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Online mathematics education as bio-eco-techno process: bibliometric analysis using co-authorship and bibliographic coupling

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Abstract
Under the COVID-19 pandemic, mathematics education has moved completely online. To tackle this new norm based on bio-eco-techno theories, this study aims to provide educators an overview of the research landscape for envisioning educational practices through bibliometric analysis of 319 articles and reviews published in peer-reviewed journals from 1993 to 2020. Country and institutional co-authorship depicts the social network structure of the field to identify top productive contributors. Bibliographic coupling of publications forms the conceptual structure, revealing research themes. Together, the results are mapped according to the bio-eco-techno perspective. The bioecological system highlights student achievement as the central concerns. The microsystem emphasizes techno-subsystems for supporting flipped learning. The exosystem and mesosystem require institution support for teacher pedagogical design, digital competencies, and collaboration. The macrosystem raises the issue of distribution or centralization in the strengths of online mathematics education and calls for greater cross-national boundary digital use and collaboration. The chronosystem asks: Does Covid-19 force the popularity of blended or flipped learning into online education? Based on the bio-eco-techno perspective, further recommendations are provided.

Keywords Bibliometric analysis · Ecological technology theories · Mathematics education · Online learning · Flipped learning

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Introduction

The ongoing COVID-19 crisis has had a profound impact on education, as the World Health Organization (WHO) Director-General declared it a public health emergency of international concern (2021, January 30). To keep transmission cases down, the WHO recommended measures of social distancing and confinement. By mid-April, 2020, schools and higher education institutions in 195 countries were closed (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2020a, b) and the pandemic forced the education sector to transition to distance education solutions and deploy remote learning systems.

As one of the core curriculums, online learning in mathematics education has become a new reality. The crisis forced educators to adopt emergency remote teaching (ERT) without time for planning or design (Hodges et al., 2020). The lack of research in this field also brought new challenges, with teachers feeling isolated and uncertain (Engelbrecht, Borba et al., 2020).

Yet new problems also bring forth new opportunities for mathematics education. The new reality forces educators to get in touch with digital technology while countries confront inequalities in education resources (Engelbrecht, Llinares et al., 2020). Domain-specific pedagogy benefits from practical examples made possible by the media using statistical representations to explain the spread of the virus (Bakker & Wagner, 2020). Through an enactive approach, the pandemic provides opportunities to reimagine new possibilities for teaching and learning as well as structuring the learning environment (Khirwadkar et al., 2020). Under the Covid-19 context of mandatory online mathematics education, new questions are raised to provide better research directives and insights. What have been the research trends in this field? What have been the prominent research topics? Which references should scholars look to in preparing for the future? Bibliometric analysis provides insights into the investigated field to answer these questions (Zupic & Cater, 2015).

While many studies employ bibliometric methods to investigate research trends in online learning (Bozkurt & Zawacki-Richter, 2021), very few have been published in online mathematics education and aiming for educational practices as a whole system. The purpose of this study, therefore, is to explore the existing literature to provide scholars in this domain with the research landscape. Visualization of research topics presents an overview of the embedded themes and their relationships, and offers insights for future developments in online mathematics education.

The bioecological model and ecological theories of educational technology

Bronfenbrenner and Morris's (2007) bioecological model contextualizes the individuals' development based on the dynamics of four core concepts: person, process, context, and time. The process characterizes every interaction that occurs between the individual and the environment. The nature of the process is dependent on the characteristics of the person, the context where interaction takes place, and the time in which interactions occur. The person possesses characteristics of demand (i.e. age, gender, etc.), resource (i.e. prior knowledge, socioeconomic status, etc.) and force (i.e. emotion, motivation, etc.), all of which influence the process. The context of the bioecological systems theory incorporates Bronfenbrenner's (1979) earlier micro-, meso-, exo-, and macro- systems. The microsystem is characterized by the complex interrelations within the immediate environment

surrounding the student (i.e. objects or people the student interacts with), whereas the exosystem comprises elements that have an indirect effect on the student (i.e. teachers' mathematics ability). The mesosystem refers to the linkages between the micro- and exo- systems, such as the interactions between the teachers (school) and the parents (home). The macrosystem represents the overarching factors such as social, cultural, national, or global values and ideologies. Lastly, time, or the chronosystem, is further categorized into microtime (consistency of process), mesotime (frequency of process), and macrotime (historical context of process).

Recognizing the increased role of technology, Johnson and Puplampu (2008) further expanded on Bronfenbrenner's ecological systems theory (1979) and bioecological model (Bronfenbrenner & Morris, 2007) and introduced the ecological techno-subsystem within the microsystem. The techno-subsystem includes use of ICTs (i.e. computers, e-books) and their patterns of use (i.e. communication, leisure, educational), both of which influence individual development in terms of learning outcome. For instance, children's internet use at home (techno-subsystem) explained more of the variance in cognitive development than did their socioeconomic status (microsystem) (Johnson, 2010). However, while educational ICT usage increases positive effects, leisure ICT usage increases negative effects (Chiu, 2020a).

In online mathematics education, ICTs are essential tools and resources (Borba, 2021; Engelbrecht, Borba, et al., 2020; Engelbrecht, Llinares, et al., 2020). Ecological theories of educational technology can therefore provide a framework in which to contextualize the field of online mathematics education (Chiu, 2020b). Specifically, a better understanding of online mathematics education can be obtained by considering the 'temporal, biological or physiological, environmental or cultural, and psychosocial or dispositional factors' (Chiu, 2021, p.156).

Defining online mathematics education

A variety of terms are intertwined and utilized in online learning. These terms include e-learning (electronic learning), m-learning (mobile learning), and d-learning (digital learning) (Kumar Basak et al., 2018). Distance learning emerged as a popular term after the COVID-19 pandemic (Lassoued et al., 2020). Blended or hybrid learning is a mix of both face-to-face and online learning (Gecer & Dag, 2012), which can be viewed as a special form of online learning with both the benefits of online and face-to-face teaching (Bouilheres et al., 2020). For example, ASSISTments is a typical web-based online tutor system for teaching mathematics (Koedinger et al., 2010).

This study focused on online mathematics education through the platform or medium of the Internet or information and communication technologies (ICT). Simple use of computer-related tools (e.g., PowerPoint) for mathematics instruction classrooms without connecting to the Internet is not included.

Bibliometric analysis and online mathematics education

Bibliometrics, first coined by Prichard (1969), is the application of mathematics and statistical methods to written documents. Bibliometric analysis provides "quantitative confirmation of subjectively derived categories in published reviews as well as for exploring the research landscape and identifying the categories (Zupic & Cater, 2015, p. 30)." Bibliometric analysis can be utilized to process mass amounts of data (Huang et al., 2020) in

an objective and quantifiable manner (Muritala et al., 2020) while providing visualization as a convenient means of depicting how research areas are distributed (Garfield, 1994). Its analysis has been applied in investigation of disciplines (Aristovnik et al., 2020), journals (Mas-Tur et al., 2020), international research collaborations (Sweileh et al., 2018) and research topics fields such as math education (Ersozlu & Karakus, 2019; Ozkaya, 2018; Ramirez & Devesa, 2019; Drijvers et al., 2020). Different bibliometric analysis techniques may require use of different tools such as VOSviewer (van Eck & Waltman, 2010), R Bibliometrix/Biblioshiny (Aria & Cuccurullo, 2017), or Citespace (Chen, 2006).

Few bibliometric analysis studies have been conducted in the field of mathematics education. A recent study by Drijvers et al. (2020) investigated instrumental orchestration (IO) in mathematics education through 19 core and 234 citing articles from Scopus. Their bibliometric analysis revealed the three stages of IO research, from introduction, development, and usage of the notion of IO. From the extended corpus based on the citing articles, five clusters were identified: (1) managing teaching complexity; (2) designing living resources; (3) teaching with technology; (4) adult learners; (5) interacting with computers. The authors further concluded that bibliographic coupling clustering technique "provided a valuable and sense-making sketch of the 'landscape' of the topic under study" (Drijvers et al., 2020, p.1466) and "inspired the domain experts to synthesize the field in a way that would not have been possible otherwise" (Drijvers et al., 2020, p.1467). Aside from reaffirming the viability of bibliometric analysis for mathematics education, the findings provide researchers with a detailed and structured look at the development and core topics in the field of IO.

Ersozlu and Karakus (2019) investigated mathematics anxiety using bibliometric methods by analyzing a total of 537 articles from Web of Science (WOS) between 2000 and 2018 and provided the research landscape of the top research themes, journals, authors, institutions, and publishing countries in the field. Other bibliometric analysis accessed different databases and timespans. For instance, Ramirez and Devesa (2019) focused on the scientific production in mathematics education by examining 5633 articles between 1978 and 2017 in SCOPUS. Ozkaya (2018) looked at 9941 articles in WOS between 1980 and 2018 and examined the performance analysis and scientific mapping in mathematics education.

Research questions (RQs)

It is in this context this paper hopes to contribute to the current literature by providing a bibliometric review of online mathematics education, especially under the ongoing pandemic to tackle this new pedagogical approach, using a bio-eco-techno perspective. There has not been bibliometric analysis targeting the field of online mathematics education. This study fills this gap by answering the following RQs:

(1) What is the current state of online mathematics education in terms of its scientific production?
(2) What does the scientific mapping of publications in online mathematics education reveal about its:

(1) Social network structure in terms of global collaboration in scientific production?

(2) Conceptual structure (research themes) dominating the field?

