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# A Systematic Review on Exploring the Potential of Educational Robotics in Mathematics Education

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## Abstract
By providing students with a highly interactive and hands-on learning experience, robotics promises to inspire a new generation of mathematical learning. This paper aims to review the empirical evidence on the application of robotics in mathematics education and to define future research perspectives of robot-assisted mathematics education. After a systematic search in online database via keyword search and snowballing approach, we analyzed 20 empirical studies on how to teach and learn mathematical knowledge through robotics. The results indicate that (1) most studies were conducted with a small sample size, the largest research groups were elementary school students and secondary school students, most studies used LEGO robots, robots were primarily applied to teach and/or learn graphics, geometry, and algebra, and almost half of the studies taught mathematics by engaging students in game-like interactions with robots; (2) half of the studies adopted a non-experimental research design, and most studies evaluated student performance through observation, test/examination, questionnaires, or verbal interviews; and (3) instructional implications proposed in the 20 papers can be clustered into four themes: human-robot interaction, connections between mathematics and real life, pedagogical suggestions, and facility conditions. The 20 papers suggest that robotics generally plays an active role in mathematics education; however, there are indeed situations in which no significant improvement was found in students' mathematical learning. In view of this, we prospect the future research perspectives of robot-assisted mathematics education and propose that more rigorous intervention studies could be conducted to further explore the integration of robotics and mathematics education.

**Keywords** Educational robotics · Mathematics education · Teaching/learning strategies · Transdisciplinary issues

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## Introduction

Popular interest in educational robotics has increased dramatically during the last two decades (Kucuk & Sisman, 2017). Studies indicated that robotics curriculum can enhance motivation (Gomoll, Hmelo-Silver, Šabanović, & Francisco, 2016; Master, Cheryan, Moscatelli, & Meltzoff, 2017), promote collaboration (Hwang & Wu, 2014; Menekse, Higashi, Schunn, & Baehr, 2017), and foster computational thinking (Bers, Flannery, Kazakoff, & Sullivan, 2014; Chen, Shen, Barth-Cohen, Jiang, Huang, & Eltoukhy, 2017; Leonard, Buss, Gamboa, Mitchell, Fashola, Hubert, & Almughyirah, 2016). Robotics is also viewed as an effective tool for hands-on learning, not only of robotics itself, but of general topics in Science, Technology, Engineering, and Mathematics (STEM) (Gomoll et al., 2016).

The use of robotics and programming has a long-standing history in mathematics education with tools such as "turtle" geometry or Logo explored in classrooms for almost 50 years. In Papert's Logo, students programmed a robotic Logo turtle to turn and move, and a pen attached to it created geometric figures (Papert, 1980). Here, research suggests that children engaging with programming a robot to move have the opportunity to explore spatial concepts, problem solving, measurement, geometry, and engage with metacognitive processes (Clements & Meredith, 1993; Yelland, 1994). Papert's seminal work indicates that educational robotics is a useful tool to "externalize" learner's ideas and to make mathematical concepts "more accessible to reflection" (Papert, 1980, p. 145).

However, robotics alone does not enhance mathematical learning, with the educator, the task, and the context of learning also playing integral roles in extending mathematics education. The lack of high-quality empirical research on robot-assisted mathematics education suggests that the possibilities of robotics are not fully harnessed for mathematical teaching and learning. One possible reason is that educators do not fully appreciate the potentials of robotics. Without an understanding of the affordances of robotics, educators struggle to make full use of it, which in turn may compromise the effectiveness of student's learning.

This study aims to review the empirical evidence on teaching and learning mathematical knowledge through robotics and to explore future research perspectives of robot-assisted mathematics education. Theoretically speaking, this study can explore the potential of educational robotics in mathematics education, and provide insights on new horizons in STEM education, robotics education, and mathematics education. It is hoped that this study will attract more teachers to visualize abstract mathematical knowledge with the tangible and manipulable nature of robots.

