



Trends and Research on the Teaching and Learning of Mathematics in Higher Education Institutions Through Mobile Learning

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ABSTRACT

In the last decade, the use of mobile devices has been intensified at all educational levels. They have recently been included in the design of strategies and methodologies that contribute to mathematics education, especially in the resolution of mathematical problems. In this research, a systematic review is carried out on the use of mobile devices in the teaching and learning of mathematics in higher education institutions, with the purpose of identifying advantages, limitations, effectiveness, trends, and characteristics that have been presented in the last 10 years. Thirty articles were selected between 2011 and 2021 in 15 indexed journals with three specialized on mobile learning. The insights found allow us to see the current state of the use of mobile learning in the teaching and learning of mathematics in higher education institutions and evolution in new research in mathematics educational scenarios.

KEYWORDS

Adaptive Learning, Advantages of Mobile Learning, Mathematical Problem Solving, Mobile Learning in Mathematics, Problem Solving Methodologies, Systematic Review

INTRODUCTION

The teaching of mathematics in higher education institutions (HEIs), presents a challenge for educators in the process of designing, implementing, and innovating new didactic or pedagogical proposals. Some options put the use of mobile devices in their proposals due to their benefits and positive results in the learning processes of the students. Due to the steep growth in access to these devices and advantages such as immediacy, ubiquity, and situated learning, among others, their implementation

DOI: 10.4018/IJMBL.313596

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by the academic community in science and mathematics education has been intensified (Almeida & Araújo, 2016).

In the educational field, many students have mobile devices at their fingertips. This has led to the predominance of the design and development of mobile educational applications as support for teaching and learning processes within the work of researchers and teachers (Baek & Guo, 2019). Additionally, the possibility of carrying out intervention processes outside the classroom, anytime and anywhere, places mobile learning (m-learning) at the top of educational research (Ozcelik & Acarturk, 2011).

In the context of mathematics, m-learning has been very useful and has provided alternatives to traditional classes (Güler et al., 2021). Research shows that students' perception, motivation, and engagement are coupled with their attitudes toward mathematics and academic achievement (Singh et al., 2002; Fast et al., 2010). This can be achieved through strategies guided by mobile devices because, according to Traxler (2018), these devices encourage the exchange of ideas, and build spaces to share and develop knowledge, elements that can be fundamental to generating positive attitudes and providing approaches to overcoming the difficulties of mathematics and the resolution of mathematical problems (understanding of concepts, application, and contextualization of learning).

By conceiving problem-solving in mathematics as the performance of mathematical tasks that have the potential to provide intellectual challenges to foster the development of skills and promote understanding and mathematical reasoning (Novita, 2012), researchers seek to mitigate the difficulties presented through the inclusion of scenarios with learning activities mediated by educational mobile applications, which support the teaching of problem-solving in mathematics and have an impact on improving the understanding and contextualization of learning in students (Rojas, et al., 2020; Arifin, et al., 2021).

In this paper, different scientific publications were analyzed in which mobile learning is articulated in the teaching and learning of mathematics in HEIs, with a particular interest in the development of problem-solving skills. The search was carried out in the main collection of the Web of Science (WOS) database and in specialized mobile learning journals. This database contains high-impact scientific documentation worldwide, which allows a rigorous and assertive systematization process to be carried out. This process is informed by the proposal of Bacca, Baldiris, Fabregat and Graf (2014) regarding the use and trends of augmented reality in education and adopts the principles of systematic review from Kitchenham (2004), which are planning, review and review report.

The literature search is carried out by posing five research questions, which guide the systematic review and subsequently help define search categories and subcategories, together with the inclusion and exclusion criteria for the analysis, coding, and selection of articles. These elements help to find information about the purposes, advantages, limitations, and effectiveness of m-learning in the teaching and learning of mathematical problem-solving in HEIs. Likewise, the adaptation and personalization offered by mobile devices in mathematics education is analyzed. In addition, it addresses the approaches, strategies, models, or methodologies of teaching or learning that support mobile learning. Elements of the research methodology used in each selected article are also shown, such as: research method, sample, data collection method, and time dimension.

This article is divided into three sections which are ordered as follows: The first section describes some related work, the second section presents the research questions addressed in this systematic review, and the third section describes the methodological design of the study, presenting results, discussion of the findings, trends, vision towards the future, and conclusions.

RELATED WORK

Constant updating and the incorporation of tools such as: smart phones, tablets, iPads, electronic agendas, smart watches, and video game consoles, among others, in all sectors, have led to effective integration at educational levels. In recent decades, and especially in the educational field, the

use of these devices has had a greater relevance and impact on the design of strategies, models or methodologies for teaching and learning (Winters, 2013).

Thus, some authors have focused their interest on the rigorous systematization of the use of mobile devices in educational settings. Sung, Chang and Liu (2016), carried out a meta-analysis and research synthesis of 110 articles in experimental and quasi-experimental journals on the effects of articulated mobile devices in education. The need for the development of well-crafted instructional designs was identified to take more advantage of the educational benefits of mobile learning. For this, some triggering elements were proposed, such as the use of the pedagogical effects of mobile devices through teaching and learning scenarios, the improvement of the quality of the experimental design for mobile intervention, and the empowerment of education professionals through the benefits offered by mobile devices, software, and pedagogical design.

Some studies have shown the impact that mobile learning has on academic performance in higher education (Crompton & Burke, 2018). Others have shown the effectiveness in the attitude and interest towards mathematics. For example, the findings of Hwang and Tsai (2011) and Almeida and Araújo (2016) see positive results in terms of interest, attitude, perception, and motivation towards mathematics with the use of mobile devices. It was also expected that its use had a significant impact on the student's learning domain.

In the review proposed by Güler, Bütüner, Danişman and Gürsoy (2021), 22 articles were selected from the WOS, Academic Search Complete, Education Resources Information Center (ERIC), EBSCO, JSTOR, ScienceDirect, Taylor & Francis databases, between the years 2010 and 2020. The main intention of this study was to test the effect of mobile learning on academic performance in mathematics. In addition, other important elements related to the flexibility, access and personalization of environments guided by m-learning are deduced. Here it is inferred that the effectiveness of mobile learning is not related to the teacher, since it focuses on the importance of mobile media. Thus, due to the advantages offered by m-learning, work outside the classroom becomes promising, allowing the role of the teacher to be smaller compared to traditional dynamics.

However, the research carried out by Crompton and Burke (2015, 2017) shows a review from 2000 to 2014, in which 36 documents on mobile learning applied to the area of mathematics were selected, and one of their findings is that a large number of studies were conducted in formal educational settings. Other relevant results of this study were: research on mobile learning is geographically dispersed, most studies focused on evaluating the effectiveness of mobile learning, and the most used research methods were experimental and case studies.

Within the trends of the systematizations proposed, studies were projected on the use of mobile learning that significantly affects the learning of mathematics, reformulating traditional classes and innovating on the practices of teachers. In accordance with Pandey and Singh (2015), m-learning has multiple potentialities for the appropriation of mathematics that make it preferable to the traditional classroom.

RESEARCH QUESTIONS

- What are the uses, purposes, advantages, limitations, effectiveness, and possibilities of mobile devices in the teaching and learning of mathematics in HEIs?
- What are the teaching and learning strategies or methodologies for problem solving in areas of mathematics and engineering in HEIs supported by mobile learning?
- What approaches, methodologies, strategies, or pedagogical models have been involved with mobile learning for the teaching of mathematics in HEIs?
- Has the inclusion of adaptive or personalized processes been considered in mathematics learning scenarios through mobile learning?

- What aspects of the research methodology are considered for the evaluation of the scenario mediated by mobile learning in HEIs?

Methodology

The methodological design is adapted from the ideas of Kitchenham (2004) to carry out systematic reviews, which defines the reviews in three major phases: planning, review, and review report (Figure 1).