Drawing on the answers to the above two RQs, this study aims to form a model for online mathematical learning by answering the following final research question:

(3) How can the field of online mathematics education be contextualized in the bioecological model and ecological theories of educational technology?

Method

Bibliometric method workflow

This study utilized a five-step workflow of bibliometric methods as suggested by Zupic and Cater (2015), with additional data analytic methods (Fig. 1). The first step was defining the research question and choice of suitable bibliometric method. The compilation of bibliometric data came next, wherein the database and search criteria were chosen, and the core document sets filtered and exported for data loading and converting for the third step—application of the selected bibliometric software. In the fourth step, the appropriate visualization method was selected. Finally, the researchers interpreted and discussed the findings.

Data Compilation

Data retrieval and search query

Clarivate Analytics' WOS Core Collection was chosen for this study. First, it is considered one of the most prestigious multidisciplinary bibliographic databases for comprehensive evaluation of research productivity (Gasparyan et al., 2018). Second, as the oldest citation database, it has the most comprehensive coverage of data dating back to 1900 (Chandegani et al., 2013). Its quantitative indicators also allow for detailed bibliometric analysis (Okubo, 1997).

The search query was as follows: TS = ("online learning" OR "online education" OR "distance learning" OR "distance education" OR "e-learning" OR "electronic learning" OR "elearning" OR "web-based learning" OR "distributed learning" OR "remote learning" OR "mobile learning" OR "blended learning" OR "flipped learning" OR "flipped classroom"

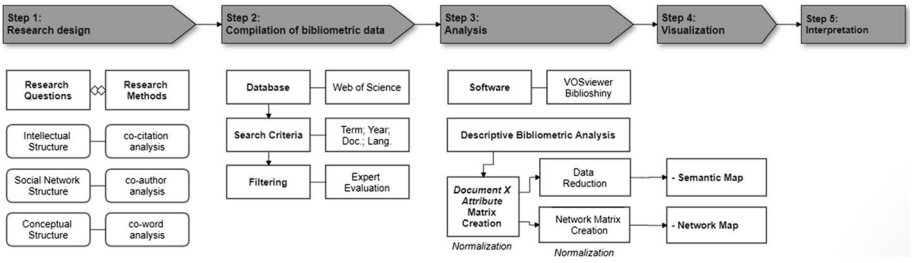

Fig. 1 The Five-Step Workflow of Bibliometric Methods in This Study

OR "virtual learning" OR "virtual classroom" OR "internet* learn*" OR "internet* teach*" OR "computer* learn*" OR "computer* teach*" OR "web* learn*" OR "web* teach*") AND TS = math*.

The result was limited to English articles and reviews using the search period from 1900 to 2020. Publications from 2021 were excluded to analyze the data on an annual basis; however, early access publications that were available in 2020 were included, and resulted in 441 documents published between 1992 and 2020.

Expert review for excluding irrelevant documents

The exported WOS documents were reviewed in 3 stages according to their relevance to online mathematics education. In Stage 1, the two authors reviewed all the 441 documents independently and concurrently using different methods. The first author reviewed all the abstracts, the titles, and when the abstract is not clear, the full text, while the second author used the same WOS search query to code four aspects (title, abstract, author keywords, and keyword plus provided by the WOS) of the documents using Python (1 = yes, 0 = no; Appendix). If none of the four aspects was coded "1 = yes", the second author also reviewed the abstract and the full text in case of unclear abstract. In Stage 2, both authors convened on result discrepancies from Stage 1. In Stage 3, the second author double-checked the exclusion review results. The three stages excluded 122 entries, resulting in a total of 319 documents published between 1993 and 2020 for subsequent analysis.

Data analysis

The software tools to analyze the data were R Bibliometrics/Biblioshiny (Aria & Cuccurullo, 2017) and VOSviewer (van Eck & Waltman, 2010). Microsoft Excel and PowerPoint were used to generate graphs and charts. The bibliometric analysis for the field of online mathematics education was conducted separately for RQ1 and RQ2.

Scientific production (RQ1)

Scientific production in online mathematics education research was examined using total production (TP), total citation (TC), and normalized citation (NC) (Gutiérrez-Salcedo et al., 2018). TP informs authorship productivity and TC is indicative of influence in the field of study (Baier-Fuentes et al., 2019). NC was used to rank contributions for publication pertinence (Waltman, 2016). These indicators were retrieved from VOSviewer to rank their contributions and impact. For an equal number of publications, NC was used.

Scientific mapping analysis (RQ2)

The second part of the analysis utilized VOSviewer (van Eck & Waltman, 2010) to identify the social (scientific community) and conceptual (research front) structures in the field of online mathematics education (Aria et al., 2020; Gutiérrez-Salcedo et al., 2018). Scientific mapping provides a visualization of the dataset to reveal the relationship between countries and documents (van Raan, 2004).

In analyzing the publications in online mathematics education, two different citation analysis methods (bibliographic coupling and co-citation) can be applied. Co-citation analysis occurs when two articles are both cited by a third article (Small, 1973) and reveals the

intellectual structure of the field. Conversely, bibliographic coupling takes place when two articles both cite a third article (Kessler, 1963) and provide an overview of the research front. This paper utilized bibliographic coupling, as it has been found to most accurately represent the research front (Boyack & Klavans, 2010), which provides insight for future educational practices. Fractional counting in VOSviewer was also used to avoid misinterpretations or misunderstanding from full counting methods (Perianes-Rodriguez et al., 2016).

Results

Scientific production (RQ1)

General trends of online mathematics education

A general descriptive analysis was conducted using R Biblioshiny (Aria & Cuccurullo, 2017). The annual scientific production is presented in Fig. 2. The dataset includes a total of 319 articles and reviews published between 1993 and 2020. On average, each publication was cited 16.52 times and averaged 2.561 citations per year. The total number of references included in the dataset is 12,794.

In the field of online mathematics education, there was an annual growth rate of 7.25% between 1993 and 2020. Publications varied between 1 and 3 publications per year until 2006. The first significant growth occurred in 2007, which jumped to 7 articles. This growth trend continued to fluctuate until 2017, when publications rose from 19 articles in the previous year to 35 articles. A surge in publication occurred in 2020, marking the highest number of articles.

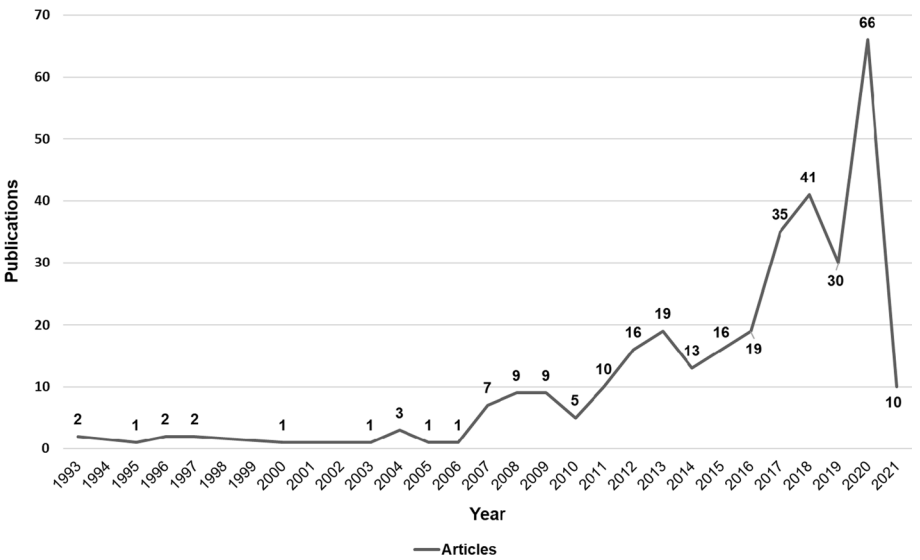

Fig. 2 Annual Scientific Production in Online Mathematics Education

A total of 60 countries and 408 higher education institutions contributed to scientific production of online mathematics education. Table 1 presents the top 10 contributors in each category ranked according to TP, and NC where there is equal TP. The top 10 countries are the USA, the UK, Taiwan, China, Spain, Australia, South Africa, Turkey, Canada and Germany. Among the top 10 institutions, 3 are situated in the USA, including University of Florida, University of Michigan, and Columbia University. University of Hong Kong and Central China Normal University are in China and National Taiwan University of Science and Technology and National Taiwan Normal University are in Taiwan. Spain, the Netherlands, and Turkey each feature 1 institution, including University of Granada, University of Amsterdam, and Karadeniz Technical University, respectively.

Social network structure (RQ2a)

A total of 60 countries participated in international collaboration in the field of online mathematics education, of which 42 engaged in at least 1internationally co-authored publication. Scientific mapping of country co-authorship was set at a minimum of 5 publications per country, resulting in 19 countries depicted in Fig. 3. Five distinct clusters form the social network structure. Each cluster represents the collection of countries that most often collaborate, and the size of each node depicts their number of publications. The links connecting the nodes indicate collaboration between them, and the strength is shown by their respective distances.

The countries with the highest level of collaboration include UK (9), USA (8), and Australia (7). These countries lead in their own clusters (UK, green; USA, blue; Australia, red) and work with countries outside their clusters. For instance, the UK, with the highest level of collaboration (9), also works with Australia, the USA, China, Netherlands, South Korea, South Africa, and Canada. The USA (8) is the second highest collaborating country and works with South Korea, Norway, Canada, Netherlands, and the UK. Australia, ranking third (7) works with Canada and South Africa from the yellow cluster and UK and Netherlands from the green cluster. Interestingly, the yellow cluster features two unconnected groups; Canada only works with Sweden, while South Africa is only linked to Finland.