In order to systematically examine the empirical research on robot-assisted mathematics education, this literature review is guided by the following research questions:

Q1: How has robotics been incorporated into mathematics education?
Q2: What intervention approaches are effective in teaching and learning mathematical knowledge through robotics?
Q3: What implications for teaching are indicated by these empirical studies?

## Method

A systematic review is a means of identifying, evaluating, and interpreting all available research relevant to a particular research question, topic area, or phenomenon of interest (Kitchenham, 2004). For a full-fledged literature review, search strategy is the key to the identification of reviewed papers and to the actual outcome of the review (Kitchenham, Brereton, Budgen, Turner, Bailey, & Linkman, 2009). For the purposes of this study, we performed a keyword search in international online bibliographic database ISI Web of Science. The following three inclusion criteria were identified to determine which papers could be included in this review.

> Inclusion Criteria 1: Papers reported the utilization of physical robots.
> Inclusion Criteria 2: Papers presented the empirical evidence of robot-assisted mathematics education.
> Inclusion Criteria 3: Papers were peer-reviewed and written in English.

We excluded papers that only involved the use of virtual robots (e.g. Logo turtle) considering that the characteristics of physical robotics (e.g. 3-dimensionality, mobility, hands on, and the presence of a real, exploratory, and measurable setting) can motivate students to invest more time and mental efforts on mathematical learning (Nussbaum & Soto, 2009). To ensure the quality of reviewed papers, we only considered peer-reviewed papers in ISI Web of Science Core Collection. Due to the limited papers found via keyword search, a snowballing approach was conducted to get as many papers as possible. A three-step iterative process recommended by Kitchenham et al. (2009) was adopted in each round of the snowballing approach.

Step 1. Start set: identify a starting set of papers for the snowballing approach from the leading journals in the field.
Step 2. Backward snowballing: go backward by looking at the reference lists of the papers identified in step 1 to determine which papers are qualified for your literature review.
Step 3. Forward snowballing: go forward by looking at the citations to the papers identified in step 1 to determine which papers are qualified for your literature review.

### Keyword Search in Database

We started the keyword search with the search string "robot* AND math*" in ISI Web of Science Core Collection. As of February 27 2018, the search returned 140 papers. To select useful papers, we quickly analyzed the titles and abstracts of the 140 papers with reference to the above inclusion criteria. As shown in Table 1, 11 papers were singled out based on the three inclusion criteria.

**Table 1** Summary of keyword selection and snowballing approach

| Search strategy | Papers resulting from the search | Selected |
|---|---|---|
| Keyword search | 140 | 11 |
| First-round snowballing approach | 215 | 7 (+2*) |
| Second-round snowballing approach | 195 | 2 (+3*) |
| Total | 550 | 20 |

*The number of papers selected before, which are not added to the total

### Snowballing Approach

The snowballing approach was conducted with two high-quality journal papers (i.e. Benitti, 2012; Wei, Hung, Lee, & Chen, 2011). It returned a total of 215 papers (82 from references and 133 from citations in ISI Web of Science Core Collection). With the above inclusion criteria, seven new papers were selected for this review (see Table 1). This was the first-round snowballing approach.

As the number of papers found in the first round was still large, we launched the second-round snowballing approach. This time, two papers (i.e. Keren & Fridin, 2014; Lindh & Holgersson, 2007) were identified as new seeds for the snowballing approach. Fifty citations from ISI Web of Science Core Collection and 145 references (a total of 195 papers) were selected. However, only two new papers were selected to add to the samples for review.

As shown in Table 1, after two rounds of snowballing approach, we found it difficult to find more qualified papers, and the repeated papers were increasing enormously. It indicated that the iterative process of snowballing approach could be ended.

After the keyword search and the snowballing approach, 20 papers were selected as samples for the subsequent literature review (see Table 1).

## Results

### How Has Robotics Been Incorporated into Mathematics Education?

In this section, we analyzed the 20 papers from the perspective of sample groups, robot types, mathematical content knowledge involved, and the way robots and mathematics are integrated. The detailed scheme is presented in Appendix Table 2.