Adapted from Kitchenham (2004)

PLANNING

Selection of Journals

For the selection of journals, a method similar to that used by Bacca, Baldiris, Fabregat and Graf (2014) was carried out, where the 5 journals with the highest H5 index in the category of Educational Technology in Google Scholar were identified, with a subsequent impact factor analysis (JCR) in the WOS Database. This is because WOS contains a more general subcategory of Social Sciences, which is Education and Educational Research, and does not have a specific subcategory of educational technology. The five journals provided by Google Scholar are shown in Table 1:

This initial analysis provided a first filter with educational technology journals corresponding to the Education and Educational Research subcategory.

This analysis was done through the impact factor of each journal, where two were selected for each group, those with the highest impact index (JCI), obtaining a final list of ten journals (GF), the most representative corresponding to educational technology (as included in the first part of Table 2). This factor was verified in the Scimago Journal & Country Rank (SJR) and Scopus (SNIP) indicators, obtaining similar results.

Figure 1. Methodological phases for the systematic review

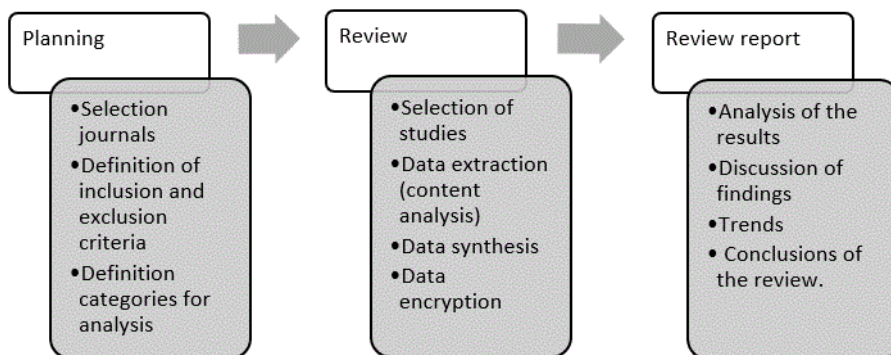


Table 1. Top 5 Google Scholar journals

| Journal | H5 |
|---|-----|
| Computers & Education | 109 |
| British Journal of Education Technology | 62 |
| The Internet and Higher Education | 59 |
| Journal of Educational Technology & Society | 54 |
| Education and information Technologies | 52 |

Another review was made of journals from the Journal Citation Reports Science Citation Index (JCR SCIE), which do not properly belong to the category of educational technology but present a relationship in citations with some journals of the mentioned category. The following list was generated, initially coming from a group called G6:

- Knowledge-based systems
- Expert systems with applications
- IEEE Intelligent Systems
- IEEE ACCESS
- IEEE TRANSACTIONS ON EDUCATION

Finally, other journals specifically related to m-learning are considered, with articles indexed in Scopus, these are:

- International Journal of Interactive Mobile Technologies.
- International Journal of Mobile and Blended Learning.
- International Journal of Mobile Learning and Organization.

Inclusion and Exclusion Criteria

Based on the research questions, general criteria defining the period of the study and the typology of relevant studies were considered. Consequently, we define the following criteria:

General criteria:

- Studies or research published between 2011 and 2021.
- Research that reports on teaching and learning strategies for mathematics mediated by m-learning in HEIs.

Specific criteria:

- Studies that report advantages, disadvantages, possibilities, limitations, characteristics, uses, challenges, and effectiveness of m-learning in mathematics teaching and learning environments in higher education.
- Studies that show the approach, methodology, strategy, or pedagogical model involved with m-learning for the teaching of mathematics in HEIs.
- Studies that show teaching and learning strategies or methodologies for problem solving in areas of mathematics and engineering in HEIs supported by m-learning.
- Studies that describe the inclusion of adaptive or personalized processes in mathematics learning scenarios through m-learning.
- Studies that describe the evaluation methods of methodologies mediated by m-learning and learning outcomes by students in mathematics in HEIs.

The following exclusion criteria were defined and studies meeting these criteria were therefore excluded:

- Studies not identified as “Articles” in the selected journals (for example, book reviews, books, information from editorial publications, book chapters, among others).
- Studies related to m-learning in mathematics education at the primary and secondary levels or in populations under 16 years of age.

- Studies that demonstrate the use of mobile devices in the teaching and learning of areas other than those related to mathematics in HEIs.

Categories for Analysis

During this study, some defined categories and subcategories emerged from the research questions. This allowed the grouping of information for subsequent coding and analysis.

1. What are the uses, purposes, advantages, limitations, effectiveness, and possibilities of mobile devices in the teaching and learning of mathematics in higher education (educational settings)?
 - Purposes informed about the use of m-learning.
 - Reported advantages of implementing m-learning.
 - Reported limitations of the use of m-learning.
 - Reported effectiveness of the use of the strategy used.
2. What approaches, methodologies, strategies, or pedagogical models have been involved with m-learning for the teaching of mathematics in HEIs?
 - Type of pedagogical model articulated in the scenario.
 - Approaches, methodologies, teaching and learning strategies used in the scenario.
3. What are the teaching and learning strategies or methodologies for problem solving in areas of mathematics and engineering in HEIs supported by m-learning?
 - Methodology for problem solving
4. Has the inclusion of adaptive or personalized processes been considered in mathematics learning scenarios through m-learning?
 - Type of adaptation process.
 - Type of user modeling.
5. What aspects of the research methodology are considered for the evaluation of the scenario mediated by m-learning in HEIs?
 - Research sample.
 - Research method.
 - Time dimension.
 - Data collection method.

REVIEW

Selection of Studies

For the selection of studies, the following initial keywords for the search process were identified and selected: mathematics, mathematics education, higher education, and mobile learning.

Considering the inclusion and exclusion criteria, 30 articles were found in the journals selected for the search (21 correspond to the list G3, 3 correspond to the G6 list, and 4 to specialized journals with articles indexed in Scopus) (see Table 2). The complete reading of each article was carried out and the data coding process was carried out considering the previously defined categories.

Data Extraction, Synthesis, and Encoding

From a record based on the categories and subcategories of analysis, the data obtained were extracted, synthesized, and coded.

From a first observation in the time window of analysis, there is evidence of an increase in the use of mobile devices in the last five years at all educational levels. This leads to the appreciation that several researchers are studying the advantages and effectiveness both in academic performance and in the learning that can be generated from the use of mobile devices, particularly in the teaching and learning of mathematics in high schools and HEIs.

Table 2. Number of articles per selected journal

| Journal | Analysis window (2011 - 2021) |
|--|-------------------------------|
| JCR – SSCI | Total 21 |
| Computer & Education | 10 |
| Internet and Higher Education | 0 |
| International Journal of Computer-supported Collaborative Learning | 0 |
| International Journal of Educational Technology in Higher Education | 1 |
| British Journal of Educational Technology | 1 |
| Interactive Learning Environments | 1 |
| Educational Technology Research and Development | 3 |
| Educational Technology & Society | 0 |
| Australasian Journal of Educational Technology | 2 |
| Education and Information Technologies | 3 |
| JCR – SCIE | Total 3 |
| Knowledge-based systems | 0 |
| Expert systems with applications | 0 |
| IEEE Intelligent Systems | 0 |
| IEEE ACCESS | 2 |
| IEEE TRANSACTIONS ON EDUCATION | 1 |
| Specialized journals with documents in Scopus | Total 6 |
| International Journal of Interactive Mobile Technologies | 2 |
| International Journal of Mobile and Blended Learning | 3 |
| International Journal of Mobile Learning and Organisation | 1 |

In the area of mathematics, some studies are based on reviewing academic performance (Güler, et al., 2021), others focus on replacing activities that can normally be carried out in traditional ways and without technology, not to enrich methodologies or didactics that affect in student learning outcomes. In the levels of students under 18 years of age, the use of mobile devices was more frequent, where the activities focused on the practice of mathematical procedures, language practice, practice of mathematical skills individually or personalized, and immediate or personalized feedback process monitoring (Crompton & Burke, 2020).