Table 1 Top 10 Contributing Countries and Institutions

Top 10 Countries				Top 10 Institutions				
Country	TP	TC	NC	Institution	Country	TP	TC	NC
USA	81	1443	90.04	University of Hong Kong	China	8	171	17.05
UK	30	365	31.36	University of Granada	Spain	6	179	10.86
Taiwan	27	616	35.36	University of Florida	USA	5	107	10.88
China	22	304	32.01	Central China Normal University	China	5	73	5.89
Spain	20	321	22.38	University of Amsterdam	Netherlands	5	33	2.6
Australia	20	380	17.77	National Taiwan University of Science and Technology	Taiwan	4	248	12.12
South Africa	19	70	6.23	University of Michigan	USA	4	89	4.63
Turkey	15	291	10.59	National Taiwan Normal University	Taiwan	4	75	4
Canada	15	109	6.5	Karadeniz Technical University	Turkey	4	98	3.84
Germany	10	94	15.71	Columbia University	USA	4	81	3.48

TP Total production, *TC* Total citation, *NC* Normalized citation

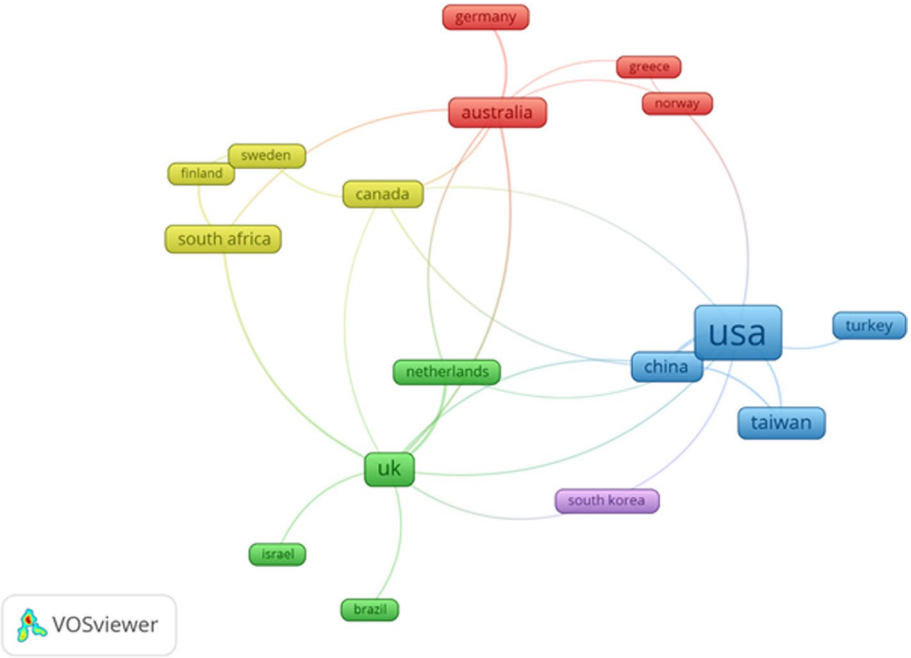

Fig. 3 Social Network Structure of Country Collaboration

Finally, South Korea occupies its own cluster (purple) and is connected to both the USA and UK.

Conceptual structure: themes (RQ2b)

Mapping of the conceptual structure of research in online mathematics education was performed through bibliometric coupling of the 319 publications. Fifty publications met the minimum citation of 30, of which 40 publications represent the largest set of connected items. The results are depicted in Fig. 4.

Publications with highly connected themes are clustered according to their color. Each node represents a publication, and its size is based on the number of citations received. The positioning of each cluster represents the prominence of the topic; that is, clusters at the center are the core topics while those at the outer positions are niche topics. Each node also features number of links and total link strength. The higher number of links and total link strength, the more cited references they share, thereby denoting their thematic similarity.

The cluster mapping reveals that online mathematics education is dominated by the flipped learning (FL) approach, evident by the four clusters' central position. The main focus is equally spread between general topics of the FL approach (blue) and its instructional design (purple). Surrounding this central theme are those pertaining to students' achievement (yellow) and perception (pink). The remaining five clusters emerge at the outer regions, though still highly connected to FL. The red cluster includes different systems of delivery while the rose cluster expands into adaptive, intelligent e-learning systems. The orange cluster discusses gamification, and the brown cluster introduces an

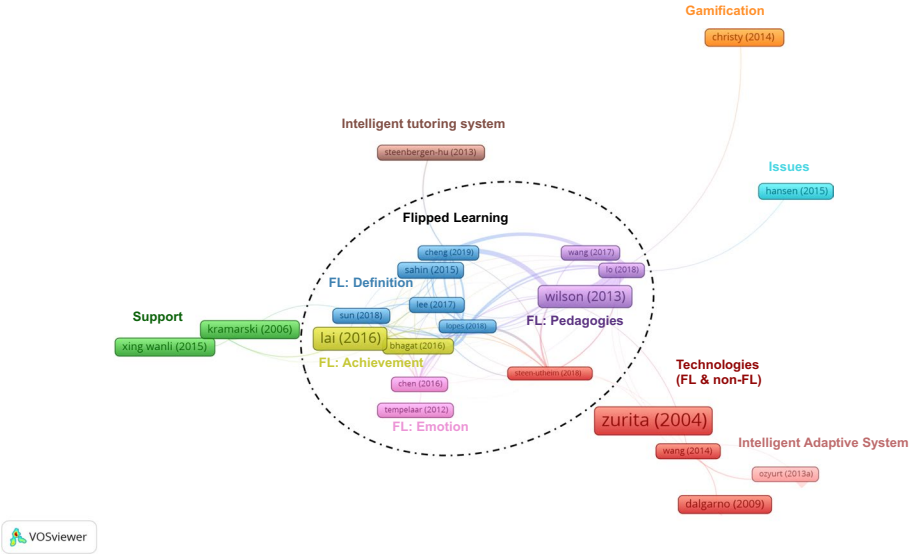

Fig. 4 Conceptual Structure of themes in online mathematics education

intelligent tutoring system. Finally, the teal cluster raises issues and possible solutions. The following results are presented according to cluster prominence in the scientific mapping of the conceptual structure. The publications are ordered according to number of links and total link strength, provided in the parenthesis.

FL: Definition

At the center is the blue cluster, representing the most prominent research theme in online mathematics education. It comprises 2 FL reviews and 4 articles investigating FL in mathematics education, totaling 6 publications including Cheng et al. (2019) (link = 14, referring to 14 publications citing the same references; total link strength = 36, referring to the 36 same references cited with the other publications), Lopes and Soares (2018) (12; 28), Sun et al. (2018) (13; 16), Lee et al. (2017) (12; 12), Lundin et al. (2018) (11; 24), and Sahin et al. (2015) (4; 8). The cluster defines FL and summarizes its effectiveness and weakness.

In terms of mathematics education, researchers studied FL in 1st year calculus (Sahin et al., 2015; Sun et al., 2018), algebra courses (Lee et al., 2017), and 2nd year financial mathematics courses (Lopes & Soares, 2018). FL was found to be especially helpful due to the nature of mathematics courses, requiring mathematical prior knowledge. As students are often lacking in their preparedness, class time was devoted to reviewing background materials (Lopes & Soares, 2018; Sahin et al., 2015; Sun et al., 2018). The pre-class online video lectures allowed students to review the necessary conceptual knowledge. Whereas the impact of preparation for high achievers was not significant (Sun et al., 2018), for students with low prior math knowledge, the ability to pause, rewind, and rewatch online video lectures allowed better learning of long complicated mathematical proofs that are especially difficult to follow (Lee et al., 2017; Sun et al., 2018). Students also preferred watching videos to reading textbooks (Sahin et al., 2015) and practicing online exercises to writing assignments (Lopes & Soares, 2018). The pre-class learning designed to introduce

foundational math concepts thus better prepared students for in-class activities, promoted students' math self-efficacy, and motivated them to engage in in-class collaborative learning when observing their peers solve math problems (Sun et al., 2018). Students' epistemological beliefs towards mathematics also increased, from regarding mathematical knowledge as absolutes and separate truth (naive layperson), to one that is complex, impermanent, and constructed through interaction (expert mathematician), and their reflective thinking moved from content and process (i.e. summaries of learning content and activities) to critical reflection (i.e. what had not been adequately discussed in class activities) (Lee et al., 2017). Thus, significant increase in student mathematics learning, reflection, and satisfaction can be accomplished by a FL design model that provides a complementary dynamic between online and in-class learning experiences.

On the other hand, the reviews supplemented a general overview of FL research through identification of shortcomings in the field. In Cheng et al. (2019) meta-analysis of 55 publications on FL and learning outcome between 2000–2016, mathematics was the most studied subject (15) and comprised the greatest proportion of students (2345). Examination of FL learning outcome showed a positive small effect size compared to traditional classroom. However, the authors cautioned that the positive effect may be a result of reverse novelty effect on students' unaccustomed pedagogy that requires in-class active participation. They also noted the use of broad statements such as video recordings and active learning with very little detail about the nature of online videos and in-class activities provided. In Lundin et al. (2018)'s systematic review of 31 publications, they similarly found that overall the FL approach and experimental setting were not fully described, mostly referring to pedagogical terms or strategies (i.e. active learning, inquiry-based, student-centered, etc.). The common understanding was FL approach as reallocation of educational activities before class and creation of meaningful interactive learning activities in class; only one study drew on existing resources from other related fields (i.e. educational technology) and very few studies could make generalization or transferrable knowledge claims.