Out of the 20 papers, the research samples were aged between 3 and 33 years old. According to Appendix Table 2, we divided the samples used in the 20 papers into four groups: kindergarteners, elementary school students, secondary school students, and university students (see Fig. 1). Three papers covered more than one category of sample groups. The largest sample groups were elementary school students (10 or 50.00%) and secondary school students (10 or 50.00%), followed by kindergarteners (two or 10.00%), and university students (one or 5.00%).

Figure 2 shows the number of samples used in the 20 papers. Thirteen or 65.00% of the papers recruited less than 40 participants, and four or 20.00% of the papers used

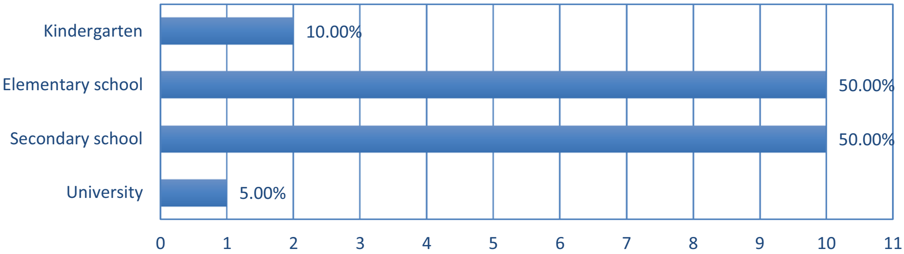


**Fig. 1** Sample groups of these empirical studies

41–60 participants in their experiments. Only two or 10.00% of the papers involved 61–80 participants. This indicates that the sample sizes were not large in the research of robot-assisted mathematics education. Promisingly, one paper distanced itself from a small sample size: Lindh and Holgersson (2007) examined the effect of a robotic training on 696 pupils' ability to solve mathematical and logical problems.

With regard to the robot types, 19 papers mentioned the specific robotics kits adopted in the mathematical activities. As observed in Fig. 3, the dominant position of LEGO is obvious (10 or 52.63%). In addition, one paper combined LEGO robot kits and Handy Cricket together in their robotic jewelry project (Martin, Lurgio, & Coffey, 2006). Three papers used humanoid robot NAO to teach mathematical knowledge (Keren, Ben-David, & Fridin, 2012; Keren & Fridin, 2014; Pinto, Tozadore, & Romero, 2015). Six papers used DARwIn-OP (Brown & Howard, 2014), Roverbot and Tank (Fernandes, Fermé, & Oliveira, 2009), Fischertechnik (Julià & Antolí, 2016), Palm Pilot Robot Kit and ER1 Robot (Mitnik, Nussbaum, & Soto, 2008), iRobot Create (Rhine & Martin, 2008), and Arduino (Shankar, Ploger, Nemeth, & Hecht, 2013), respectively.

A total of 19 papers specified the mathematical content knowledge involved in their experiments. The mathematical knowledge, which is depicted in column 5 "Content knowledge" of Appendix Table 2, can be subdivided into four categories: (1) graphics and geometry: measurement, distances, angles, lengths, vectors, etc.; (2) number and algebra: counting, computation, proportion, function, etc.; (3) practice and synthesis application: mathematical problem solving, metacognitive skills, etc.; and (4) statistics and probability: data collection and analysis, likelihood, etc. As shown in Fig. 4, 12 or 63.16% of the papers touched on the areas of graphics and geometry. Nine or 47.37% of the papers dealt with the knowledge of number and algebra. Six or 31.58% of the