REVIEW REPORT

Analysis of Results and Discussion of Findings

The following section presents the findings according to the analysis carried out for each research question.

What are the uses, purposes, advantages, limitations, effectiveness, and possibilities of mobile devices in the teaching and learning of mathematics in HEIs?

Purposes and Advantages

The purpose of some research lies in evaluating the effectiveness of mobile applications, mobile platform interfaces to Learning Management Systems (LMS), and tools that are manipulated in mobile scenarios, designed to improve the preparation and learning outcomes of university students (Sommerauer & Müller, 2014; Conley, Atkinson, Nguyen & Nelson, 2020). Other studies investigate students' perceptions of mobile learning, trends, and insights into higher-order processing skills through mobile learning-mediated and problem-solving activities (Hwang, Lai, Liang, Chu, & Tsai,

2018), likewise, the purpose of reviewing the attitude toward m-learning in mathematics by students and teachers is highlighted (Fabian, Topping & Barron, 2016).

Some studies focus on determining the degree of acceptance or learning outcomes of students. One insight from this is that research that shows findings on the benefits for teachers such as continuous improvement of the design and development of scenarios guided by mobile learning is needed. That is, planning and development of learning activities, digital literacy, and the level of acceptance of m-learning by teachers. Since research in educational technology must respond to the implementation and pedagogical innovation on a regular basis, the acceptance of appropriate mobile devices and the belief in the expansion of m-learning needs to be reviewed in that way (Romero-Rodríguez, Aznar-Díaz, Hinojo-Lucena, & Gómez -García, 2020).

Advantages for the Student

The following advantages are described in the studies reviewed by the authors:

Contextualization of learning (CL), Collaborative Learning (CLL), Ubiquity (U), Situated Learning (SL), evaluation (E), Ease of use (EU), Participation (P), Interaction (IN), Autonomous Learning (AL), accessibility (A); and some of these are highlighted, both for the student and for the teacher.

Promoting CL and CLL are the most outstanding advantages in this study. One of the important findings shows that 36.6% of the studies evidence CL through mobile learning as the main advantage. Of this percentage, 83% show it with other associated advantages. For example, 6.6% of the investigations jointly show advantages such as promoting CL, CLL, SL, and facilitating IN. This shows a relatively low value compared to the many advantages that mobile learning can provide. Likewise, 6.6% of the studies associate the advantages of CLL and U. In the same way, the advantages of CL and E are presented simultaneously. While only 3.3% of the studies show the advantages of CL, E, U, P, and A and in the same way the advantages CL, CLL, SL, and P (3.3%) are presented.

This shows that CL is one of the most pronounced advantages, because the current strategies are focused on promoting in the student the development of problem-solving skills, the application of mathematical concepts, and the development of mathematical logical reasoning. In accordance with Sugden et al., (2021), this can be developed through authentic and realistic activities that encourage the student to solve problems and reflect on their own learning, in turn, that can establish connections between theory and applications in real contexts.

While the CLL has a representation of 33.3%, these investigations are also related to the advantages of SL (10%), CL (20%) and AA (3.3%). Only one document lists the CL, CLL, IN, and AA benefits together. As evidenced, the most outstanding advantages are CL and CLL. It is observed that research is betting on the efficiency of mobile learning on collaborative learning and contextualization of learning. However, some studies relate CLL with other advantages such as Interaction (IN), participation (P) and autonomous learning (AA). CLL has been contributing to improving study habits and increasing both knowledge and confidence in the ability to solve problems effectively, contributing to socio-cognitive results and improving academic performance (Micari & Pazos, 2021).

Advantages for the Teacher

Very few studies show advantages for the teacher (13.3%). Of this percentage, only two investigations show that the implementation of the scenario provided support for teachers as well as for students. The most accentuated advantages are the innovation in its practices, digital literacy in terms of the design of learning activities mediated by mobile devices, and the optimization of time in evaluation, qualification, feedback, and follow-up processes in students.

For example, 3.3% refer to the design of educational material and its effectiveness in pedagogical processes. The importance of constant updating by teachers regarding the design of this material is highlighted. In general, learning mediated by information and communication technologies (ICT) provides the advantage of knowing about the theory and principles that govern the design

and development of multimedia resources or tools. Some research shows the application of certain characteristics based on the principles proposed by Mayer (2014) for the design of multimedia learning. Among these, the characteristics of a significant design, a design of cognitive capacity of the student, and a friendly design and appearance stand out. These principles are mainly used to meet the needs of the student's cognitive thinking (Chiu & Churchill, 2015).

In the evaluation processes, in addition to attributing advantages related to immediate feedback and follow-up by the teacher, knowledge is promoted about the perceptions of students regarding the evaluation and the influence of methods used in their mathematical training (Iannone & Simpson, 2013). On the other hand, it is important to know what students think about their learning of mathematics mediated by technological tools. This perception allows planning and rigorous use of the benefits provided by educational technology (Acosta-Gonzaga & Walet, 2018), in this particular case, mobile devices.

More appreciation is projected on the advantages that m-learning is promoting in teaching practices. However, many of the teaching proposals depend on educational programs and the adoption of technology in these practices. According to Romero-Rodríguez, et. al. (2020), this adoption should not be limited to the simple use of technology to attract the attention of students, but should be accompanied by good teaching practices that are referenced and replicated by other teachers in order to improve their learning activities with the use of these technologies.

Limitations and Effectiveness

Several limitations have been evidenced in the selected investigations. The most pronounced limitation has to do with the choice of the sample (Table 3). Since the samples are not representative, it is possible that the investigations do not produce results that are generalizable and applicable to other disciplines. This is partly due to the possible intervention of other variables (for example, the students' attitude towards mathematics) that can obstruct the development of the research objectives.

Due to the short time of intervention by the student during the development of the research and activities carried out, it is possible that short-term learning is generated, and it is difficult for long-term learning to be promoted. To counteract this, it is suggested that contextualization and application of knowledge through problem-solving be considered within the designed activities (Sommerauer, & Müller, 2014). However, a balance must be managed in the realization and design of the proposals for the resolution of problems within the study plans, since this has generated more workloads that demand more time than contemplated for teachers in terms of preparation, feedback, and guidance to students (Blackburn, 2017).

The effectiveness evidenced by the selected documents is related to the following subcategories: academic performance, learning outcomes, student participation, development of mathematical skills, attitude, and motivation toward the study of mathematics through mobile learning. As indicated in table 4, gains in learning using mobile devices as facilitating media predominates.

In this review, six documents show learning gain and five participation as the best results obtained. Only one of them shows the exclusivity that the research led to better learning results. From this, it can be inferred that the participation and identification of the student as a central subject in the

Table 3. Main limitations

| Limitation | Number studies | Percentage value (%) |
|---------------------------|----------------|----------------------|
| Non-representative sample | 9 | 30 |
| Short term learning | 2 | 6.6 |
| Workloads | 2 | 6.6 |
| Temporality | 1 | 3.3 |
| Control by the teacher | 1 | 3.3 |
| Ethical limitations | 1 | 3.3 |

Table 4. Efficacy of mobile learning in mathematics

| Effectiveness | Number studies | Percentage value (%) |
|-------------------------|----------------|----------------------|
| Learning gain | 6 | 20 |
| Skill development | 5 | 16.6 |
| Participation | 5 | 16.6 |
| Attitude and motivation | 5 | 16.6 |
| Academic performance | 2 | 6.6 |
| Cognitive processing | 1 | 3.3 |
| Learning communities | 1 | 3.3 |
| They do not report | 5 | 16.6 |

educational setting contributes to the learning of mathematics. This is also due to the high interaction between peers, promoted through collaborative activities and mediated by m-learning (Nova et al. 2005; Spikol & Otero 2012).

