount of scientific data on a certain topic [26, 39]. Metrics studied in bibliometric research include annual publications, source titles, authors, institutions, nations, and keywords, covering data from primary, secondary, and tertiary journals over a

specific time period. It should be noted that no ethical approval was required for this study as it did not involve humans or animals.

2.2 Data collection

In this study, data were gathered from the Scopus database (https://www.scopus.com). Scopus was chosen because it covers a wider range of documents than any other scientific database [23, 28, 35]. Scopus is the world's largest abstracting and indexing database, with 84 million records containing over 18.0 million open access items, including gold, hybrid gold, green, and bronze, as well as 10.9 million conference papers, 25.8 thousand active peer-reviewed journals, and over 7000 publishers [14]. In addition, Scopus covers a wider range of educational disciplines than other databases, such as the Web of Science (WoS) [23, 27, 34]. As a result, using the Scopus database enables researchers to shed light on areas that may not be covered in WoS.

Electronic data search and retrieval were conducted on February 25, 2023. Keyword search was set to include title, abstract, and keywords. The keyword search was set to include the title, abstract, and keywords. The combination of search strings, operators, and filters used in this study was TITLE-ABS-KEY ("Thought-experiments" AND "Science" OR "Physics"). Quotation marks were used to focus on documents containing this exact phrase, thus ensuring high relevance to the study's scope. The Scopus database retrieved 898 documents related to these keywords with full bibliographical information, including articles (67.04%), paper proceedings (10.13%), book chapters (10.02%), and other types of documents (12.81%). By using the Scopus filter, other types of publications (12.81%), including review articles, were excluded from the list of documents. The exclusion of review articles was intentional to focus on original research contributions that advance the field of TEs directly. Including reviews could confound the analysis as they often summarize existing research rather than introduce new findings. Therefore, concentrating on the three most prevalent types of documents—articles, conference papers, and book chapters—allowed for a clearer interpretation of trends and patterns in original research outputs over the specified period. Additionally, we limited the year of publication to studies published within the last 20 years (2003–2022) to ensure the relevance and currency of our analysis. After using a filtering process to eliminate papers that did not meet the inclusion and exclusion criteria, a total of 679 articles were identified for bibliometric analysis. These articles included 504 articles, 92 book chapters, and 83 conference papers.

2.3 Data analysis

The data analysis process began with acquiring the necessary raw data by downloading it from the Scopus database in either comma-separated value (CSV) or research information system (RIS) format. For data analysis and visualization, we used VOSviewer and Microsoft Excel. VOSviewer, a sophisticated mapping tool, was employed to create collaborative networks for various variables and keywords, while Microsoft Excel was used for descriptive analysis, such as determining the number of articles published each year and identifying the most prolific source titles.

The network graphs in this study were generated using VOSviewer, based on co-authorship, co-occurrence, and citation data from Scopus. The analysis type focused on the co-occurrence of keywords and co-authorship, with a full counting method. Keywords with a minimum of four occurrences were included. The visualization settings in VOSviewer were mainly default, with the attraction parameter set to 2 and the repulsion parameter set to 0. These settings ensured that the most relevant and frequently occurring terms were highlighted, providing a clear overview of research trends and collaborations in the field of TEs over the past 20 years.

In this study, we explored the most productive publishers, the most referenced articles, the most productive authors, the most productive nations, and author keyword occurrences across time. An analysis of co-authorship and co-occurrence was performed at this stage. The analysis of co-authorship provides insights into the interactions between authors. This methodology was also used for metrics related to countries. For country attribution, we included all the countries of all authors involved in each publication, not just the corresponding author. This method ensures that all co-authors' contributions are acknowledged and provides a comprehensive representation of the global distribution of research. Co-occurrence analysis was employed as a means of investigating current keywords and their interrelationships with other phrases associated with TEs. Within this particular framework, the term "node size" refers to the frequency at which a certain keyword appears in comparison to other words. Additionally, interconnected nodes are visually represented by lines known as connections. The link establishes a connection between two nodes, while the width of the link signifies the intensity or potency of the connection between the aforementioned nodes [36, 39].

In the context of network map visualization, nodes that exhibit a high degree of association are categorized into clusters. The clustering of items was performed using the Louvain algorithm, a popular method for community detection in large networks due to its efficiency and accuracy in handling large datasets [36, 39]. This algorithm was chosen for its ability to uncover modular structures within large networks, which is particularly useful for identifying distinct research themes and collaboration groups in bibliometric data. Subsequently, a distinct color code was assigned to each cluster, wherein nodes within the same cluster exhibit a high degree of homogeneity. Therefore, this bibliometric mapping approach enabled researchers to discern patterns and emerging areas of interest throughout the timeframe spanning from 2003 to 2022. Figure 1 shows the stages in the process of collecting and analyzing data in this study.