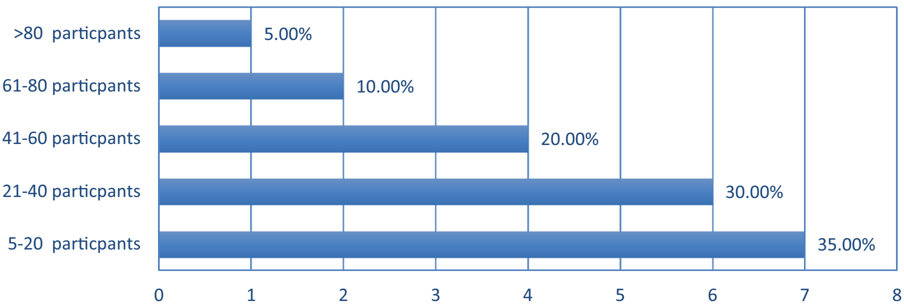


**Fig. 2** Sample sizes of these empirical studies

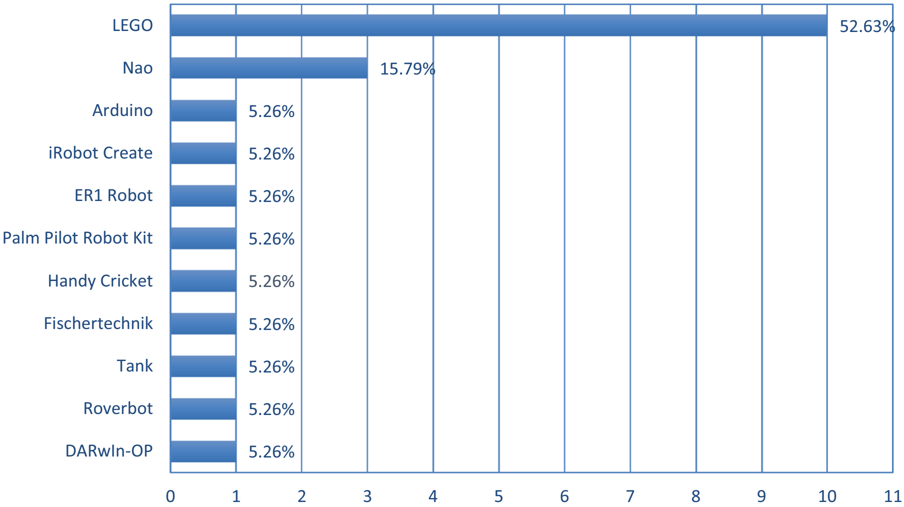


**Fig. 3** Robot types in these empirical studies

papers used robotics to exercise mathematical practice and synthesis application. Only one paper concerned the basic knowledge of statistics and probability.

In terms of the way robots and mathematics are integrated, three categories emerged from the 20 papers: learning by interacting with robots, learning by programming robots, and learning by building and programming robots. As shown in Fig. 5, nine or 45.00% of the papers taught mathematical knowledge by human-robot interaction, in which students participated in some game-like math activities with robots. Students in three or 15.00% of the papers learnt mathematics by programming robots, while eight or 40.00% of the papers taught mathematics by building and programming robots.

## What Intervention Approaches Are Effective in Teaching and Learning Mathematical Knowledge Through Robotics?

In this section, we abstracted the study type, major findings, and data collection methods reported in the 20 papers. The detailed scheme is presented in Appendix Table 3.

As observed in Appendix Table 3, we classified the 20 papers into non-experimental, quasi-experimental, and (true) experimental study according to the taxonomy of