FL: Pedagogies

The publications in the purple cluster, 'Pedagogies', include Lo et al. (2018) (link = 16; total link strength = 46), Lo et al. (2017) (15; 49), Wang and Antonenko (2017) (2; 2), and Wilson (2013) (1; 1) with an emphasis on FL instructional approaches.

Lo et al. (2018) provided a theoretical framework for the FL approach across four subjects (Math, Physics, Chinese, and ICT) by applying Merrill's 'First Principles of Instruction' (problem-centered, activation, demonstration, application, and integration) and found improved student achievement in all but the ICT course, which showed roughly equal levels of achievement. The nature of the FL approach allows moving basic knowledge acquisition out of the classroom to afford interactive activities during class time, thus positively impacting students' attitude and decreasing their anxiety (Wilson, 2013).

For FL approach in mathematics education, Lo et al. (2017) specified 10 design principles across 3 themes based on a review of 72 flipped math courses instructional activities and follow-up meta-analysis of 21 studies. First, instructors should begin by articulating the rationale, benefits, challenges, syllabus implementation, and required tasks to familiarize students with this approach. Second, the out-of-class learning design should encompass introductory video lectures online to prepare students and motivate them with graded exercises. Thirdly, the in-class learning experience, designed according to students' out-of-class learning performance from the previous stage, emphasizes formative assessment

and application of knowledge to solve real-world problems. Instructors also provide feedback and differentiated instruction while facilitating peer-assisted learning through group activities. However, it should be noted that of the 21 studies in the meta-analysis, only 2 provided clear description of question types (i.e. computational and conceptual problems) and 2 used validated assessment tools (i.e. calculus concept inventory), with mixed effect of FL on types of questions found. Moreover, none of the studies explicitly described and assessed the effects of FL approach on near transfers (similar math problems sufficiently different from practice problems) versus far transfers (math problems entirely different from practice problems).

Mathematical video lectures in college level geometry and algebra can also be improved by instructor presence (Wang & Antonenko, 2017). First, it can better attract students' visual attention and increase students' perceived learning and satisfaction in both easy (similar triangle) and hard (trigonometric function) mathematical topics. Students also demonstrated enhanced ability to recall information in easy topics, while reporting lower levels of mental effort for difficult topics. Instructor presence in video neither improved nor hindered transfer of learning (application of learned concept).

FL: Achievements

The yellow cluster is 'Achievements' given the publications focus on variables associated with student mathematics achievement. There are 5 publications in this cluster, namely Hwang and Lai (2017) (link = 14; total link strength = 20), Lai and Hwang (2016) (13; 19), Bhagat et al. (2016) (13; 11), Walker (2012) (5; 2), and Maag (2004) (2; 3).

Introducing interactive multimedia without the FL approach construct did not impact student math achievement and math self-efficacy. For instance, no significant findings for increased math achievement and math self-efficacy were found in undergraduate nursing students studying basic math review and medication dosage calculation when comparing content presented between text only, text and image, multimedia, and interactive multimedia (Maag, 2004). On the other hand, it was found that high school trigonometry class post-test results based on the Mathematics Achievement Test (MAT) in FL outperformed traditional face-to-face classes for all levels except high achievers (Bhaget et al., 2016).

Supplementing conventional FL approach with other constructs further enhanced the positive impact. For elementary school students learning math concepts of 'area and perimeter', the use of interactive e-book-based FL with videos, quizzes and learning guidance, and annotation function showed improved learning achievement regardless of self-efficacy level, whereas students with higher self-efficacy outperformed those with lower self-efficacy in conventional video-based FL approach (Hwang & Lai, 2017). Likewise, students given self-regulated FL learning model outperformed those with conventional FL approach (Lai & Hwang, 2016). Within the self-regulated FL approach, students with higher self-regulation also showed significantly higher achievement than those with lower self-regulation.

Significant gains in students' behavior (i.e. spend time learning on my own), knowledge (i.e. knowing enough to teach friends), and attitude (I like this topic very much) was also found in professional development that integrated technology and problem-based learning (PBL) activities (Walker, 2012). Compared to professional development that exclusively focused on technology knowledge, integration of technology and PBL showed a positive impact on math and science teachers' technological-pedagogical knowledge, skill, and usage, and this benefit subsequently transferred to their students' learning.

FL: Emotion

The pink cluster is 'Emotion' and features 2 publications, Chen et al. (2016) (link = 12; total link strength = 18) and Templelaar et al. (2012) (1; 1). In terms of students' preference for online learning, positive learning emotions (enjoyment) contribute positively while negative learning emotions (boredom) contribute negatively to students becoming intensive online learners in a blended integrated college freshman mathematics and statistics course (Templelaar et al., 2012). However, this was not necessary for collaborative, face-to-face learning.

In terms of student's performance, students' interest in the topic positively significantly predicted their performance in a flipped high school precalculus course (Chen et al., 2016). Math performance was predicted by feeling (i.e. confidence and fulfillment) for male students and feedback on course design (i.e. FL approach) for female students. This cluster reveals that design of online learning components in the FL approach requires providing adequate instruction and favorable learning conditions to enhance positive perception and performance.

Technologies (FL and non-FL)

The 'Technologies' cluster (red) showcases the different types of technological use for online mathematics education to enhance students' mathematical learning experience. There are 7 publications in this cluster, including Steen-Htheim and Foldnes (2018) (link = 13; total link strength = 15), Wang (2014) (7; 5), Walton and Hepworth (2011) (4; 4), Zurita and Nussbaum (2004) (3; 1); Chi (2009), Dalgarno et al. (2009), and Makri and Kynigos (2007) all have 1 link and total link strength of 1.

Collaborative learning through technology can positively contribute to student learning. Compared to traditional lectures, mathematical problem-solving in an introductory college math course through the FL approach encourages stronger student affective engagement (Steen-Htheim & Foldnes, 2018). Watching pre-class lecture videos stimulates the need for discussion, and students' feelings of commitment, safety, and recognition in class contributed to group participation, through which knowledge emerges. Use of handheld computers can also be used as an effective means to support collaborative learning activities in elementary school language and math classes (Zurita & Nussbaum, 2004). Use of online social networks can benefit students in terms of achieving higher order learning and cognitive states (Walton & Hepworth, 2011) and encourage emergence of collaborative narratives for math teachers through their use of blogs (Makri & Kynigos, 2007).

Outside of class, delivery of course material and assignments through e-learning technologies also enhanced students' learning. Wang (2014) utilized personalized e-learning assessment and material annotations for 6th grade elementary students learning conceptual mathematics knowledge of 'speed'. The personalized dynamic assessment, which generates mathematics problem sets based on students' performance, improved student learning achievement and misconceptions, especially for students with low-level prior knowledge. The personalized e-learning material, which adaptively annotates material based on students' performance, increased students' reading time of the e-learning material. Another curriculum sequence design system, using algebra based on the Taiwan's "General Guidelines of Grade 1–9 Curriculum", was developed by Chi (2009) and features adaptive knowledge learning route and competence assessments based on students' needs. However, mere utilization of CD-ROM with virtual laboratory as preparatory tool for distance education,

though useful, did not address students' anxiety about mathematical concepts, potentially due to lack of calculation support or scaffolding in simulated experiments (Dalgarno et al., 2009).

Support

The green cluster is 'Support', as the publications focus on how aspects of online mathematics education can be reinforced to foster students' learning and performance. Among the 7 publications, Ibáñez and Delgado-Kloos (2018) is the main publication with 4 links and total link strength of 4, followed by Kramarski and Gutman (2006) with 3 links and total link strength of 3. Bano et al. (2018), Perrotta and Williamson (2018), and Wanli et al. (2015) all had 2 links and total link strength of 2, and Brahimi and Sarirete (2015) and Martin (2009) had 1 link and total link strength of 1.

Two reviews in this cluster investigated how augmented reality (AR) in STEM (Ibáñez & Delgado-Kloos, 2018) and mobile apps for mathematics and science education (Bano et al., 2018) can be used to support various pedagogical approaches. Collaborative learning is most often studied using mobile apps (Bano et al., 2018), with AR technology offering knowledge sharing features and differentiating student roles to solve real world mathematical problems. Bano et al. (2018) further constructed a grouping of pedagogies under realistic mathematics, including experiential learning, knowledge building, situated learning, and realistic/context-aware ubiquitous learning, as mobile apps afford virtual contexts that are easily imagined and understood as real for students. In terms of inquiry-based and project/problem-based learning, wherein students questioned, investigated, critically thought, and solved problems, AR can support exploration and simulation activities (Ibáñez & Delgado-Kloos, 2018). Game-based learning is also utilized along with the aforementioned pedagogical approaches through mobile apps (Bano et al., 2018).