Some scenarios show that participation and learning is possible with the intervention of mobile applications based on Augmented Reality (AR) or platforms that articulate Artificial Intelligence as a means of support. This facilitates the student's approach with real or simulated scenarios, effective in the application of mathematical concepts, since AR brings positive effects on learning in students with low prior knowledge (Conley, et al., 2020), and artificial intelligence favors the implementation of personalized mathematics teaching and learning systems, especially through formative assessments in simulation environments and problem-solving (Reimann, Kickmeier-Rust & Albert, 2013).

The gain in attitude, motivation, and academic performance are other more significant reports. M-learning is expected to encourage the performance of activities and favor academic performance with respect to mathematics courses offered in the first semesters at HEIs. 6.6% of the investigations show the effectiveness in terms of academic performance and 13.3% highlight the increase in attitude on the part of the students in the solution of the proposed learning activities. This is because these investigations relate attitude and motivation to the level of interaction and participation mentioned above, while academic performance is connected to learning outcomes and the gains that occur in them.

The implementation of online communities becomes increasingly efficient in the construction of knowledge. Social networks and online digital platforms have facilitated the development of these, predominating the recognition of the student's digital context as essential variables for the functioning of an online community and the inclusion of teacher participation as a support for learning (Blayone, Barber, DiGiuseppe, & Childs, 2017). Only 6.6% of studies show how effective m-learning can be in building online learning communities.

Finally, among the outstanding efficiencies is the development of mathematical skills, especially those required for problem-solving. This is because the use of educational technology has had a positive impact on the development of interdisciplinary skills, research and problem-solving, especially in engineering students (Huang, et al., 2021), as well as the integration of evaluation components. Simulation and problem-solving environments are effective for the development of these skills (Mislevy, 2011). The following research question expands on the work and results around the development of problem-solving competence in HEIs.

Teaching and Learning Strategies or Methodologies for Problem-Solving in Areas of Mathematics and Engineering in HEIs Supported by M-Learning

For the teaching and learning of mathematics, and problem-solving in particular, several methods or strategies have been proposed that complement m-learning. Problem-based learning (PBL), flipped classroom, situated learning and inquiry learning are some evidenced in the consulted studies. PBL, situated learning and online learning are among the prominent methods with 13.3% each, while

collaborative learning with 20% leads the list and is the most used. Others are inquiry learning and flipped classroom with an implementation of 6.6% each.

For this category, studies that used some empirical model or guide for problem-solving were selected. Of the consulted investigations, it is shown that 46.6% mention problem-solving as a strategy for teaching mathematical concepts and the articulation of these with applications in real contexts. 6.6% show the Polya model (1973) as a route to solve mathematical problems (comprehension, design of a plan, execution of a plan, analysis of results).

Among the findings in other investigations, in each phase proposed by Polya there are challenges on the part of the students (Tambychik, Meerah & Aziz, 2010; Phonapichat, Wongwanich & Sujiva, 2014). These usually occur when concepts, procedures and attitudes are related. For example, in relation to concepts there are difficulties related to functions, problems where the derivative is contextualized, among others. In relation to the procedures, the greatest difficulties arise with the understanding of the mathematical text and the transposition of a problem into mathematical language. At the attitudinal level, there are difficulties related to low interest in the course, little participation and a tendency to distractions generated by digital content.

However, the research consulted presents different evidence on the positive influence of the use of mobile devices in problem-solving and the relationship that exists with elements such as interaction (Fuad, Deb, Etim & Gloster, 2018), participation (Lai & Hwang, 2014) and collaborative discussions through situated scenarios (Hou, 2011). This motivates the development of activities that integrate these elements in search not only of problem-solving, but also encourages reflection on their learning, which finally manages to establish significant connections between theory and real applications.

One article shows the importance of evaluation in the development of problem-solving skills through an adaptive tutoring system using artificial intelligence mechanisms (Reimann, Kickmeier-Rust & Albert, 2013). The authors mentioned four forms of evaluation of this competence described by Jonassen (2011): the evaluation of (1) knowledge about problem schemes, (2) performance in problem-solving, (3) cognitive abilities (representation of problems, reasoning causal, among others), and (4) the ability to construct arguments. Of these, they consider (2) for the design of an evidence-based formative evaluation.

More work is expected to be carried out on the evaluation of this competence mediated by artificial intelligence systems, adopting diagnostics, training, and formative evaluations and investigating the four components proposed by Jonassen and the phases proposed by Polya for problem-solving. Through the development of these studies, in addition to improving the teaching and learning of problem-solving, they tend to generate interactive and mobile spaces, important for the advances and challenges that this technological society demands (Arifin, et al., 2021).

For example, Fuad et al. (2018), developed a mobile application they call the Mobile Response System (MRS), which facilitates the execution and evaluation of interactive problem-solving activities during class through the mobile device. This scenario involves the student with various visual representations and instantaneous feedback on their answers, thus making a more adaptive, active, and rigorous problem-solving learning process.

To answer the question: **What approaches, methodologies, strategies, or pedagogical models have been involved with mobile learning for the teaching of mathematics in HEIs?** Table 5 shows a summary where collaborative learning and PBL are highlighted as the main models articulated with the teaching and learning of mathematics and mobile learning. Others are situated learning, student-centered learning, game-based learning, and the flipped classroom, among others.

Constructivism is the most predominant pedagogical model in the teaching and learning of mathematics mediated by mobile devices in HEIs (33.3%). This finding is because the characteristics that support it, such as promoting the development of skills for cooperative, independent and autonomous work, which encourage cognitive work and the construction of knowledge (Wadsworth, 1996), are encouraged through mobile learning.

Table 5. Approaches that complement mobile learning in mathematics

| Approaches | Number studies | Percentage value (%) |
|---|----------------|----------------------|
| Collaborative learning | 6 | 20 |
| Online learning | 5 | 16.6 |
| Problem-based learning (PBL) | 4 | 13.3 |
| Situated Learning | 4 | 13.3 |
| Flipped classroom | 2 | 6.6 |
| STEM | 2 | 6.6 |
| Cognitive theory of multimedia learning | 2 | 6.6 |
| Student centered learning | 2 | 6.6 |
| Evidence-focused evaluation | 2 | 6.6 |
| Game based learning | 2 | 6.6 |
| Active learning | 1 | 3,3 |
| Inquiry learning | 1 | 3,3 |
| Deep learning | 1 | 3,3 |
| Case study | 1 | 3,3 |
| Autonomous Learning | 1 | 3,3 |

In that order of ideas, the teaching of mathematics from the constructivist approach has revealed better results and learning experiences in higher education (Abdulwahed, Jaworski, & Crawford, 2012). From this same approach, methodologies such as problem-based learning (13.3%) and collaborative learning (20%) are commonly used in the teaching of mathematics, particularly problem solving. The latter as a mechanism for the assimilation and understanding of concepts. In addition, Chang (2011) states that one of the relevant characteristics of constructivist pedagogies is the contextualization of learning, with authentic and real scenarios, advantages offered by mobile learning.

Similarly, the selected investigations show the ease of involving mobile devices with various approaches in mathematics teaching and learning scenarios. For example, STEM approaches have been helped by mobile devices for the development of interdisciplinary collaborative learning and online formative assessments. Which propose systematic interdisciplinary engineering models through cutting-edge technologies, practical projects, and real-world simulations, among others (Acosta-Gonzaga, & Walet, 2018; Huang et al., 2021).

Within this category, there are subcategories related to the area of mathematics most taught through the aforementioned approaches and the most used technological resources or tools in these processes. The area of mathematics with the highest participation in scenarios guided by mobile devices is Differential Calculus with approximately 20% and pre-calculus or basic mathematics with 16.6%, followed by areas such as Algebra, Statistics, Mathematical Logic, Calculus II and Differential Equations.