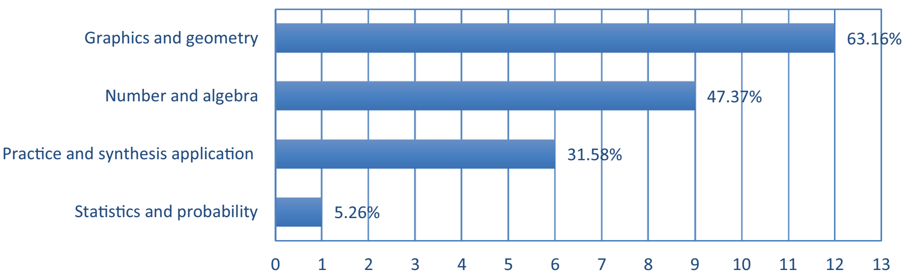


**Fig. 4** Mathematical knowledge involved in these empirical studies

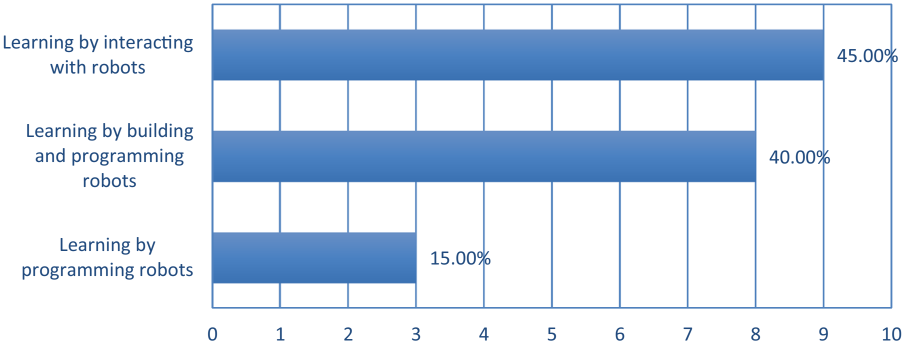


**Fig. 5** The way robots and mathematics are integrated

Benitti (2012) and Trochim and Donnelly (2006). For an experiment to be classified as a true experimental design, it must use random assignment to groups (random assignment is not the same thing as random selection of a sample from a population). If random assignment is not used, we have to ask the second question: does the design use either multiple groups or multiple waves of measurement? If the answer is yes, we would label it a quasi-experimental design. If not, we would call it a non-experimental design. As shown in Fig. 6, 10 or 50.00% of the papers were included in a non-experimental research design. Four or 20.00% of the papers conducted a quasi-experimental research. Six or 30.00% of the papers administrated an experimental design. Among the 10 experimental or quasi-experimental studies, eight were conducted with a control group.

The results reported in the 20 papers are depicted in the column "Major findings" in Appendix Table 3. Overall, robotics can help students benefit in (1) understanding of mathematical concepts (e.g. angles, function, proportion, etc.), (2) change of attitudes (e.g. promoting engagement, confidence, motivation, etc.), and (3) skills development (e.g. problem-solving skills, metacognitive skills, mathematical thinking, etc.).

However, this is not always the case, as there are studies that have reported situations in which there was no significant improvement in students' mathematical learning. Adams and Cook (2017) reported that using a robot controlled via a speech-generating device could contribute to students with physical and communication impairments perform hands-on and communicative mathematics measurement activities. However, measuring curvy objects was still very difficult for all participants. Julià and Antolí

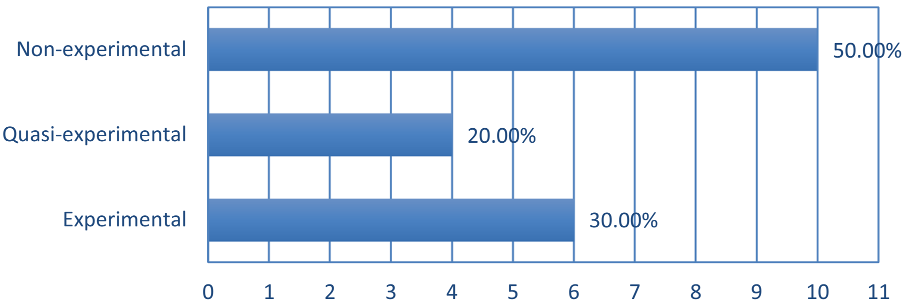


**Fig. 6** Study type of these empirical studies

(2016) showed that students who participated in the robotics course scored significantly higher in some posttests, but they did not improve their overall performance in other posttests. In another attempt to apply robotics to mathematics education, Lindh and Holgersson (2007) concluded that, there was no obvious over-all effect of LEGO, though there were significant positive effects of LEGO for sub-groups of pupils. Walker, Girotto, Kim, and Muldner (2016) suggested that positive perceptions of the teachable robot (i.e. robo-Tangible Activities for Geometry system) were related to smaller learning gains, because students with more positive perceptions of the system may have been distracted by its novel elements.