3 Results

3.1 Statistics analysis

In this analysis, we use statistical data to observe differences in the number of articles published each year. The goal is to determine whether the quantity of publications on the topic of TEs has increased or decreased annually. Figure 2 illustrates the number of papers published over the last 20 years (2003–2022). As we can see, there has been an increase in the interest and attention of researchers, scholars, and experts in researching TEs. The growth started in 2004 and continued until 2006. The number of papers published then fluctuated between 2006 and 2015. The increase started again in 2015 and continued until 2021. The number of publications increased significantly in 2021, with 69 articles published. This growth demonstrates that research and publications on TEs are in high demand and have garnered significant attention globally in the last eight years despite a reduction in 2022. Although studies in this area are still ongoing, these findings indicate an annual growth in the writing and publication of TEs on Scopus.

Statistical data are also used to see the number of source titles that have made the greatest contributions to TEs during the last 20 years. A total of 679 papers have been published from various sources with different types of documents in the form of articles (504), conference papers (92), and book chapters (83). According to statistical data in the Scopus database, publication in journals is very significant in publishing research on the topic of TEs, while publication in proceedings and book chapters with the main scope of TEs is not very significant. Therefore, researchers, academics, and experts are advised to submit their articles focused on TEs to journals rather than proceedings and chapter books. Table 1 lists the top 20 sources of scientific research publications covering the topic of TEs from 2003 to 2022.

As seen in Table 1, 90% of the source titles contributing to the TEs topic are journals, with only one publishing conference proceedings. Philosophical studies ranks first, with 17 documents published in the last 20 years. This is followed by the AIP Conference Proceedings with 15 documents. The American Journal of Physics, Science and Education, and Studies in History and Philosophy of Science Part A have published 11 documents each. Other source titles, such as Synthese (10), Foundations of Science (9), Physics Teacher (9), Journal for General Philosophy of Science (8), and Philosophy of Science (8), also contributed to publishing TEs topics. Minds and Machines and Physics Education each published seven documents. Erkenntnis, European Journal of Physics, Physics Essays, and Religions each published six documents, Acta Analytica published five documents, while Axiomathes, Boston Studies in the Philosophy of and History of Science, and European Journal for Philosophy of Science each published four documents.