This participation shows that the investigations are being developed mainly in courses of the first semesters and even in level or pre-university courses. The foregoing due to the need to promote the development of essential mathematical skills in other disciplines, reduce loss rates and increase the understanding of basic mathematical concepts (Tang & Yu, 2018).

These scenarios are mainly based on the development of mobile applications and the design of digital content mediated by specialized platforms (Chuang, Jou, Lin, & Lu, 2015; Azevedo, Pereira, Fernandes & Pacheco 2021), and interactive (LMS) such as Blackboard and Moodle, some with the support of software such as GeoGebra, Maple, Mathematica and online forms made with tools provided by Google and social networks.

The use of resources such as mobile applications has led to great achievements in learning outcomes and academic performance in mathematics in the first higher education courses (Tang & Yu, 2018; Rojas, et al., 2020; Arifin, et al., 2021). For example, the Geogebra application, due to its powerful resources and access, has become a catalyst for mobile scenarios and a potential enhancer for practicums, class laboratories and collaborative work (Rueda, 2021). Likewise, Takači, Stankov

and Milanovic (2015), Tatar and Zengin (2016) and Ponce Campuzano, Matthews, and Adams (2018), indicate that the use of GeoGebra can significantly improve learning outcomes in mathematics. Another case is that of Nygren, et al. (2012), who used the UFractions application to solve real life problems through interactive games.

Table 6 organizes three large groups of tools commonly used in the research reviewed, educational applications (app), platforms (LMS), and external resources such as online software and multimedia resources, among others.

Some studies show the efficiency of the integration of mobile devices with various tools offered by multimedia for the teaching and learning of mathematics. For example, Kay and Kletskin (2012) show the influence of podcasts on learning mathematical concepts and problem solving. Evans, Kensington-Miller and Novak (2021) demonstrate the efficiency of online forms to improve student participation and preparation of mathematics studies (Abu-Al-Aish, Love & Hunaiti, 2012), and the development of communication skills. Andrade-Aréchiga, López and López-Morteo (2012), use the virtual object of learning (VOL) through learning units articulated in platforms, in order to overcome the difficulties of Calculus at the undergraduate level.

This shows how important the articulation of different resources is in the construction of learning activities that integrate mobile devices. In addition to promoting digitally rich scenarios in collaborative learning contexts (Blayone, Mykhailenko, VanOostveen & Barber, 2018), it favors the design and implementation of activities aimed at improving the understanding of the different ways of representing (Chen & Wu, 2020).

However, it is necessary to mention that the design of activities mediated with technology or multimedia material for mathematics education often do not contain enough rigor to affect student learning. Possibly this mishap is due to teachers' lack of knowledge of the theories and principles that govern the design of digital learning material (Blackburn, 2017). This is how the linking of technology in educational settings goes beyond knowing technical aspects, psychological principles related to the interaction between human and technology must also be reviewed (Reeves & Nass, 1996).

The analyzed studies cover a series of tools, which are articulated with mobile scenarios. There is the challenge of being able to generate our own scenarios that focus more on the development of

Table 6. Technological tools incorporated in mobile scenarios

| Resource | Usage Number |
|---|--------------|
| Platforms (LMS) | Total 8 |
| Moodle | 3 |
| Blackboard | 2 |
| Others | 4 |
| Mobile apps | Total 5 |
| App developed for the study | 5 |
| App already built | 1 |
| External resources (Social networks, Software, Hardware or media resources) | Total 10 |
| Videos | 2 |
| Calculator | 1 |
| Online forms | 2 |
| Social networks | 2 |
| Software | 2 |
| Virtual learning objects | 1 |

skills or competencies transferable to the real world, such as critical thinking and problem solving in real contexts and have less emphasis on activities that promote superficial learning and memory, with study for a test or short-term learning (Kek & Huijser 2011).

To generate the transfer of skills to the real world, Augmented Reality (AR) has been the object of study in mathematics education scenarios in HEIs. Research focuses on providing students with 3D content, since the resources offered by advances in mobile technologies such as cameras, GPS, and Internet access open up more possibilities for anyone who has at least one smartphone. In general, AR has been shown to be effective when applied to science education (Bacca, et. al., 2014).

The empirical evidence that has been gathered shows that AR has the potential to be an effective tool not only in the teaching and learning of mathematics in HEIs, but also in increasing the level of participation and interaction of students within a specific context (Conley, et. al., 2020), as well as providing scenarios to learn formal mathematics content in informal learning environments (Sommerauer & Müller, 2014).

Regarding the question, has the inclusion of adaptive or personalized processes been considered in mathematics learning scenarios through mobile learning?

Three studies were found where the characteristics of the student such as personality, performance and competence were taken into account for their classification and assignment of tasks.

Among these, a study arises where an intelligent tutorial system (ITS) was implemented to benefit students in solving problems outside the classroom. Here the flipped classroom strategy was involved to manage learning from anytime and anywhere through videos and online materials provided by the system according to their classification. This classification allowed access to a collaborative group who helped the student in their learning process (Mohamed & Lamia, 2018).

Depending on the difficulties or needs presented by the student when solving a problem situation, the system adapts to them and provides help, offering a more personalized and adaptive learning. Some of these aids are based on diagnostic evaluations that during the process become formative evaluations, maintaining an explicit model of the student's knowledge (Reimann, Kickmeier-Rust & Albert, 2013).

The results shown not only evidenced favorable benefits on learning, but also perceived a good attitude and use by the students (Chen & Wu, 2020). However, there are few works that show adaptive or personalized processes. This can occur due to the demanding times and costs for its design and development.

Not only is it necessary to pay attention to the fundamental concepts and procedures in solving a problem, but it is also essential to keep in mind the difficulties, preconceptions and learning rhythms of each student. Therefore, the call is made for methodologies that enable the design of adaptation strategies and the use of tools provided by ITS and mobile devices and that provide support in the appropriation of conceptual and symbolic structures typical of mathematics.

What aspects of the research methodology are taken into account for the evaluation of the scenario mediated by mobile learning in HEIs?

For this category, four subcategories related to the research sample (Table 7), research method (Table 8), temporality (Table 9). and data collection method were defined

35.7% of the studies discriminated against gender, on average 54% were men and 46% women. No research used an equitable sample (men - women), but in terms of their results, they mentioned general approaches for the research participants.

The ages of the sample ranged between 16 and 29 years for students and only 30% of the studies reported an average or age range of the population, where 16.6% recorded a job in students of ages ranging between 16 and 18 years old. While 6.6% were between 20 and 22 years old. Only 6.6% reported an average age of 29 years. From this it can be inferred that, even though few studies reported the ages, others indicate that they worked with first and second semester university students, which

Table 7. Sample size

| Sample size | Number of studies | Percentage value (%) |
|------------------------------------|-------------------|----------------------|
| Small sample (between 15 and 30) | 2 | 6.6 |
| Median sample (between 31 and 200) | 18 | 60 |
| Large sample (over 200) | 8 | 26.6 |
| Does not evidence the study | 2 | 6.6 |

reveals that work is being carried out with adolescent students of the first semesters of undergraduate in the HEIs that are the ones that frequently report difficulties in learning mathematics, especially in the application of concepts or problem-solving.

However, some investigations included postgraduate students and teachers, where they played the role of principal investigators, observers, experimental object or collaborators depending on the study, which showed leading roles of various members of the academic community within their studies.

Regarding the subcategory of the research method used, important findings were found (Table 8). The most widely used methodology is mixed methods (40%), followed by the quantitative-experimental research design with a descriptive scope (23.3%).