The availability of these e-learning technologies can also positively impact learning outcomes in online mathematics education. MOOCs can be incorporated into existing curriculums to help students better prepare for their coursework (Brahimi & Sarirete, 2015). Though the physical actions involving physical manipulatives are important for learning of abstract mathematical concepts (Martin, 2009), AR-enabled exploration and simulation can help students visualize 3D concrete or abstract objects (Ibáñez & Delgado-Kloos, 2018). Student's mathematics problem-solving (procedural and transfer tasks) and mathematical explanations and self-monitoring strategies in SRL can also be enhanced through incorporation of IMPROVE self-metacognitive questioning approach in e-learning (Kramarski & Gutman, 2006). Learning analytics utilizing data log from collaborative geometry problem-solving environments (Virtual Math Teams with Geogebra) can provide teachers with interpretable prediction models for pertinent interventions (Wanli et al., 2015). However, Perrotta and Williamson (2018) caution that learning analytics are open to re-interpretations and require methodological sensibilities.

Issues

In the teal cluster, 3 publications raised 'Issues' and provides suggestions concerning online mathematics, including Recker et al. (2004) (link = 3; total link strength = 2), Hansen and Reich (2015) (2; 1), and Khaddage et al. (2016) (2; 1). For math (and science) teachers, recommended design of educational digital repositories addresses barriers such as quality of resources, availability, and updates are provided (Recker et al., 2004). For students,

approaches in bridging formal and informal STEAM learning through mobile technologies are recommended (Khaddage et al., 2016). Finally, educational outcomes based on technology (ie. MOOCs) must consider students' gap in their socioeconomic status (Hansen & Reich, 2015).

Gamification

The orange cluster is 'Gamification', with studies by Jagušt et al. (2018) (link = 2; total link strength = 4) and Christy and Fox (2014) (1; 3) in online mathematics education. Jagušt et al. (2018) found gamification could contribute to sustaining and improving performance of primary school students through integrating different game elements of leaderboards, badges, narratives, and adaptive mechanisms based on individual performance. However, instructors should be cautious when using leaderboards at university level, as female participants in a female-dominated leaderboard performed more poorly than one dominated by male participants (Christy & Fox, 2014).

Intelligent tutoring system

'Intelligent Tutoring System', the brown cluster, is represented by 2 publications: Steenbergen-Hu and Cooper (2013) (link = 2, total link strength = 3) and Sarrafzadeh et al. (2008) (1, 1). In a meta-analysis of 26 studies between 1997 and 2010, Steenbergen-Hu and Cooper (2013), examined the effectiveness of intelligent tutoring systems (ITS) on K-12 mathematics learning and found a very small positive effect relative to traditional classroom instruction (Steenbergen-Hu & Cooper, 2013). The effectiveness of ITS was lower for courses lasting more than 1 year and greater for low achievers.

The second publication (Sarrafzadeh et al., 2008) presented an affective tutoring system that monitored students' knowledge of part-whole addition through students' affective states (i.e. confusion, anxiety, inattention, etc.), reacted accordingly through facial expressions and gestures, and responded with tutoring recommendations. However, the study did not evaluate the effectiveness of this system.

Intelligent adaptive systems

The final cluster (rose) is 'Intelligent Adaptive System' and comprises two publications: Özyurt et al. (2013b) (link = 2; total link strength = 22) and Özyurt et al. (2013a) (2; 21). An adaptive and intelligent web-based e-learning system, UZWEBMAT (adaptive and intelligent web-based mathematics teaching–learning system) was developed to teach secondary school level mathematics probability (Özyurt et al., 2013b). The system featured learning objects presented according to the students' dominant learning styles (visual, auditory, or kinesthetic) and controlled learner progress, adapting to students' needs with intelligent support and tips within learning objects. Students reported positive experience and satisfaction with UZWEBMAT (Özyurt et al., 2013a). They experienced the process of discovery, realized their own strengths and weaknesses, and gained self-confidence. Interestingly, students undertook their own learning responsibility and could learn without teachers.

Discussion

Using bibliometric analysis techniques, this study investigated the field of online mathematics education. Scientific productivity suggests that FL and psychological constructs appear to generate more research than those involved in mathematics knowledge. The scope of the most productive journals is related to technology, while themes of online mathematics education in the conceptual structure indicate that soft aspects (i.e. self-regulation, student engagement, affect, motivation, and performance) occupy the core categories, with supplementary topics on the hard aspect (i.e. intelligent tutoring and adaptive systems, learning analytics).

RQ3 is answered by combining all these key findings to form a bio-eco-techno (BET) model for online mathematics learning, as illustrated in Fig. 5, based on bioecological theories of human development (Bronfenbrenner & Morris, 2007) and educational technology (Chiu, 2020a, b; Johnson, 2010; Johnson & Puplampu, 2008). The following discussion is grounded in each context to provide recommendations for online mathematics education.

Bioecological system: student achievement in online mathematics education

The student is at the core of the bioecological model (Bronfenbrenner & Morris, 2007), and implementation of online mathematics education must begin by considering the various characteristics of the person. Specifically, these include the students' gender (Chen et al., 2016; Christy & Fox, 2014), prior mathematical knowledge (Maag, 2004; Özyurt et al., 2013a; Bhaget et al., 2016; Lee et al., 2017; Hwang & Lai, 2017; Sun et al., 2018), socioeconomic status (Hansen & Reich, 2015), self-regulation (Kramarski & Gutman, 2006; Özyurt et al., 2013a), interest (Chen et al., 2016; Lopes & Soares, 2018; Sahin et al., 2015), and emotion (Templelaar et al., 2012), all of which constitute the demand, resource, and force characteristics that contribute to students' mathematics achievement.

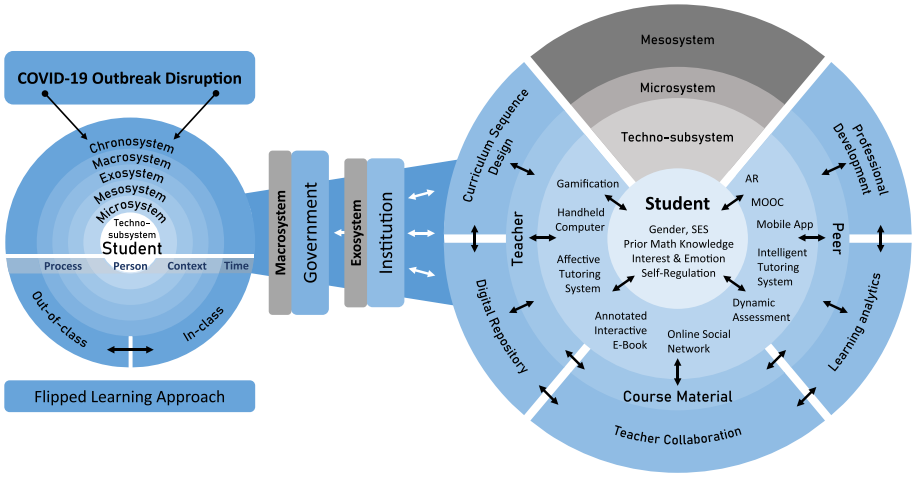

Fig. 5 A Bio-Eco-Techno (BET) Model for Online Mathematics Education

Microsystem: techno-subsystems for supporting flipped learning

In the context of the bioecological model (Bronfenbrenner & Morris, 2007), the predominance of technology application reveals how processes between the student and the teacher, peer, and course material within the microsystem is mediated by the techno-subsystem (Johnson, 2010). Technologies such as lecture videos in FL (Steen-Htheim & Foldnes, 2018), handheld computers (Zurita & Nussbaum, 2004), online social networks (Walton & Hepworth, 2011), mobile apps (Bano et al., 2018), and gamification (Christy & Fox, 2014; Jagušt et al., 2018) promote student interaction with peers by reducing anxiety (Wilson, 2013) and contribute to processes of collaborative learning. Teacher feedback to and interaction with students are afforded through an FL approach (Cheng et al., 2019; Sahin et al., 2015; Sun et al., 2018). Course material with lecture videos featuring the instructor (Wang & Antonenko, 2017), materials and activities responding to students' emotion (Sarrafzadeh et al., 2008) or performance (Hwang & Lai, 2017; Özyurt et al., 2013a, 2013b; Steenbergen-Hu & Cooper, 2013; Wang, 2014) can enhance student understanding. This can also be supplemented with CD-ROMs (Dalgarno et al., 2009) and MOOCs (Brahimi & Sarirete, 2015) and further enhanced through simulations and explorations utilizing AR (Ibáñez & Delgado-Kloos, 2018).

Exosystem and mesosystem: institution support for teacher pedagogical design, digital competencies, and collaboration

Institutional support is crucial to implementation of online learning (Tartavulea et al., 2020). Reliance on technology in online mathematics education calls for the need for institutions to support online mathematics education by providing professional development in digital competency (Walker, 2012). IT departmental support and provision of online platforms for professional collaboration (Makri & Kynigos, 2007), curriculum sequence design (Chi, 2009), and digital repositories for teaching resources (Recker et al., 2004) can mitigate the workload required of teachers (Sahin et al., 2015). Training in the use of learning analytics provides teachers a better understanding of student learning and necessary intervention (Wanli et al., 2015). At the departmental level, workshops and training seminars on guidance in FL instructional design and pedagogy can positively impact student learning (Lo et al., 2017, 2018). Policymakers must seek to mitigate the risk or inequalities caused by income or workload disparities (Talib et al., 2021).

Macrosystem: distribution or centralization?

At the national level, research productivity in online mathematics education can be considered from both the perspectives of government policies and how collaboration takes place between countries.