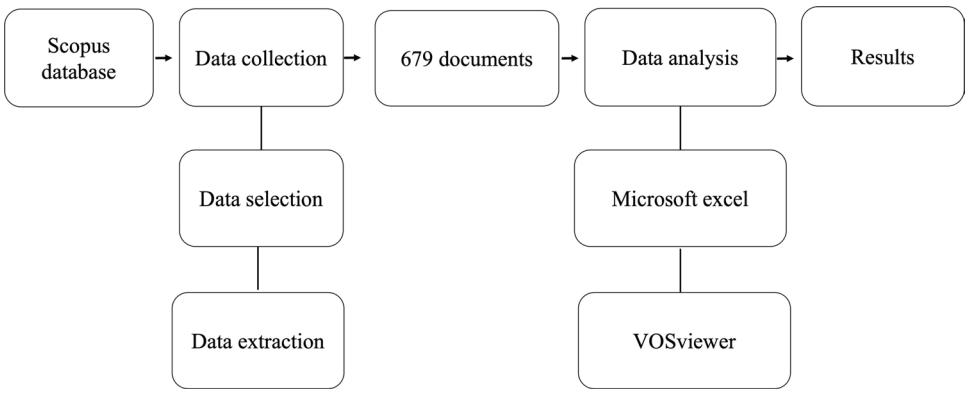

Fig. 1 The steps in collecting and analyzing the data

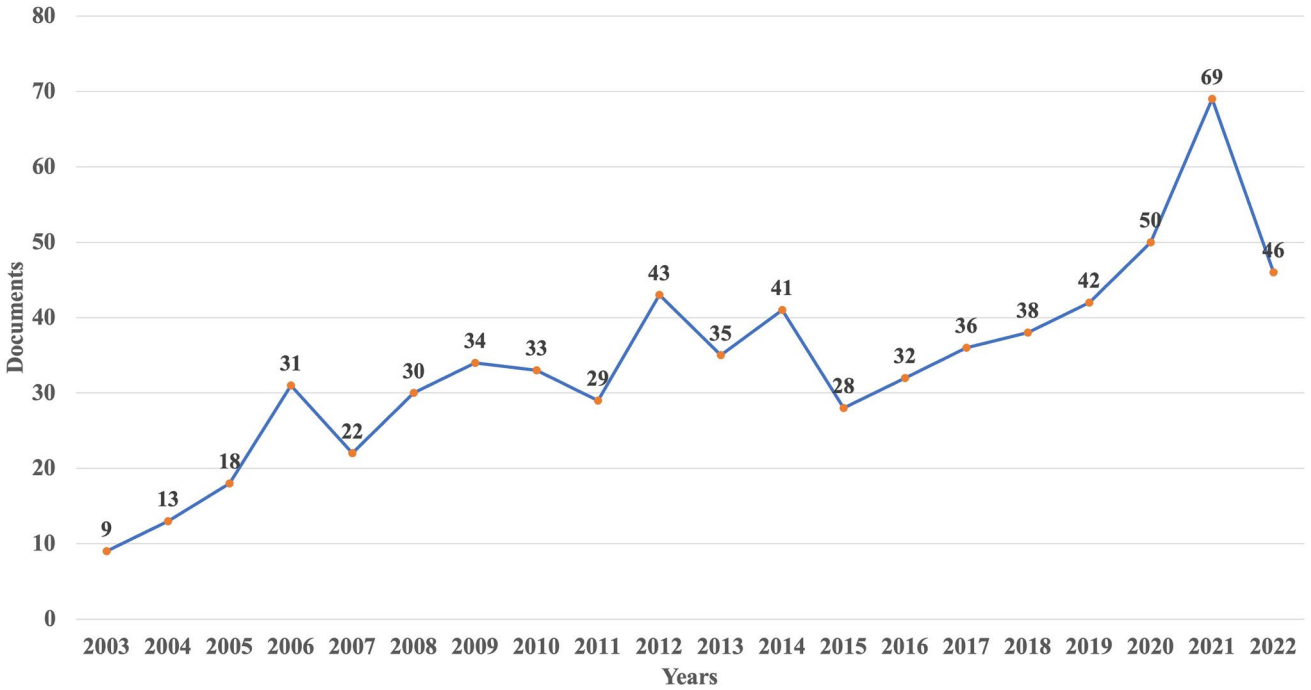

Fig. 2 Number of articles published each year

3.2 Bibliometric analysis

3.2.1 Contributions of authors

Table 2 shows the 10 most prolific authors based on the total number of published articles from 2003 to 2022. As shown in this list, Stuart is the most significant author with 7 papers (51 citations), followed by Bancong from Universitas Muhammadiyah Makassar, Indonesia, with 5 papers (15 citations). Following Bancong, Fehige from the University of Toronto, Canada, has also published 5 articles. The majority of Fehige's research focuses on TEs in the context of religion. In contrast to Fehige, Brown, also from the University of Toronto in Canada, has studied TEs through the lens of history and philosophy of science in several of his works (4 documents, 52 citations). Similarly, Buzzoni (3 documents, 15 citations) and El Skaf (3 documents, 29 citations) from Italy, discuss TEs from historical and philosophical perspectives of science. Meanwhile, Halkia and Velentzas from the University of Athens, Greece, have analyzed TEs thoroughly from an educational standpoint, with the number of documents being 4 and 86 citations.

3.2.2 Contributions of country

In the context of the leading countries, authors from 64 different countries/territories published a total of 679 documents. Table 3 lists the top 20 countries in terms of TE contributions based on the number of papers published. As shown, the United States contributes the most to TEs research, with 213 documents, 2592 citations, and 47 links. The number of papers is about three times that of the United Kingdom, which comes second (75 documents, 1016 citations, and 31 links). European countries continue to hold third to sixth place, with Germany publishing 50 documents with 634 citations, followed by Canada (43 documents, 410 citations, and 17 links), Italy (33 documents, 96 citations, 6 links), and the Netherlands (28 documents, 342 citations, and 12 links). This suggests that countries in America and Europe contribute the most to TEs. The Asian country that has contributed the most to TEs is China, with 18 documents, 286 citations, and 11 links, followed by India (14 documents), Japan (12 documents), and South Korea (12 documents), with 97, 111, and 27 citations, respectively. The three countries below these are European countries, with Austria having issued 10 documents related to TEs with a total of 135 citations, followed by Finland (9 documents, 31 citations) and Spain (9 documents, 47 citations).