Gender difference is also an important issue to implement robotics activities in mathematics education. Among the 20 papers, Keren et al. (2012) and Keren and Fridin (2014) suggested that gender did not have a significant impact on the quality of child-robot interaction when learning mathematics with kindergarten assistive robotics. Similarly, Mitnik et al. (2008) indicated that, regarding gender, there were no significant differences between the learning accomplished by boys and girls throughout the experiments. However, two studies revealed opposite findings. Although no significant difference was found between boys and girls concerning the ability to build, program, and more generally handle the LEGO material, gender difference was significant in strategies of learning the material: boys more often were less willing to follow the instructions, whereas girls were more concentrated and intent on following the written task (Lindh & Holgersson, 2007; Shih, Chang, Chen, Chen, & Liang, 2012).

Different data collection methods were used in the 20 papers to evaluate students' performance. According to Appendix Table 3, seven methods emerged from the 20 papers: (1) observation, (2) test/examination, (3) questionnaire, (4) verbal interview, (5) evaluation of artifacts, (6) think-aloud protocol, and (7) sociograms. Generally, most of the papers utilized more than one method for evaluation. As shown in Fig. 7, 15 or 75.00% of the papers used observation to obtain first-hand information of student performance. Eleven or 55.00% of the papers implemented tests or examinations to assess the quality of the learning activities. Eight or 40.00% of the papers conducted a questionnaire survey while eight or 40.00% of the papers implemented verbal interviews. Three or 15.00% of the papers evaluated students' artifacts (e.g. robots). One paper tested the learning effects through think-aloud protocol (Mandin, De Simone, & Soury-Lavergne, 2017). In addition, one distinct method was found in these papers:

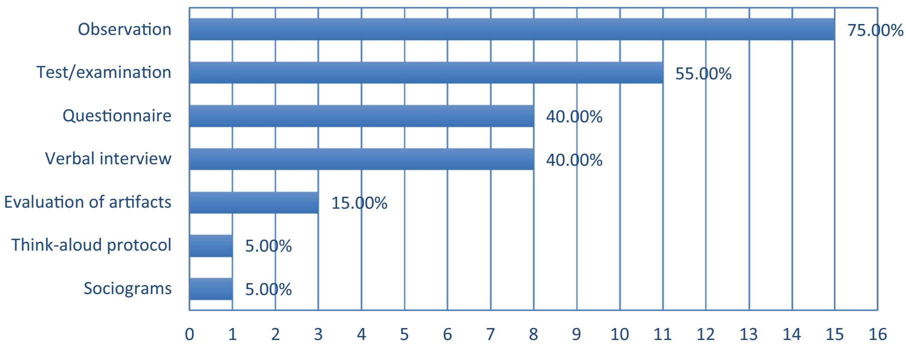


**Fig. 7** Data collection methods of these empirical studies

Mitnik et al. (2008) measured the social interactions using sociograms in which each student scored his/her social appreciation of each of his/her classmates.

### What Implications for Teaching Are Indicated by These Empirical Studies?

The 20 reviewed papers proposed some useful instructional implications to support the application of robotics in mathematics education. We list out these teaching implications to provide both theoretical and practical reference for researchers and educators alike.

**Interaction with Physical Robots Promotes Engagement in Mathematical Learning.** Having access to a robot gives students the opportunity to participate interactively with the learning process (Adams & Cook, 2017; Keren et al., 2012; Keren & Fridin, 2014; La Paglia, La Cascia, Francomano, & La Barbera, 2017). For example, Brown and Howard (2014) reported that, when compared to non-interactive methods, verbal interactions with a robot were able to increase and/or maintain student engagement regardless of student age and math content level. Pinto et al. (2015) further pointed out that, increasing the interaction levels of humanoid robots brought about better learning outcomes than just visual and auditory contacts. Except for the visual and/or verbal interactions with robots, Mandin et al. (2017) claimed that the moves of a robot, like its position, can be perceived as tangible feedback of help in mathematical games. Moreover, Keren and Fridin (2014) suggested that interactions with a real robot might generate greater enjoyment than interactions with a virtual agent.