On the one hand, the pandemic did not deter overall research in the field of online mathematics education at the global and national scale. Performance analysis (Fig. 2) results show increasing interest since 1993, and despite a decline in 2019, scientific production doubled in 2020. As seen in the social network structure (Fig. 3), there is a dominance by the Organization for Economic Co-operation and Development (OECD) member countries such as the UK, USA, Australia, and Canada. This result lends further support to the centralization of global academic research by core countries that are both economically influential and academically dominant (Zhu et al., 2021). However, the absence of less

privileged countries raises concern as to the aforementioned social inequality issues not only at the student-level but national policies as well.

On the other hand, the experience of the top productive countries can provide an example for other nations. Of special note is that among the top productive countries, only Taiwan belongs to neither OECD nations nor its 5 key partners. Considering its positions across each metric, however, Taiwan appears to be one of the core influential contributors in online mathematics education. As the third highest contributing country, it houses 2 of the top 10 institutions [Taiwan University of Science and Technology (6th) and Taiwan Normal University (8th)]. Moreover, despite generating 27 total publications, its total citations received (616) and normalized citations (35.3646) outperformed all the countries except the USA (1443). Likewise, Taiwan's top 5 ranked achievement in PISA math scores since 2006 (OECD, 2007, 2010, 2014, 2016, 2019) may be indicative of the dynamic between mathematics educational research and practice. This accomplishment may be attributed to Taiwan's national public policy successfully promoting access and use of digitized knowledge (Tibaná-Herrera et al., 2018). Future studies examining the dynamics between national policy in government support, education, and culture of Taiwan can thus provide better insights in online mathematics education.

Chronosystem: COVID-19 forcing blended/flipped to online education?

Research themes in online mathematics education are disproportionately vested in the integration of face-to-face and online learning, rather than fully online (FO) mathematics education. This is not surprising. FO mathematics education faces the unique challenges of higher engagement required of students, reduced benefit of student–student online discussion, the nature of communicating mathematical concepts, the limitations of communication channels, lack of real-time interactivity, and assessment issues (Trenholm & Peschke, 2020). Nevertheless, that ERT must be carried out during the pandemic (Hodges et al., 2020) underscores the dearth of FO mathematics education and greater need for educators to confront its challenges.

The current pandemic has provided a natural setting to study the impact of online mathematics education on students' learning (Bakker & Wagner, 2020). The forced digital transition has exposed inherent problems within the system, providing an impetus for change and innovation (Talib et al., 2021). It calls for the groundwork needed for the transformation of mathematics educators to innovate in principles of design, social interaction and knowledge construction, and tools and resources (Engelbrecht, Llinares, et al., 2020). On top of digital technology and mathematics education, educators must contemplate how social inequality under the pandemic can be addressed (Borba, 2021). Successfully tackling these issues require concerted efforts in global collaboration, national policies, institutional support, and educator competency.

Returning to the element of time (Bronfenbrenner & Morris, 2007), online mathematics education can be framed under the subcategories of microtime, mesotime, and macrotime in the element of time in the bioecological model. For microtime, the FL approach can foster formal and informal learning in online mathematics education by fully taking advantage of the alternation between in-class and out-of-class activities (Khaddage et al., 2016). Nevertheless, educators must be aware of potential short-lived positive effects attributed to the novelty effect of pedagogy (Cheng et al., 2019) and that positive impacts might not be observed in the long run (Lundin et al., 2018). The current COVID-19 outbreak (macrotime) has forced implementation of social distancing measures and FO mathematics

education. This study provides the foundation of how current knowledge in the benefits of FL can complement and overcome the challenges of FO mathematics education.

Conclusion

Contributions

In light of the increasing prevalence of ICTs and the uncertainties that lie ahead under the COVID-19 pandemic, online mathematics education will remain an important part of research and teaching. Equipped with a general and better understanding of the research trends and concepts in this field will better prepare academics and policymakers for better implementation while overcoming potential challenges and previous mistakes.

This study thus presented a bibliometric analysis to provide a reference for stakeholders of online mathematics education. Using publications retrieved from WOS between 1993 and 2020, a performance analysis was first conducted to examine scientific productivity and provide an overview of the field. The annual scientific production displayed exponential growth since 2017, marking the increasing importance of online mathematics education. With an overview of the top productive countries, journals, organizations, and authors, scholars may be directed to delve deeper in identifying unique features to aid and support potential research issues.

Scientific mapping also revealed the social and conceptual networks in online mathematics education. The social network structure shows that the international collaborative efforts are indicative of a highly diversified and globalized collection of different countries in each cluster. Insights from future research in comparing and investigating the countries' policies, culture, and systems in mathematics can be leveraged for better development and quality assurance of online mathematics research. The conceptual structure presented the 10 research themes including the central 4 relating to FL—Definition, Pedagogies, Achievements, and Emotion, and the remaining in the areas of that discusses the Technologies, Support, Issues, Gamification, Intelligent Tutoring System, and Intelligent Adaptive System in online mathematics education. Given the current context of the COVID-19 pandemic, a clearer differentiation between the concepts of fully online and partial online education, or ERT and online learning, must be made.

This study has provided the groundwork for future endeavors in identification of potential research gaps. It is evident that dominance of the FL approach must be expanded to cope with potential FO mathematics education. Better coordination and communication of learning activities to replace the in-class portion of flipped classroom will be needed. Educators may consider ICTs and updated pedagogical designs that resolve this issue. A new construct that supports a fully online learning experience while retaining the advantages of flipped learning will be invaluable.

Limitations and suggestions for future research

Despite the steps taken to ensure accuracy and precision in the current bibliometric analysis, there are some limitations in the current study. Limiting publications to WOS database to ensure the highest quality standards also meant the exclusion of other databases. Research from other countries in other languages and other types of publications are also missing, as only English articles and reviews were included. Finally, with the rapid

technological development and uncertainty of the COVID-19 pandemic, the results of the current study may quickly become obsolete. However, in addressing the research questions raised in this study, the current bibliometric analysis can contribute to the literature as a reference guide for initiating future research.

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Declarations

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

References

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics, 11*, 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Aria, M., Misuraca, M., & Spano, M. (2020). Mapping the evolution of social research and data science on 30 years of social indicators research. *Social Indicators Research, 149*, 803–831. https://doi.org/10.1007/s11205-020-02281-3

Aristovnik, A., Ravšelj, D., & Umek, L. (2020). A bibliometric analysis of COVID-19 across science and social science research landscape. *Sustainability, 12*(21), 9132. https://doi.org/10.3390/su12219132

Baier-Fuentes, H., Merigó, J. M., Amorós, J. E., & Gaviria-Marín, M. (2019). International entrepreneurship: A bibliometric overview. *International Entrepreneurship and Management Journal, 15*, 385–429. https://doi.org/10.1007/s11365-017-0487-y

Bakker, A., & Wagner, D. (2020). Pandemic: Lessons for today and tomorrow? *Educational Studies in Mathematics, 104*, 1–4. https://doi.org/10.1007/s10649-020-09946-3

Bano, M., Zowghi, D., Kearney, M., Schuck, S., & Aubusson, P. (2018). Mobile learning for science and mathematics school education: A systematic review of empirical evidence. *Computers & Education, 121*, 30–58. https://doi.org/10.1016/j.compedu.2018.02.006

Bhagat, K. K., Chang, C. N., & Chang, C. Y. (2016). The impact of the flipped classroom on mathematics concept learning in high school. *Educational Technology & Society, 19*(3), 134–142.

Borba, M. C. (2021). The future of mathematics education since COVID-19: Humans-with-media or humans-with-non-living-things. *Educational Studies in Mathematics*. https://doi.org/10.1007/s10649-021-10043-2

Bouilheres, F., McDonald, S., Nkhoma, C., & Jandug-Montera, L. (2020). Defining student learning experience through blended learning. *Education and Information Technologies, 25*, 3049–3069.

Boyack, K. W., & Klavans, R. (2010). Co-citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately? *Journal of the American Society for Information Science and Technology, 61*(12), 2389–2404.

Bozkurt, A., & Zawacki-Richter, O. (2021). Trends and patterns in distance education (2014–2019): A synthesis of scholarly publications and a visualization of the intellectual landscape. *The International Review of Research in Open and Distributed Learning, 22*(2), 19–45. https://doi.org/10.19173/irrodl.v22i2.5381

Brahimi, T., & Sarirete, A. (2015). Learning outside the classroom through MOOCs. *Computers in Human Behavior, 51*, 604–609. https://doi.org/10.1016/j.chb.2015.03.013