Table 1 Top 20 source titles contributing to TEs

No.	Source titles	Records	Quartile	Focus area
1	Philosophical studies	17	Q1	Philosophy
2	AIP conference proceedings	15	–	Physics and astronomy (miscellaneous)
3	American journal of physics	11	Q2	Educational and cultural aspects of physics
4	Science and education	11	Q1	History, philosophy, and sociology of science and mathematics
5	Studies in history and philosophy of science part A	11	Q1 (History); Q1 (History and philosophy of science)	History, philosophy, and sociology of science
6	Synthese	10	Q1 (Philosophy); Q1 (Social science)	Philosophy of science
7	Foundations of science	9	Q2 (History and philosophy of science); Q2 (Multidisciplinary)	Methodological and philosophical of foundational significance concerning the structure and the growth of science
8	Physics teacher	9	Q2 (Education); Q2 (Physics and astronomy)	Teaching of introductory physics, contemporary physics, applied physics, and the history of physics
9	Journal for general philosophy of science	8	Q1 (History and philosophy of science); Q1 (Philosophy); Q2 (Social science)	History and philosophy of science
10	Philosophy of science	8	Q1 (History); Q1 (History and philosophy of science); Q1 (Philosophy)	History and philosophy of science
11	Minds and machines	7	Q1 (Artificial intelligence); Q1 (Philosophy)	philosophical aspects of computer science
12	Physics education	7	Q2 (Education); Q2 (Physics and astronomy)	Teaching of physics in schools and colleges
13	Erkenntnis	6	Q1 (Logic); Q1 (Philosophy)	Philosophy
14	European journal of physics	6	Q2	Taught physics in universities and other higher education institutes
15	Physics essays	6	–	Theoretical and experimental aspects of fundamental problems in physics
16	Religions	6	Q2 (History); Q2 (Religious study)	Religious thought and practice
17	Acta analytica	5	Q1	Philosophy
18	Axiomathes	4	Q2 (Philosophy); Q4 (Mathematics)	Ideas, perspectives, and methods in science, mathematics, and philosophy
19	Boston studies in the philosophy and history of science	4	Q2 (Literature and literary theory); Q3 (History and philosophy of science); Q3 (Anthropology); Q4 (Social science)	History and philosophy of science, literature and literary theory, anthropology
20	European journal for philosophy of science	4	Q1 (History and philosophy of science); Q1 (Philosophy)	History and philosophy of science

Table 2 Top 10 authors who contributed to the topic of TEs

No.	Author	Affiliation	Country	Documents	Citation	Total links
1	Stuart, M.T	London School of Economics and Political Science	United Kingdom	7	51	1
2	Bancong, H	Universitas Muhammadiyah Makassar	Indonesia	5	15	4
3	Fehige, Y	University of Toronto	Canada	5	8	1
4	Brown, J.R	University of Toronto	Canada	4	52	0
5	Halkia, K	University of Athens	Greece	4	86	4
6	Huggins, E	Dartmouth College	United States	4	15	0
7	Song, J	Seoul National University	South Korea	4	15	4
8	Velentzas, A	University of Athens	Greece	4	86	4
9	Buzzoni, M	Università di Macerata	Italy	3	15	0
10	El Skaf, R	Politecnico di Milano	Italy	3	29	1

Table 3 Top 20 countries contributing to the topic of TEs

No	Country	Documents	Citation	Total links
1	United States	213	2592	47
2	United Kingdom	75	1016	31
3	Germany	51	634	21
4	Canada	43	410	17
5	Italy	33	96	6
6	Netherlands	28	342	12
7	Australia	25	233	10
8	France	25	504	10
9	China	18	286	11
10	Russian Federation	18	91	3
11	Switzerland	17	171	7
12	India	14	97	6
13	Belgium	12	50	4
14	Israel	12	149	6
15	Japan	12	111	6
16	South Korea	12	27	5
17	Brazil	11	21	1
18	Austria	10	135	6
19	Finland	9	31	4
20	Spain	9	47	3

3.2.3 Keywords

The results of a keyword analysis can be used in further investigation of the topic at hand. This study employs a minimum threshold of two occurrences of keywords in all research articles that were examined using VOSviewer. Figure 3 displays the 253 authors' keywords detected from 1990, which may be categorized into six distinct clusters. Cluster 1 is characterized by a red color, Cluster 2 by a green color, while Cluster 3 is distinguished by a blue color. In addition, Cluster 4 is characterized by a yellow color, Cluster 5 has a purple hue, and Cluster 6 is distinguished by a light blue shade. Each cluster is comprised of interconnected keywords that are visually represented by the same colors. It is important to note that the size and shape of the node are indicative of the frequency of its occurrences [36, 39]. In other words, there is a positive correlation between the size of the node and the frequency of occurrences of these terms. Clustering is employed as a means to gain insights or a comprehensive understanding of bibliometric groupings, whereas image mapping serves the purpose of obtaining a holistic depiction of a bibliometric network.