Regarding the temporal dimension of the studies reviewed, Table 9 shows that most of the studies are cross-sectional (93.3%) and few are longitudinal (6.6%). This may be due to the immediacy of the results offered by cross-sectional studies regarding the use of mobile devices in innovative educational scenarios and their data collection at unique times and specific places. In addition, longitudinal studies require complex statistics and are costly studies in monetary, logistical, and temporal terms. However, it is essential to carry out more longitudinal research, important for the identification of long-term learning, in addition to visualizing advantages and limitations of mobile learning over long periods of time, since this type of study facilitates the solution of endogeneity problems resulting from variables omitted during the period. to period, it allows us to measure undetected effects in cross-sectional samples and improve the precision of the estimators (Sampieri, 2018).

Finally, with respect to the subcategory of data collection methods, the most used methods are the questionnaire (66.6) and the survey (43.3). While very little used are the interview (13.3), the

Table 8. Research methodologies

| Research method | Number of studies | Percentage value (%) |
|---|-------------------|----------------------|
| Qualitative - case study | 4 | 13.3 |
| Qualitative - exploratory - pilot study | 1 | 3.3 |
| Qualitative – exploratory – Experience survey | 0 | 0.0 |
| Quantitative – exploratory | 4 | 13.3 |
| Quantitative – descriptive | 7 | 23.3 |
| Quantitative – correlational | 2 | 6.6 |
| Quantitative – explanatory | 0 | 0.0 |
| mixed methods | 12 | 40 |
| Other | 0 | 0.0 |

Table 9. Time dimension

| Time dimension | Number of studies | Percentage value (%) |
|--------------------------|-------------------|----------------------|
| Cross-sectional research | 28 | 93.3 |
| longitudinal research | 2 | 6.6 |

focus group (10%), the observation (6.6), and the test (3.3). It is worth mentioning that 56.7% of the studies used two or more data collection instruments in their research.

Trends and Future Research

In this study, a detailed systematic review of the state of the art on the use of mobile devices in the teaching and learning of mathematics in HEIs was carried out, with a main interest in studies that evidenced the development of problem-solving competence through mobile learning. The main findings and research trends in this field are presented below.

The use of mobile devices by teachers and students for educational and beneficial purposes for the educational community is expected to grow significantly. Likewise, it is projected that HEIs within their educational programs adopt laboratories or rigorous practices mediated by mobile learning for the teaching of mathematical problem-solving. Since it has been perceived that the advantages offered by this learning such as ubiquity, interaction, contextualization, among others, favor the learning results and academic performance of the students. However, this adoption should not be limited to the simple use of technology to get the attention of students, but should be accompanied by good practices that tend to improve traditional methodologies and can be replicated to other teachers (Romero-Rodríguez, et al., 2020).

There is an ambition to implement and validate collaborative online communities that according to Blayone, et al. (2017), are effective in supporting problem-solving learning. Initially, tools provided by social networks and digital platforms have been implemented in order to provide support services, such as tutoring, access to content and educational material, diagnostic and formative evaluations, where the student plays an important role in learning with their peers.

More mobile interdisciplinary work should be carried out that leads to the contextualization of learning (context-awareness), mathematical logical reasoning and the construction of integrating scenarios of mathematics with engineering (Acosta-Gonzaga, & Walet, 2018; Huang et al., 2021).

The need arises to implement and articulate cutting-edge technologies such as augmented reality (AR) and artificial intelligence (AI) with mobile learning for the teaching of problem-solving. As suggested by Bacca et al. (2014), the study of AR is a good option to explore learning from the devices that students usually have. This is due to its scope in terms of costs, access, and handling. Regarding AI, more intelligent tutorial systems are projected that advocate the adaptability and personalization of mathematics learning, since students learn problem-solving at different rates (Reimann, et al., 2013).

It is also important to carry out more research with longitudinal analysis, since most of the studies consider cross-sectional scopes. It is important to review long-term or long-term mobile learning, for which longitudinal studies are appropriate, since they allow solutions to problems of omitted variables in each period to be found and facilitate the measurement of effects not detected in cross-sectional studies (Sampieri, 2018).

This research limited its search to the analysis of articles in the English language in journals with significant indexing between the years 2011 - 2021. However, it is recommended to carry out studies on systematic reviews of scientific documentation (books, book chapters, and articles) in other languages. In addition, the review of studies published in years prior to 2011 is recommended and likewise, the review at all educational levels of the elements of mobile learning of mathematics considered in this study as proposals, advantages, limitations, effectiveness, among others.

CONCLUSION

This systematic review of the literature reported on the purposes, advantages, limitations, and effectiveness of the use of mobile devices in the teaching and learning of mathematics, especially problem-solving. The 30 selected documents evidenced the adaptability processes used, the most used technological tools, the areas of mathematics most intervened and the teaching approaches articulated with mobile devices for problem-solving. Likewise, elements of the research methodologies used

were shown, such as: sample, research method, data collection method, and temporality. In addition, a rigorous research method defined in other investigations was conditioned for the selection of journals to consult.

With respect to the findings found, the following summary is shown:

Mobile learning facilitates the development of problem-solving skills, due to the advantages it provides such as ubiquity, immediacy, contextualization of mathematical concepts, follow-up in mathematical processes and reasoning, dynamism, and feedback in evaluations. diagnostic and formative skills and the ease of providing situated learning.

The use of mobile devices has facilitated the development of learning communities in all areas, particularly in mathematics. The foregoing has shown the effectiveness of collaborative work in learning to solve problems based on constructive criticality.

It is important to highlight the growth during the last 3 years of the use of mobile devices in educational settings. During the pandemic, it was an effective and efficient alternative used by teachers to support student learning in mathematics in HEIs.

With respect to the analysis of variables, a scope is perceived in mixed-type research with exploratory and descriptive quantitative analysis and few correlational and explanatory studies. With respect to the most used qualitative methodology is the case study. This does not change much with respect to the results obtained in the systematization study carried out by Crompton and Burke (2017). The most used data collection methods are questionnaires and surveys, and the most used samples range between 31 and 200 participants.

Student learning in problem-solving is favored using mobile devices, since this generates a good attitude toward carrying out activities based on interaction, contextualization, and collaboration. In addition, the theory of constructivism is the most predominant in support of mobile learning, followed by the pedagogical models of collaborative learning and PBL.

COVID-19 notably influenced the growth in the use of mobile devices in educational proposals, since the characteristics offered such as ubiquity, learning in context, work in situated scenarios, among others, allowed students to work from home, due to the fears that this problem had been causing in the academic community (Alhumaid, Habes, & Salloum, 2021).

ACKNOWLEDGMENTS

The work of Francisco Niño Rojas and Sergio Eduardo Gomez Ardila has been partly supported by the Entorno virtual de aprendizaje inteligente para la enseñanza y aprendizaje de las matemáticas Project (DCBS212-188) that is funded by the Universidad de La Salle, Bogotá, Colombia, and has been supported by the Doctorado en Educación y Sociedad, to one of the authors, as part of the work done in the doctoral process. On the other hand, the work is also supported by the research groups MATESTASIS (COL0022647) in which Francisco is an active member and Grupo de investigación en automatización, visión artificial y robótica - AVARC (COL0017431), in which Sergio is an active member.

Moreover, we declare that our work does not present any conflict of interest.