Bronfenbrenner, U. (1979). *The ecology of human development: Experiments in nature and design*. Harvard University Press.
Bronfenbrenner, U., & Morris, P. A. (2007). The bioecological model of human development. In W. Damon, R. M. Lerner, & N. Eisenberg (Eds.), *Handbook of child psychology* (pp. 793–828). Wiley.
Chandegani, A. A., Salehi, H., Yunus, M. M., Farhadi, H., Fooladi, M., Farhadi, M., & Ebrahim, N. A. (2013). A comparison between two main academic literature collections: Web of science and scopus databases. *Asian Social Science, 9*(5), 18–26. https://doi.org/10.5539/ass.v9n5p18
Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the Association for Information Science and Technology, 57*(3), 359–377. https://doi.org/10.1002/asi.20317
Chen, S. C., Yang, S. J., & Hsiao, C. C. (2016). Exploring student perceptions, learning outcomes and gender differences in a flipped mathematics course. *British Journal of Educational Technology, 47*(6), 1096–1112. https://doi.org/10.1111/bjet.12278
Cheng, L., Ditzhaupt, A. D., & Antonenko, P. (2019). Effects of the flipped classroom instructional strategy on students' learning outcomes: A meta-analysis. *Educational Technology Research and Development, 67*(4), 793–824. https://doi.org/10.1007/s11423-018-9633-7
Chi, Y. L. (2009). Ontology-based curriculum content sequencing system with semantic rules. *Expert Systems with Applications, 36*(4), 7838–7847. https://doi.org/10.1016/j.eswa.2008.11.048
Chiu, M.-S. (2020a). Exploring models for increasing the effects of school information and communication technology use on learning outcomes through outside-school use and socioeconomic status mediation: The Ecological Techno-Process. *Educational Technology Research and Development, 68*, 413–436. https://doi.org/10.1007/s11423-019-09707-x
Chiu, M.-S. (2020b). Linear or quadratic effects of ICT use on science and mathematics achievements moderated by SES: Conditioned ecological techno-process. *Research in Science & Technological Education*. https://doi.org/10.1080/02635143.2020.1830270
Chiu, M.-S. (2021). An ecological approach to adolescent mathematics ability development: Differences in demographics, parenting, mathematics teaching, and student behaviors and emotions. *Educational Studies, 47*(2), 155–178. https://doi.org/10.1080/03055698.2019.1672522
Christy, K. R., & Fox, J. (2014). Leaderboards in a virtual classroom: A test of stereotype threat and social comparison explanations for women's math performance. *Computers & Education, 78*, 66–77. https://doi.org/10.1016/j.compedu.2014.05.005
Dalgarno, B., Bishop, A. G., Adlong, W., & Bedgood, D. R., Jr. (2009). Effectiveness of a Virtual Laboratory as a preparatory resource for Distance Education chemistry students. *Computers & Education, 53*(3), 853–865. https://doi.org/10.1016/j.compedu.2009.05.005
Drijvers, P., Grauwin, S., & Trouche, L. (2020). When bibliometrics met mathematics education research: The case of instrumental orchestration. *ZDM, 52*, 1455–1469. https://doi.org/10.1007/s11858-020-01169-3
Engelbrecht, J., Borba, M. C., Llinares, S., & Kaiser, G. (2020). Will 2020 be remembered as the year in which education was changed? *ZDM, 52*, 821–824. https://doi.org/10.1007/s11858-020-01185-3
Engelbrecht, J., Llinares, S., & Borba, M. C. (2020). Transformation of the mathematics classroom with the internet. *ZDM, 52*, 825–841. https://doi.org/10.1007/s11858-020-01176-4
Ersozlu, Z., & Karakus, M. (2019). Mathematics anxiety: Mapping the literature by bibliometric analysis. *EURASIA Journal of Mathematics, Science and Technology Education, 15*(2), em1673. https://doi.org/10.29333/ejmste/102441
Garfield, E. (1994). Scientography: Mapping the tracks of science. *Current Contents: Social & Behavioural Sciences, 7*, 5–10.
Gasparyan, A. Y., Yessirkepov, M., Duisenova, A., Trukhachev, V. I., Kostyukova, E. I., & Kitas, G. D. (2018). Researcher and author impact metrics: Variety, value, and context. *Journal of Korean Medical Sciences, 33*(18), e139. https://doi.org/10.3346/jkms.2018.33.e139
Gecer, A., & Dag, F. (2012). A blended learning experience. *Educational Sciences: Theory and Practice, 12*, 438–442.
Gutiérrez-Salcedo, M., Martínez, M. Á., Moral-Muñoz, J. A., Herrera-Viedma, E., & Cobo, M. J. (2018). Some bibliometric procedures for analyzing and evaluating research fields. *Applied Intelligence, 48*, 1275–1287. https://doi.org/10.1007/s10489-017-1105-y
Hansen, J. D., & Reich, J. (2015). Democratizing education? Examining access and usage patterns in massive open online courses. *Science, 350*(6265), 1245–1248. https://doi.org/10.1126/science.aab3782
Hodges, C., & Moore, S., Lockee, B., Trust, T., & Bond, M. (2020, March 27). The Difference Between Emergency Remote Teaching and Online Learning. EDUCAUSE. Retrieved May 9, 2021, from https://er.educause.edu/articles/2020/3/the-difference-between-emergency-remote-teaching-and-online-learning

Huang, C., Yang, C., Wang, S., Wu, W., Su, J., & Liang, C. (2020). Evolution of topics in education research: A systematic review using bibliometric analysis. *Educational Review, 72*, 281–297. https://doi.org/10.1080/00131911.2019.1566212

Hwang, G. J., & Lai, C. L. (2017). Facilitating and bridging out-of-class and in-class learning: An interactive e-bookbased flipped learning approach for math courses. *Educational Technology & Society, 20*(1), 184–197.

Ibáñez, M.-B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education, 123*, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

Jagušt, T., Botički, I., & So, H. J. (2018). Examining competitive, collaborative and adaptive gamification in young learners' math learning. *Computers & Education, 125*, 444–457. https://doi.org/10.1016/j.compedu.2018.06.022

Johnson, G. M. (2010). Internet use and child development: Validation of the ecological techno-subsystem. *Educational Technology & Society, 13*(1), 176–185.

Johnson, G. M., & Puplampu, P. (2008). A conceptual framework for understanding the effect of the Internet on child development: The ecological techno-subsystem. *Canadian Journal of Learning and Technology, 34*, 19–28.

Kessler, M. M. (1963). Bibliographic coupling between scientific papers. *American Documentation, 24*, 123–131. https://doi.org/10.1002/asi.5090140103

Khaddage, F., Müller, W., & Flintoff, K. (2016). Advancing mobile learning in formal and informal settings via mobile app technology: Where to from here, and how? *Educational Technology & Society, 19*(3), 16–26.

Khirwadkar, A., Khan, S. I., Mgombelo, J., Obradović-Ratković, S., & Forbes, W. A. (2020). Reimagining mathematics education during the COVID-19 pandemic. *Brock Education Journal, 29*, 42–46. https://doi.org/10.26522/BROCKED.V29I2.839

Koedinger, K. R., McLaughlin, E. A., & Heffernan, N. T. (2010). A quasi-experimental evaluation of an on-line formative assessment and tutoring system. *Journal of Educational Computing Research, 43*, 489–510. https://doi.org/10.2190/EC.43.4.d

Kramarski, B., & Gutman, M. (2006). How can self-regulated learning be supported in mathematical E-learning environments? *Journal of Computer Assisted Learning, 22*(1), 24–33. https://doi.org/10.1111/j.1365-2729.2006.00157.x

Kumar Basak, S., Wotto, M., & Bélanger, P. (2018). E-learning, M-learning and D-learning: Conceptual definition and comparative analysis. *E-Learning and Digital Media, 15*, 191–216. https://doi.org/10.1177/2042753018785180

Lai, C.-L., & Hwang, G.-J. (2016). A self-regulated flipped classroom approach to improving students' learning performance in a mathematics course. *Computers & Education, 100*, 126–140. https://doi.org/10.1016/j.compedu.2016.05.006

Lassoued, Z., Alhendawi, M., & Bashitialshaaer, R. (2020). An exploratory study of the obstacles for achieving quality in distance learning during the COVID-19 pandemic. *Education Sciences, 10*(9), 232. https://doi.org/10.3390/educsci10090232

Lee, J., Lim, C., & Kim, H. (2017). Development of an instructional design model for flipped learning in higher education. *Educational Technology Research and Development, 65*(2), 427–453. https://doi.org/10.1007/s11423-016-9502-1

Lo, C. K., Hew, K. F., & Chen, G. (2017). Toward a set of design principles for mathematics flipped classrooms: A synthesis of research in mathematics education. *Educational Research Review, 22*, 50–73. https://doi.org/10.1016/j.edurev.2017.08.002

Lo, C. K., Lie, C. W., & Hew, K. F. (2018). Applying "First Principles of Instruction" as a design theory of the flipped classroom: Findings from a collective study of four secondary school subjects. *Computers & Education, 118*, 150–165. https://doi.org/10.1016/j.compedu.2017.12.003

Lopes, A. P., & Soares, F. (2018). Perception and performance in a flipped Financial Mathematics classroom. *International Journal of Management Education, 16*(1), 105–113. https://doi.org/10.1016/j.ijme.2018.01.001

Lundin, M., Rensfeldt, A. B., Hillman, T., Lantz-Andersson, A., & Peterson, L. (2018). Higher education dominance and siloed knowledge: A systematic review of flipped classroom research. *International Journal of Educational Technology in Higher Education*. https://doi.org/10.1186/s41239-018-0101-6

Maag, M. (2004). The effectiveness of an interactive multimedia learning tool on nursing students' math knowledge and self-efficacy. *Computers Informatics Nursing, 22*(1), 26–33. https://doi.org/10.1097/00024665-200401000-00007

Makri, K., & Kynigos, C. (2007). The role of blogs in studying the discourse and social practices of mathematics teachers. *Educational Technology & Society, 10*(1), 73–84.