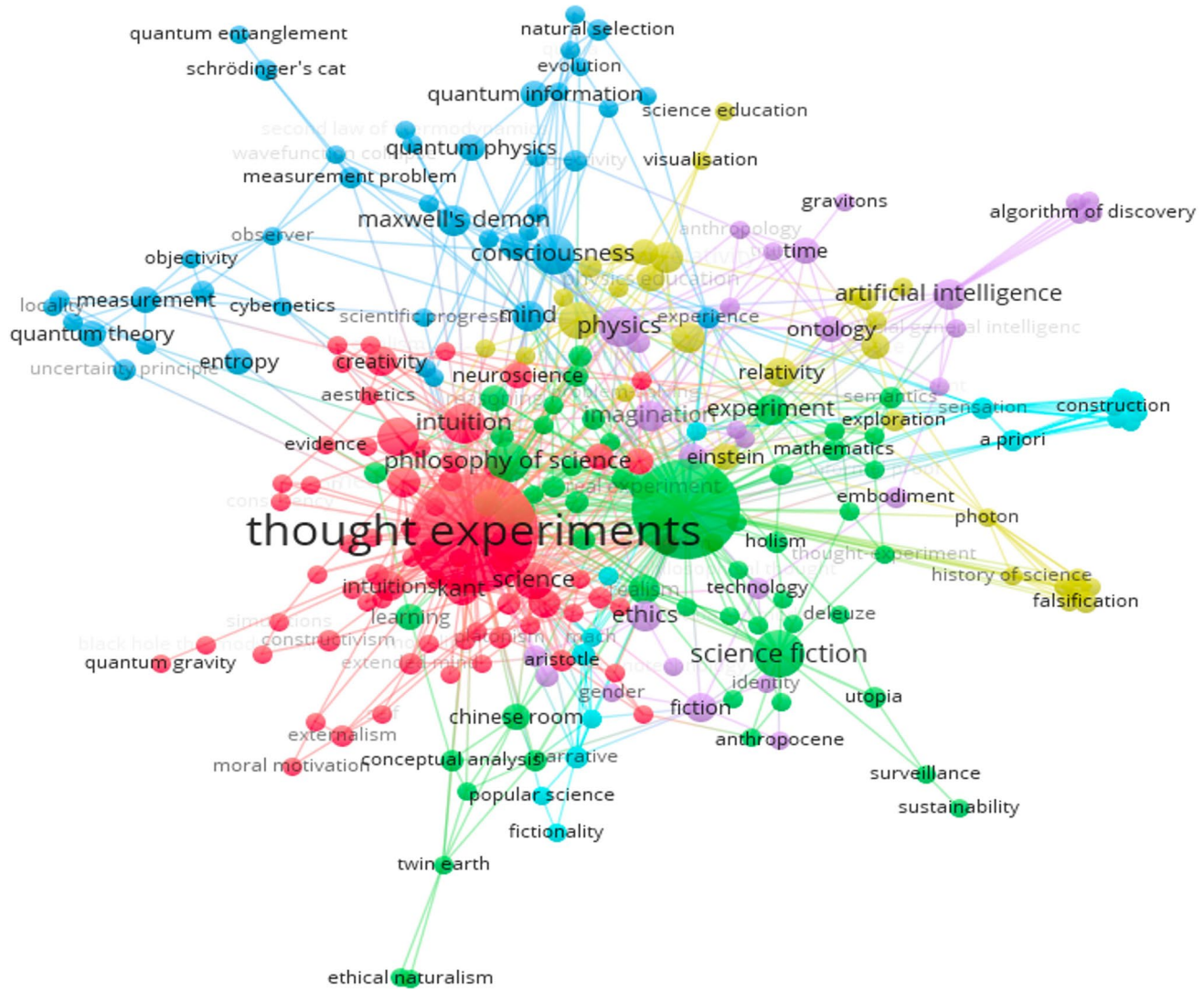

Fig. 3 Network visualization of TEs

Figure 3 shows Cluster 1 (red) with 68 items such as thought experiments, intuition, Science, Kant, Aristotle, Galileo, Platonism, personal identity, theology, fiction narrative, moral motivation, and neuroscience. Cluster 2 (green) consists of 57 categories, such as science fiction, philosophy of science, philosophy of physics, philosophical thought, epistemology, knowledge, scientific reasoning, experiments, models, and realism. Cluster 3 (blue) contains 41 items, such as consciousness, Maxwell's demon, Schrodinger's cat, quantum theory, entropy, uncertainty principle, quantum entanglement, quantum information, quantum physics, and Newton's bucket. Furthermore, cluster 4 (yellow) consists of 30 items: physics education, science education, visualization, special theory of relativity, history of physics, problem-solving, exploration, Einstein, relativity, and falsification. Cluster 5 (purple) consists of 29 items: imagination, ontology, physics, truth time, algorithm of discovery, artificial intelligence, ethics, nanotechnology, fiction, philosophy, and technology. Finally, cluster 6 (light blue) contains 16 categories, including popular science, fictionality, narrative, construction, sensation, a priori, story, Mach, memory, productive imagination, and schema.