Furthermore, robot can even act as an interaction mediator of the learning activity. By establishing interaction rules and guaranteeing students' fulfillment, robot can mediate interactions among students, thus resolving the potential conflicts in the mathematical learning process. With these interaction rules, the robot can also prevent students from developing free-riding behaviors, compelling them to work as a team (Mitnik et al., 2008).

**Connections Between Abstract Mathematics and Real-world Experience.** Learning mathematics with robots helps students visualize challenging real-world applications and supports multiple representations of a problem (Shankar et al., 2013). The experience with robots can help students transit from the abstract perfection of mathematics to the practical reality of everyday experience (Fernandes et al., 2009; Martin et al., 2006; Rhine & Martin, 2008). Therefore, it is important that students can relate the learning material to their ordinary school work (Lindh & Holgersson, 2007). When students apply their knowledge of math concepts solving real-world problems with the help of robots, they develop a lasting hands-on experience in a social context and a better attitude towards mathematics education (Shankar et al., 2013). It is also important to allow every learner to have the "fair opportunity" to do each hands-on practice, which in turn deepened their impressions about the learning contents. Moreover, all learners should have opportunities to practice repeatedly with the support of the robotics system. This is very useful for constructing one's own mathematics knowledge (Wei et al., 2011).

**Pedagogical Suggestions for Robot-Assisted Mathematics Education.** Instructional design is identified by many researchers as an important factor for supporting the successful application of robotics in mathematics education. Hence, most studies have put forward a series of pedagogical suggestions for educators. For example, Adams and Cook (2017) found that robot use was most appropriate in short tasks requiring reasonable operational skills. Lindh and Holgersson (2007) concluded that the robotic task given to the pupils must be both relevant and realistic to solve.

With regard to teacher's role, Shih et al. (2012) suggested that teachers should motivate students, especially low-level students, to actively participate in the learning process. More importantly, teachers should understand the affordances of robotics in mathematics education. Without teacher's acceptance, it is difficult for robotics to play an active role in mathematics education (Keren & Fridin, 2014).

When applying robotics to mathematics education, the added motivational elements may increase students' cognitive load (Walker et al., 2016). The more students attended to the novel features of robotics, the less they may have attended to the problem-solving content. It has to be clarified in future research to what extent motivational strategies in robotics are seductive and how strategies can be implemented in robotics without producing the risk of being too seductive (Astleitner & Wiesner, 2004).

**Facility Conditions to Support Robot-Assisted Mathematics Education.** With respect to the physical facilities provided for students, Lindh and Holgersson (2007) emphasized the importance of a large space for the pupils to spread the LEGO material on the ground, "play around," and test different kind of solutions for each kind of project they face. Besides, it is also important to build low-cost robots that are reliable, robust, and be customizable for the specific needs of the teacher and the student teams (Shankar et al., 2013).

## Discussion

In this section, we generalize the main viewpoints of the 20 reviewed papers based on the above analyses and make a comparison with existing studies. Further, we point out the future research perspectives of robot-assisted mathematics education.

### Incorporation of Robotics into Mathematics Education

Most of the applications of robotics to education have focused on teaching of content knowledge that is closely related to the robotics field (e.g. robot programming, robot construction, or mechatronics) (Mitnik et al., 2008). That is to say, the way robotics is currently introduced in educational settings is narrow (Rusk, Resnick, Berg, & Pezalla-Granlund, 2008). In fact, robots are flexible to teach kids a range of topics besides robotics per se (Ponce, Molina, Hernández, Acha, Morales, & Huitron, 2017). Although the use of robotics has a long-standing history in mathematics education, there is not much high-quality empirical research on robot-assisted mathematics education. As shown in Fig. 8, despite we did not impose any restrictions on the publication time of the papers included in this review, among the 20 selected papers, only six of them were published before 2012. In 2017, the number of empirical studies reached a peak of five papers. The trend line (see the red line in Fig. 8) shows the potential for future research and the rapid development of evidence-based research on teaching and learning mathematical content knowledge through robotics.