REFERENCES

- Abdulwahed, M., Jaworski, B., & Crawford, A. (2012). *Innovative approaches to teaching mathematics in higher education: A review and critique*. Academic Press.
- Abu-Al-Aish, A., Love, S., & Hunaiti, Z. (2012). Mathematics students' readiness for mobile learning. *International Journal of Mobile and Blended Learning*, 4(4), 1–20. doi:10.4018/jmbL.2012100101
- Acosta-Gonzaga, E., & Walet, N. R. (2018). The role of attitudinal factors in mathematical on-line assessments: A study of undergraduate STEM students. *Assessment & Evaluation in Higher Education*, 43(5), 710–726. doi:10.1080/02602938.2017.1401976
- Alhumaid, K., Habes, M., & Salloum, S. A. (2021). Examining the factors influencing the mobile learning usage during COVID-19 Pandemic: An Integrated SEM-ANN Method. *IEEE Access: Practical Innovations, Open Solutions*, 9, 102567–102578. doi:10.1109/ACCESS.2021.3097753
- Almeida, R. R., & Araújo Jr, C. F. (2016). Mobile learning in science and mathematics teaching: A systematic review. *Mobile and blended learning innovations for improved learning outcomes*, 277–296. 10.4018/978-1-5225-0359-0.ch014
- Andrade-Aréchiga, M., López, G., & López-Morteo, G. (2012). Assessing effectiveness of learning units under the teaching unit model in an undergraduate mathematics course. *Computers & Education*, 59(2), 594–606. doi:10.1016/j.compedu.2012.03.010
- Arifin, M., Sholeh, M., Hafiz, A., Agustin, R., & Wardana, M. (2021). *Developing Interactive Mobile Mathematics Inquiry to Enhance Students' Problem-solving Skill*. 10.3991/ijim.v15i01.20067
- Azevedo, B. F., Pereira, A. I., Fernandes, F. P., & Pacheco, M. F. (2021). Mathematics learning and assessment using MathE platform: A case study. *Education and Information Technologies*, 1–23. doi:10.1007/s10639-021-10669-y PMID:34366693
- Bacca Acosta, J. L., Baldiris Navarro, S. M., Fabregat Gesa, R., & Graf, S. (2014). Augmented reality trends in education: a systematic review of research and applications. *Journal of Educational Technology and Society*, 17(4), 133–149.
- Baek, E. O., & Guo, Q. (2019). Instructional design principles for mobile learning. In Y. A. Zhang & D. Cristol (Eds.), *Handbook of Mobile Teaching and Learning* (pp. 1–22). Springer.
- Blackburn, G. (2017). A university's strategic adoption process of an PBL-aligned eLearning environment: An exploratory case study. *Educational Technology Research and Development*, 65(1), 147–176. doi:10.1007/s11423-016-9472-3
- Blayone, T. J., Barber, W., DiGiuseppe, M., & Childs, E. (2017). Democratizing digital learning: Theorizing the fully online learning community model. *International Journal of Educational Technology in Higher Education*, 14(1), 1–16. doi:10.1186/s41239-017-0051-4
- Blayone, T. J., Mykhailenko, O., VanOostveen, R., & Barber, W. (2018). Ready for digital learning? A mixed-methods exploration of surveyed technology competencies and authentic performance activity. *Education and Information Technologies*, 23(3), 1377–1402. doi:10.1007/s10639-017-9662-6
- Chang, J. M. (2011). A practical approach to inquiry-based learning in linear algebra. *International Journal of Mathematical Education in Science and Technology*, 42(2), 245–259. doi:10.1080/0020739X.2010.519795
- Chen, C. L., & Wu, C. C. (2020). Students' behavioral intention to use and achievements in ICT-Integrated mathematics remedial instruction: Case study of a calculus course. *Computers & Education*, 145, 103740. doi:10.1016/j.compedu.2019.103740
- Chiu, T. K., & Churchill, D. (2015). Exploring the characteristics of an optimal design of digital materials for concept learning in mathematics: Multimedia learning and variation theory. *Computers & Education*, 82, 280–291. doi:10.1016/j.compedu.2014.12.001
- Chuang, C. P., Jou, M., Lin, Y. T., & Lu, C. T. (2015). Development of a situated spectrum analyzer learning platform for enhancing student technical skills. *Interactive Learning Environments*, 23(3), 373–384. 10.1080/10494820.2013.765896

- Conley, Q., Atkinson, R. K., Nguyen, F., & Nelson, B. C. (2020). MantarayAR: Leveraging augmented reality to teach probability and sampling. *Computers & Education, 153*, 103895. doi:10.1016/j.compedu.2020.103895
- Crompton, H., & Burke, D. (2015). Research Trends in the Use of Mobile Learning in Mathematics. *International Journal of Mobile and Blended Learning, 7*(4), 1–15. doi:10.4018/IJMBL.2015100101
- Crompton, H., & Burke, D. (2017). Research trends in the use of mobile learning in mathematics. *Blended learning: Concepts, methodologies, tools, and applications*, 2090-2104. 10.4018/978-1-5225-0783-3.ch101
- Crompton, H., & Burke, D. (2018). The use of mobile learning in higher education: A systematic review. *Computers & Education, 123*, 53–64. doi:10.1016/j.compedu.2018.04.007
- Crompton, H., & Burke, D. (2020). Mobile learning and pedagogical opportunities: A configurative systematic review of PreK-12 research using the SAMR framework. *Computers & Education, 156*, 103945. doi:10.1016/j.compedu.2020.103945
- Evans, T., Kensington-Miller, B., & Novak, J. (2021). Effectiveness, efficiency, engagement: Mapping the impact of pre-lecture quizzes on educational exchange. *Australasian Journal of Educational Technology, 37*(1), 163–177. doi:10.14742/ajet.6258
- Fabian, K., Topping, K. J., & Barron, I. G. (2016). Mobile technology and mathematics: Effects on students' attitudes, engagement, and achievement. *Journal of Computers in Education, 3*(1), 77–104. doi:10.1007/s40692-015-0048-8
- Fast, L. A., Lewis, J. L., Bryant, M. J., Bocian, K. A., Cardullo, R. A., Rettig, M., & Hammond, K. A. (2010). Does math self-efficacy mediate the effect of the perceived classroom environment on standardized math test performance? *Journal of Educational Psychology, 102*(3), 729–740. doi:10.1037/a0018863
- Fuad, M., Deb, D., Etim, J., & Gloster, C. (2018). Mobile response system: A novel approach to interactive and hands-on activity in the classroom. *Educational Technology Research and Development, 66*(2), 493–514. doi:10.1007/s11423-018-9570-5
- Güler, M., Büttiner, S. Ö., Danişman, Ş., & Gürsoy, K. (2021). A meta-analysis of the impact of mobile learning on mathematics achievement. *Education and Information Technologies, 1–21*. doi:10.1007/s10639-021-10640-x
- Hou, H. T. (2011). A case study of online instructional collaborative discussion activities for problem-solving using situated scenarios: An examination of content and behavior cluster analysis. *Computers & Education, 56*(3), 712–719. doi:10.1016/j.compedu.2010.10.013
- Huang, Z., Kougiannos, E., Ge, X., Wang, S., Chen, P. D., & Cai, L. (2021). A Systematic Interdisciplinary Engineering and Technology Model Using Cutting-Edge Technologies for STEM Education. *IEEE Transactions on Education, 64*(4), 390–397. Advance online publication. doi:10.1109/TE.2021.3062153
- Hwang, G. J., Lai, C. L., Liang, J. C., Chu, H. C., & Tsai, C. C. (2018). A long-term experiment to investigate the relationships between high school students' perceptions of mobile learning and peer interaction and higher-order thinking tendencies. *Educational Technology Research and Development, 66*(1), 75–93. doi:10.1007/s11423-017-9540-3
- Hwang, G. J., & Tsai, C. C. (2011). Research trends in mobile and ubiquitous learning: A review of publications in selected journals from 2001 to 2010. *British Journal of Educational Technology, 42*(4), E65–E70. doi:10.1111/j.1467-8535.2011.01183.x
- Iannone, P., & Simpson, A. (2013). Students' perceptions of assessment in undergraduate mathematics. *Research in Mathematics Education, 15*(1), 17–33. doi:10.1080/14794802.2012.756634
- Jonassen, D. H. (2011). *Learning to solve problems*. Routledge.
- Kay, R., & Kletschin, I. (2012). Evaluating the use of problem-based video podcasts to teach mathematics in higher education. *Computers & Education, 59*(2), 619–627. doi:10.1016/j.compedu.2012.03.007
- Kek, M. Y. C. A., & Huijser, H. (2011). The power of problem-based learning in developing critical thinking skills: Preparing students for tomorrow's digital futures in today's classrooms. *Higher Education Research & Development, 30*(3), 329–341. doi:10.1080/07294360.2010.501074