Keywords in clusters 1 and 2 have a high number of occurrences and a high total link strength. The term thought experiment ranks first with 85 occurrences and a total link strength of 91. This is followed by the term thought experiment with 60 occurrences, a total link strength of 98, and several other keywords. The high number of occurrences and high total link strength indicate that scientific research publications on the topic of TEs in the 2003–2022 range indexed by Scopus have a strong and direct relationship with these keywords. Table 4 displays the ten keywords with the highest occurrence and overall link strength in the last 20 years on the topic of TEs.

VOSviewer, on the other hand, is also used to visualize the progress of keywords over a certain period. Figure 4 illustrates the overlay visualization of the TEs topic in the time range 2003 to 2022.

Figure 4 depicts the annual distribution of the number of articles containing keywords. The various colors represent the publication dates of the related papers where these keywords appear together. The data in Fig. 4 indicate that the most frequently used topics related to TEs from 2010 to 2014 were quantum theory, ethical naturalism, ethical naturalism, quantum mechanics, scientific discovery, and mental models. Then, from 2014 to 2018, keywords such as scientific reasoning, intuition, science education, computer simulation, history of science, and science fiction began to appear in the TEs topic. The hottest topics in TEs research are shown in yellow color, including fiction, artificial intelligence, God, theology, speculative design, critical design, and methods of case. These findings indicate that these keywords have gained popularity in recent years. It can be concluded that scholars have increasingly turned to research on the mentioned topics in recent years.

4 Discussion

The goal of this study is to use the bibliometric mapping method to examine the trend of studies on TEs during the last 20 years (2003–2022). According to the findings of the study, there has been an increase in the interest and attention of researchers, scholars, and professionals in studying TEs. Although research in this area is ongoing, these findings indicate an annual growth in the writing and publication of TEs on Scopus. This growth demonstrates that research and publications on TEs are in high demand and receive significant global attention.

Interestingly, 90% of the top 20 source titles contributing to TEs research are journals in the first quartile (Q1) and second quartile (Q2). Among these, 10 journals are in the highest quartile, Q1, and 8 journals are in Q2. The quartile level indicates that these journals have the highest quality and the greatest influence [39, 40]. Furthermore, 7 source titles (Philosophical Studies, Synthese, Foundations of Science, Minds and Machines, Erkenntnis, Acta Analytica, and Axiomathes) that publish TEs topics focus on the field of philosophy. When studying TEs from a philosophical standpoint, researchers, scholars, and professionals have the option of submitting their articles to these journals. Alternatively, if TEs are studied from a historical perspective, journals such as Science and Education, Studies in History and Philosophy of Science Part A, Journal for General Philosophy of Science, Philosophy of Science, Boston Studies in the Philosophy and History of Science, and European Journal for Philosophy of Science are appropriate. Meanwhile, if TEs are studied from an educational perspective, Physics Teacher, Science and Education, Physics Education, American Journal of Physics, and European Journal of Physics are ideal choices for publishing articles. These journals regularly publish articles in physics education studies.

If we look at the authors who have made the greatest contributions to the topic of TEs in the previous 20 years (2003–2022), Stuart is the most significant author with 7 articles (51 citations). Stuart's work focuses on the history and philosophy of TEs [31–33], with the first publication in 2014 in the journal Perspectives of Science. In contrast to Stuart, Bancong's work, which ranks second, investigates various TEs from an educational standpoint. His first work, published in 2018, examined TEs in high school physics textbooks [3], followed by an investigation of how students construct TEs collaboratively [4], and an identification of factors influencing TEs during problem-solving activities [5]. Following

Table 4 Occurrences and total link strength of keywords

No	Author's keyword	Occurrences	Total link strength
1	Thought experiments	85	91
2	Thought experiment	60	79
3	Science fiction	14	8
4	Consciousness	10	17
5	Philosophy of Science	10	17
6	Intuition	10	15
7	Physics	10	14
8	Experimental philosophy	9	17
9	Personal identity	9	6
10	Science	8	22