Martin, T. (2009). A theory of physically distributed learning: How external environments and internal states interact in mathematics learning. *Child Development Perspectives, 3*(3), 140–144. https://doi.org/10.1111/j.1750-8606.2009.00094.x

Mas-Tur, A., Kraus, S., Brandtner, M., Ewert, R., & Kürsten, W. (2020). Advances in management research: A bibliometric overview of the Review of Managerial Science. *Review of Managerial Science, 14*, 933–958. https://doi.org/10.1007/s11846-020-00406-z

Muritala, B. A., Sánchez-Rebull, M., & Hernández-Lara, A. (2020). A bibliometric analysis of online reviews research in tourism and hospitality. *Sustainability, 12*, 9977. https://doi.org/10.3390/su12239977

OECD. (2007). PISA 2006: Science competencies for tomorrow's world (Volume 1: Analysis). *OECD*. https://doi.org/10.1787/9789264040014-en

OECD. (2010). PISA 2009 results: What students know and can do: Student performance in reading, mathematics and science (Volume I). *OECD*. https://doi.org/10.1787/9789264091450-en

OECD. (2014). PISA 2012 results: What students know and can do (Volume I, Revised edition, February 2014): Student performance in mathematics, reading and science. *OECD*. https://doi.org/10.1787/9789264208780-en

OECD. (2016). PISA 2015 results (Volume I): Excellence and equity in education. *OECD*. https://doi.org/10.1787/9789264266490-en

OECD. (2019). PISA 2018 results (Volume I): What students know and can do. *OECD*. https://doi.org/10.1787/5f07c754-en

Okubo, Y. (1997). Bibliometric indicators and analysis of research systems: Methods and examples. *OECD Science, Technology and Industry Working Papers 1997/01*. https://doi.org/10.1787/208277770603

Özkaya, A. (2018). Bibliometric analysis of the studies in the field of mathematics education. *Educational Research and Reviews, 13*, 723–734. https://doi.org/10.5897/ERR2018.3603

Özyurt, Ö., Özyurt, H., & Baki, A. (2013b). Design and development of an innovative individualized adaptive and intelligent e-learning system for teaching–learning of probability unit: Details of UZWEBMAT. *Expert Systems with Applications, 40*(8), 2914–2940. https://doi.org/10.1016/j.eswa.2012.12.008

Özyurt, Ö., Özyurt, H., Baki, A., & Güven, B. (2013a). Integration into mathematics classrooms of an adaptive and intelligent individualized e-learning environment: Implementation and evaluation of UZWEBMAT. *Computers in Human Behavior, 29*(3), 726–738. https://doi.org/10.1016/j.chb.2012.11.013

Perianes-Rodriguez, A., Waltman, L., & van Eck, N. J. (2016). Constructing bibliometric networks: A comparison between full and fractional counting. *Journal of Informetrics, 10*(4), 1178–1195. https://doi.org/10.1016/j.joi.2016.10.006

Perrotta, C., & Williamson, B. (2018). The social life of Learning Analytics: Cluster analysis and the "performance" of algorithmic education. *Learning Media and Technology, 43*(1), 3–16. https://doi.org/10.1080/17439884.2016.1182927

Pritchard, A. (1969). Statistical bibliography or bibliometrics. *Journal of Documentation, 25*, 348–349.

Ramirez, M. C., & Rodriguez Devesa, R. A. (2019). A scientometric look at mathematics education from Scopus database. *The Mathematics Enthusiast, 16*(1), 37–46.

Recker, M. M., Dorward, J., & Nelson, L. M. (2004). Discovery and use of online learning resources: Case study findings. *Educational Technology & Society, 7*(2), 93–104.

Sahin, A., Cavlazoglu, B., & Zeytuncu, Y. E. (2015). Flipping a college calculus course: A case study. *Educational Technology & Society, 18*(3), 142–152.

Sarrafzadeh, A., Alexander, S., Dadgostar, F., Fan, C., & Bigdeli, A. (2008). "How do you know that I don't understand?" A look at the future of intelligent tutoring systems. *Computers in Human Behavior, 24*(4), 1342–1363. https://doi.org/10.1016/j.chb.2007.07.008

Small, H. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents. *Journal of the American Society for Information Science, 24*, 265–269.

Steenbergen-Hu, S., & Cooper, H. (2013). A meta-analysis of the effectiveness of intelligent tutoring systems on K-12 students' mathematical learning. *Journal of Educational Psychology, 105*(4), 970–987. https://doi.org/10.1037/a0032447

Steen-Htheim, A. T., & Foldnes, N. (2018). A qualitative investigation of student engagement in a flipped classroom. *Teaching in Higher Education, 23*(3), 307–324. https://doi.org/10.1080/13562517.2017.1379481

Sun, Z., Xie, K., & Anderman, L. H. (2018). The role of self-regulated learning in students' success in flipped undergraduate math courses. *Internet and Higher Education, 36*, 41–53. https://doi.org/10.1016/j.iheduc.2017.09.003

Sweileh, W. M., Wickramage, K., Pottie, K., Hui, C., Roberts, B., Sawalha, A. F., & Zyoud, S. H. (2018). Bibliometric analysis of global migration health research in peer-reviewed literature (2000–2016). *BMC Public Health, 18*(1), 777. https://doi.org/10.1186/s12889-018-5689-x

Talib, M. A., Bettayeb, A. M., & Omer, R. I. (2021). Analytical study on the impact of technology in higher education during the age of COVID-19: Systematic literature review. *Education and Information Technologies*. https://doi.org/10.1007/s10639-021-10507-1

Tartavulea, C. V., Albu, C. N., Albu, N., Dieaconescu, R. I., & Petre, S. (2020). Online teaching practices and the effectiveness of the educational process in the wake of the COVID-19 pandemic. *Amfiteatru Economic, 22*(55), 920–936. https://doi.org/10.24818/EA/2020/55/920

Templelaar, D. T., Niculescu, A., Rienties, B., Gijselaers, W. H., & Giesbers, B. (2012). How achievement emotions impact students' decisions for online learning, and what precedes those emotions. *Internet and Higher Education, 15*(3), 161–169. https://doi.org/10.1016/j.iheduc.2011.10.003

Tibaná-Herrera, G., Fernández-Bajón, M.-T., & De-Moya-Anegón, F. (2018). Output, collaboration and impact of e-learning research: Bibliometric analysis and visualizations at the country and institutional level (Scopus 2003–2016). *Profesional De La Información, 27*(5), 1082–1096. https://doi.org/10.3145/epi.2018.sep.12

Trenholm, S., & Peschke, J. (2020). Teaching undergraduates mathematics fully online: a review from the perspective of communities of practice. *International Journal of Educational Technology in Higher Education*. https://doi.org/10.1186/s41239-020-00215-0

UNESCO. (2020a, March 19). Half of world's student population not attending school: UNESCO launches global coalition to accelerate deployment of remote learning solutions. Retrieved May 9, 2021, from https://en.unesco.org/news/half-worlds-student-population-not-attending-school-unesco-launches-global-coalition-accelerate

UNESCO. (2020b, April 29). 1.3 billion learners are still affected by school or university closures, as educational institutions start reopening around the world, says UNESCO. Retrieved May 9, 2021, from https://en.unesco.org/news/13-billion-learners-are-still-affected-school-university-closures-educational-institutions

van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics, 84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

van Raan, A. F. J. (2004). Measuring Science. In H. F. Moed, W. Glänzel, & U. Schmoch (Eds.), *Handbook of Quantitative Science and Technology Research.* Springer.

Walker, A. (2012). Comparing technology-related teacher professional development designs: A multilevel study of teacher and student impacts. *Educational Technology Research and Development, 60*(3), 421–444. https://doi.org/10.1007/s11423-012-9243-8

Waltman, L. (2016). A review of the literature on citation impact indicators. *Journal of Informetrics, 10*(2), 365–391. https://doi.org/10.1016/j.joi.2016.02.007

Walton, G., & Hepworth, M. (2011). A longitudinal study of changes in learners' cognitive states during and following an information literacy teaching intervention. *Journal of Documentation, 67*(3), 449–479. https://doi.org/10.1108/00220411111124541

Wang, J., & Antonenko, P. D. (2017). Instructor presence in instructional video: Effects on visual attention, recall, and perceived learning. *Computers in Human Behavior, 71*, 79–89. https://doi.org/10.1016/j.chb.2017.01.049

Wang, T. H. (2014). Developing an assessment-centered e-Learning system for improving student learning effectiveness. *Computers & Education, 73*, 189–203. https://doi.org/10.1016/j.compedu.2013.12.002

Wanli, X., Rui, G., Eva, P., & Sean, G. (2015). Participation-based student final performance prediction model through interpretable Genetic Programming: Integrating learning analytics, educational data mining and theory. *Computers in Human Behavior, 47*, 168–181. https://doi.org/10.1016/j.chb.2014.09.034

WHO (2021, January 30). WHO Director-General's statement on IHR Emergency Committee on Novel Coronavirus (2019-nCoV). Retrieved May 9, 2021, from https://www.who.int/director-general/speeches/detail/who-director-general-s-statement-on-ihr-emergency-committee-on-novel-coronavirus-(2019-ncov

Wilson, S. G. (2013). The flipped class: A method to address the challenges of an undergraduate statistics course. *Teaching of Psychology, 40*(3), 193–199. https://doi.org/10.1177/0098628313487461

Zhu, M., Guo, C.-Y., Hou, A.Y.-C., & Chiu, M.-S. (2021). Graduate employment in higher education: Applying bibliometrics to world-system theory. *Journal of Education and Work, 34*(3), 356–372. https://doi.org/10.1080/13639080.2021.1922621

Zupic, I., & Cater, T. (2015). Bibliometric methods in management and organization. *Organizational Research Methods, 18*(3), 429–472.

Zurita, G., & Nussbaum, M. (2004). Computer supported collaborative learning using wirelessly interconnected handheld computers. *Computers & Education, 42*(3), 289–314. https://doi.org/10.1016/j.compedu.2003.08.005