- Kitchenham, B. (2004). *Procedures for performing systematic reviews*. <https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.122.3308>
- Lai, C. L., & Hwang, G. J. (2014). Effects of mobile learning time on students' conception of collaboration, communication, complex problem-solving, meta-cognitive awareness and creativity. *International Journal of Mobile Learning and Organisation*, 8(3), 276–291. doi:10.1504/IJML0.2014.067029
- Mayer, R. E. (2014). Incorporating motivation into multimedia learning. *Learning and Instruction*, 29, 171–173. doi:10.1016/j.learninstruc.2013.04.003
- Micari, M., & Pazos, P. (2021). Beyond grades: Improving college students' social-cognitive outcomes in STEM through a collaborative learning environment. *Learning Environments Research*, 24(1), 123–136. doi:10.1007/s10984-020-09325-y
- Mislevy, R. J. (2011). *Evidence-Centered Design for Simulation-Based Assessment. CRESST Report 800. National Center for Research on Evaluation, Standards, and Student Testing*. CRESST.
- Mohamed, H., & Lamia, M. (2018). Implementing flipped classroom that used an intelligent tutoring system into learning process. *Computers & Education*, 124, 62–76. doi:10.1016/j.compedu.2018.05.011
- Nova, N., Girardin, F., & Dillenbourg, P. (2005). 'Location is not enough!': An empirical study of location-awareness in mobile collaboration. Paper presented at the IEEE International Workshop on Wireless and Mobile Technologies in Education (WMTE'05). doi:10.1109/WMTE.2005.2
- Novita, R., Zulkardi, Z., & Hartono, Y. (2012). Exploring Primary Student's Problem-Solving Ability by Doing Tasks Like PISA's Question. *Indonesian Mathematical Society Journal on Mathematics Education*, 3(2), 133–150. doi:10.22342/jme.3.2.571.133-150
- Nygren, E., Sutinen, E., Bignaut, A. S., Laine, T. H., & Els, C. J. (2012). Motivations for play in the UFractions mobile game in three countries. *International Journal of Mobile and Blended Learning*, 4(2), 30–48. doi:10.4018/jmbl.2012040103
- Ozcelik, E., & Acarturk, C. (2011). Reducing the spatial distance between printed and online information sources by means of mobile technology enhances learning: Using 2D barcodes. *Computers & Education*, 57(3), 2077–2085. doi:10.1016/j.compedu.2011.05.019
- Pandey, K., & Singh, N. (2015). Mobile learning: Critical pedagogy to education for all. *Handbook of mobile teaching and learning*, 107-132.
- Phonapichat, P., Wongwanich, S., & Sujiva, S. (2014). An analysis of elementary school students' difficulties in mathematical problem solving. *Procedia: Social and Behavioral Sciences*, 116, 3169–3174. doi:10.1016/j.sbspro.2014.01.728
- Polya, G. (1973). *How to Solve It*. Princeton University Press.
- Ponce Campuzano, J. C., Matthews, K. E., & Adams, P. (2018). On the use of history of mathematics: An introduction to Galileo's study of free fall motion. *International Journal of Mathematical Education in Science and Technology*, 49(4), 517–529. doi:10.1080/0020739X.2017.1377301
- Reeves, B., & Nass, C. (1996). *The media equation: How people treat computers, television, and new media like real people*. Cambridge university press.
- Reimann, P., Kickmeier-Rust, M., & Albert, D. (2013). Problem solving learning environments and assessment: A knowledge space theory approach. *Computers & Education*, 64, 183–193. doi:10.1016/j.compedu.2012.11.024
- Rojas, F. N., Valderrama, M. T. P. J., Lancheros-Cuesta, D. J., & Ardila, S. E. G. (2020, June). Development of a mobile application: optimization problems for differential calculus. In *2020 15th Iberian Conference on Information Systems and Technologies (CISTI)* (pp. 1-6). IEEE. doi:10.23919/CISTI49556.2020.9140868
- Romero-Rodríguez, J. M., Aznar-Díaz, I., Hinojo-Lucena, F. J., & Gómez-García, G. (2020). Mobile learning in higher education: Structural equation model for good teaching practices. *IEEE Access: Practical Innovations, Open Solutions*, 8, 91761–91769. doi:10.1109/ACCESS.2020.2994967 PMID:34192098
- Rueda, R. A. S. (2021). Students' perceptions of the use of the flipped classroom during the educational process of linear functions. *Cultura y Educación*, 33(3), 431–454. doi:10.1080/11356405.2021.1949109

- Sampieri, R. (2018). *Research Methodology: The Quantitative, Qualitative and Mixed Routes*.
- Singh, K., Granville, M., & Dika, S. (2002). Mathematics and science achievement: Effects of motivation, interest, and academic engagement. *The Journal of Educational Research*, 95(6), 323–332. doi:10.1080/00220670209596607
- Sommerauer, P., & Müller, O. (2014). Augmented reality in informal learning environments: A field experiment in a mathematics exhibition. *Computers & Education*, 79, 59–68. doi:10.1016/j.compedu.2014.07.013
- Spikol, D., & Otero, N. (2012). *Designing better mobile collaborative laboratories for ecology field work for upper secondary schools*. Paper presented at the Wireless, Mobile and Ubiquitous Technology in Education (WMUTE), 2012 IEEE Seventh International Conference on. doi:10.1109/WMUTE.2012.20
- Sugden, N., Brunton, R., MacDonald, J., Yeo, M., & Hicks, B. (2021). Evaluating student engagement and deep learning in interactive online psychology learning activities. *Australasian Journal of Educational Technology*, 37(2), 45–65. doi:10.14742/ajet.6632
- Sung, Y. T., Chang, K. E., & Liu, T. C. (2016). The effects of integrating mobile devices with teaching and learning on students' learning performance: A meta-analysis and research synthesis. *Computers & Education*, 94, 252–275. doi:10.1016/j.compedu.2015.11.008
- Takači, D., Stankov, G., & Milanovic, I. (2015). Efficiency of learning environment using GeoGebra when calculus contents are learned in collaborative groups. *Computers & Education*, 82, 421–431. doi:10.1016/j.compedu.2014.12.002
- Tambychik, T., Meerah, T. S. M., & Aziz, Z. (2010). Mathematics skills difficulties: A mixture of intricacies. *Procedia: Social and Behavioral Sciences*, 7, 171–180. doi:10.1016/j.sbspro.2010.10.025
- Tang, Y. M., & Yu, K. M. (2018). Development and evaluation of a mobile platform for teaching mathematics of CAD subjects. *Computer-Aided Design and Applications*, 15(2), 164–169. doi:10.1080/16864360.2017.1375665
- Tatar, E., & Zengin, Y. (2016). Conceptual understanding of definite integral with Geogebra. *Computers in the Schools*, 33(2), 120–132. doi:10.1080/07380569.2016.1177480
- Traxler, J. (2018). Learning with mobile in the digital age. *Pedagogika*, 68(2), 293–310. doi:10.14712/23362189.2018.860
- Wadsworth, B. J. (1996). *Piaget's theory of cognitive and affective development: Foundations of constructivism*. Longman Publishing.
- Winters, N., Sharples, M., Shuler, C., Vosloo, S., & West, M. (2013). *UNESCO/Nokia The Future of Mobile Learning Report: Implications for Policymakers and Planners*. Academic Press.