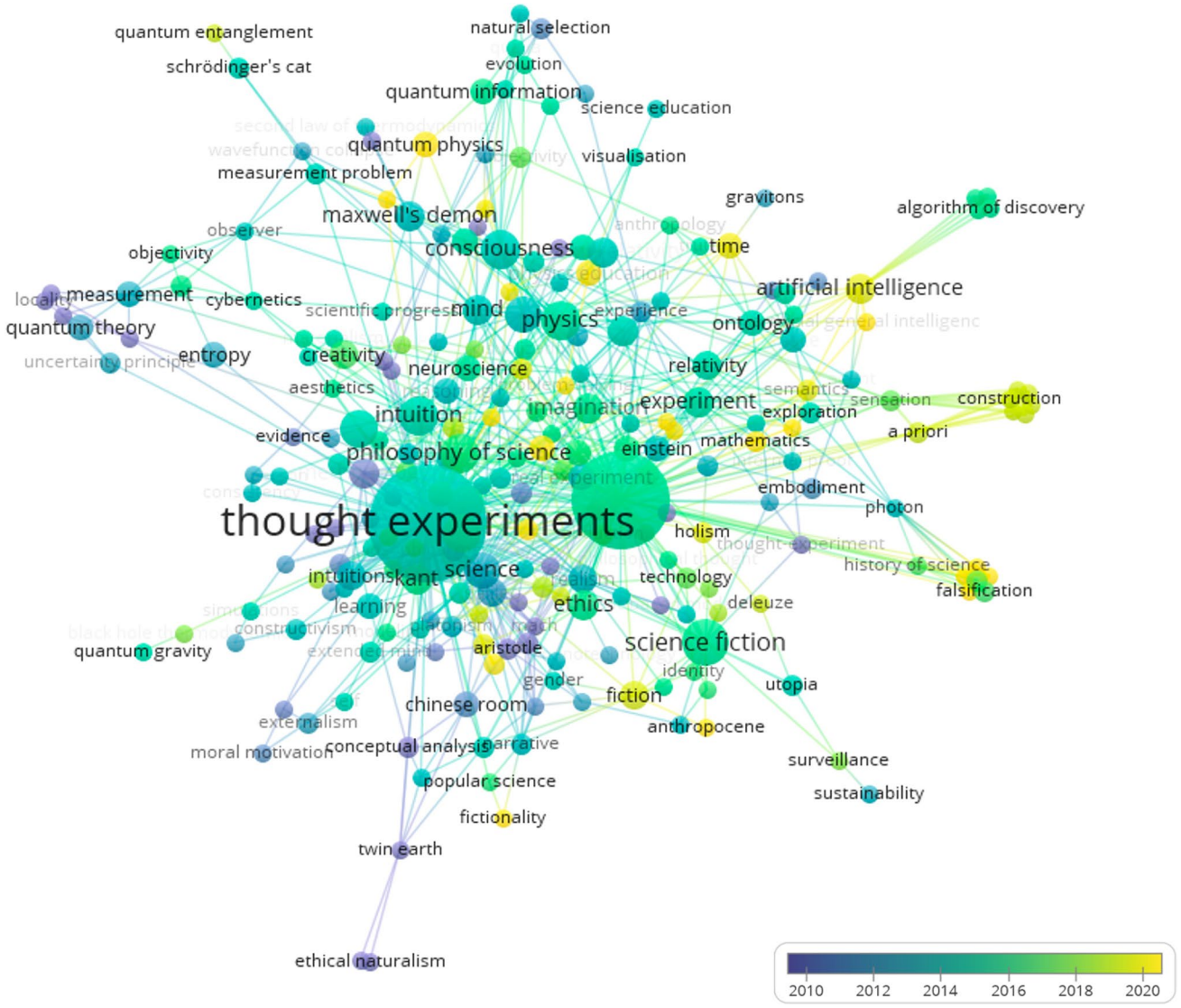

Fig. 4 Overlay visualization of TEs

Bancong, Fehige from the University of Toronto, Canada, has also published 5 articles. Most of his work examines TEs in religious contexts, such as thought experiments, Christianity and science in novalis [15], thought experiments and theology [16], and the book of job as a thought experiment: on science, religion, and literature [17] which was published in the journal Religions in 2019. Brown examines TEs in several of his works in light of the history and philosophy of science [6, 7], as do Buzzoni and El Skaf from Italy, who mostly discuss TEs in light of the history and philosophy of science [8, 12]. Meanwhile, Halkia and Velentzas from the University of Athens, Greece, have discussed TEs from an educational perspective, such as using TEs from Newton's Cannon for teaching satellite physics [37] and using TEs from the theory of relativity for teaching relativity theories [38].

Over the past two decades, authors have examined TEs from diverse perspectives, including history, philosophy, education, and religion. This variety highlights a significant shift in the disciplinary landscape of TE research, which is historically rooted in the philosophy of science [18, 24]. The true strength of TEs lies in their adaptability across disciplines, rather than in resolving philosophical disputes. Although TEs were traditionally centered on history and philosophy of science (HPS), recent trends show a growing application in education and technology, particularly in artificial intelligence and speculative design. This shift indicates that TEs have not lost their significance but have instead found new areas of relevance. In HPS, the focus has moved toward understanding the methodological and epistemological implications of

TEs, confirming their essential role in scientific reasoning [7, 30]. Additionally, in fields such as physics education, TEs are increasingly utilized to explore complex theoretical concepts and enhance educational methodologies [2, 12].

Based on the most commonly used keywords in the last 20 years, research on TEs has mostly focused on understanding TEs from a philosophical perspective in the first five years (2003–2007). Thought experiments rethought and reperceived [19], on thought experiments: is there more to the argument? [24] and thought experiments [9] are a few examples. Then, over the next five years (2008–2012), many studies looked at how TEs contributed to physical theories, including the special theory of relativity and quantum theory. The keywords that emerged frequently during this period were quantum theory, scientific discovery, methodology, quantum mechanics, twin earths, falling bodies, and others. In the last ten years, TEs have been studied from various perspectives. For example, in 2013, Velentzas and Halkia [38] also used TEs as a didactic tool in teaching physics to upper-secondary students. Fehige, on the other hand, began to connect TEs to theology, with a specific focus on the interaction between Christianity and science [15, 16]. There are also researchers who continue to study the existence of TEs from a philosophical point of view and claim that TEs are science fiction [1, 20]. In recent years, TEs have become increasingly popular in education and have been linked to artificial intelligence. Artificial intelligence, physics education, productive imagination, technology, and speculative design are some of the keywords that appear frequently. This is not surprising because TEs, as experimental activities using mental models, are not easy for students to perform on their own [4, 5]. Therefore, technology that can assist students in creating an imaginative world for constructing TEs is required.

Since no studies have charted the trends in TEs research so far, it is difficult to compare the research results obtained with those of others. Nevertheless, several studies that examine trends in physics education reveal that although research on experiments is declining in physics education, TEs are still important to physics teaching and learning [41]. Hallswoth et al. [21] have also used artificial intelligence technologies to support TEs in the field of wet biology research, which is dominated by experiments on microbial growth and survival. The use of artificial intelligence in learning is based on the growing interest in artificial intelligence methods in science, technology, and education [11]. Overall, our study contributes to a more comprehensive understanding of TEs research trends during the last 20 years. In addition, this research also contributes to providing an overview of several potential topics that can be the focus of future researchers, such as the use of artificial intelligence in TEs. By situating our findings within the broader context of previous studies, we provide a clearer picture of how TE research has evolved and where it is heading.

5 Conclusions

This study aims to present a more comprehensive understanding of the trend of studies on TEs during the last 20 years (2003–2022). Research on this topic began in 1976, and its progress has continued to the present. A total of 679 published papers from various sources, including articles (504), conference papers (92), and book chapters (83), were analyzed. The results of the study show that research and publications on TEs are of interest and have received a lot of attention during the last eight years. A significant increase occurred in 2021, with 69 published articles. According to the findings, 95% of the top 20 source titles contributing to TEs are from journals in the first and second quartiles (Q1 and Q2). This quartile ranking shows the quality and significant influence of a journal. The geographical distribution reveals that the United States contributes the most to TEs research, with 213 documents, 2592 citations, and 47 links. We also identified several prospective keywords that could be the focus of future research, including artificial intelligence, physics education, fiction, God, theology, productive imagination, technology, speculative design, and critical design. Therefore, this study contributes to providing a thorough picture of thought experiment research trends and future directions of potential topics that can be the focus of future researchers.

This research has several limitations. The exclusive source of publication data utilized in this study is the Scopus database, which is recognized as one of the most extensive databases in the field. However, it is worth noting that future research endeavors may consider including publication data from other prominent sources such as WoS and Google Scholar. Furthermore, the utilization of the search function in the TITLE-ABS-KEY field, specifically employing the terms "Thought-experiments" AND "Science" OR "Physics," was used for the purpose of data retrieval. However, it is important to acknowledge that this approach is not infallible, as there is a potential for some papers to be overlooked, making the process less than completely accurate. Despite its limitations, this research is often regarded as a pioneering contribution to the field of bibliometric studies on the subject of TEs during the past two decades.

Author contributions The author contributed to the conception and design of the study, data collection and analysis as well as the preparation of the manuscript.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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