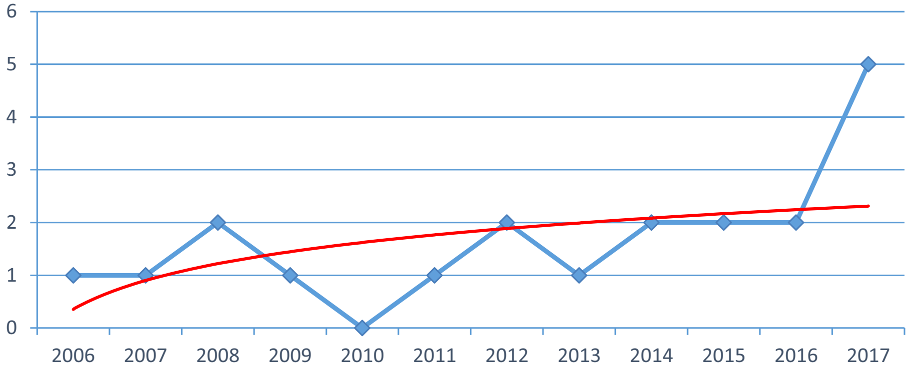


**Fig. 8** Publication time of these empirical studies

As indicated in Fig. 2, among the 20 papers, most of them applied robotics to teach and/or learn mathematical knowledge with a rather small sample size. Two studies (Adams & Cook, 2017; Nickels & Cullen, 2017) implemented robotics activities that were tailored to each participant, rather than designed exactly the same for all participants, so the treatment integrity could be called into question. Considering the small sample groups adopted in existing studies, it is evident that the research findings are not generalizable. Future research should work with larger sample sizes, with the hope of increasing effect size. In addition, a longitudinal study is a promising method for providing more reliable results in the future.

For this review, robotics has been applied to mathematics education with a wide profile of students aged between 3 and 33, from kindergarteners to university students. Future research should replicate current findings with diverse sample groups and pay the path to the younger (PreK-K) and older (university) students who are also able to learn and apply the same powerful ideas.

In spite of the variety of robotics kits available in the market now, most of the 20 papers (52.63%) used LEGO robots. However, it is impossible to provide each student this expensive robot equipment because of the limited budget. In terms of this, one study stands out for teaching mathematical knowledge using open source hardware Arduino (Shankar et al., 2013). This open source tool allows one to use low-cost off-the-shelf components to assemble and rapidly program a microcontroller-based system. Future research can be conducted to further explore the practical value of open-source robot kits (e.g. Arduino) in mathematics education, especially compared with commonly used LEGO.

With regard to the mathematical content knowledge involved in these papers, due to the tangible and observable nature of robotics, it was often used to learn graphic, geometric, and algebraic concepts (e.g. angles, measurement, multiplication, proportion, etc.) in a manner that is concrete, authentic, accessible, and motivating. In addition, the practice and synthesis application of mathematics in robotics activities was also prevailing in some papers (e.g. Keren & Fridin, 2014; La Paglia et al., 2017; Lindh & Holgersson, 2007; Mandin et al., 2017). Nonetheless, the existing attempts to apply robotics to teach and/or learn statistics and probability is rather limited. Future research can start from this point and explore how to make more innovative use of robotics to teach statistics and probability.

In terms of the way robots and mathematics are integrated, three categories emerged: learning by interacting with robots, learning by programming robots, and learning by building and programming robots. Among the 20 papers, almost half of them taught mathematics by engaging students in game-like interactions with robots. Several studies suggested that students can better understand the concept of number and algebra by programming robots (Fernandes et al., 2009; Martin et al., 2006). Moreover, some studies indicated that the experience of building and programming a robot can promote students' understanding of graphics and geometry (Adams & Cook, 2017; Julià & Antolí, 2016). There is, clearly, a need to explore more diverse ways to integrate robotics and mathematics education. It is important to provide multiple entry points into robot-assisted mathematics education for young people with diverse interests and learning styles.

### Effective Intervention Approaches in Teaching and Learning Mathematical Knowledge

In this systematic review, we classified the study type of the 20 papers into three categories according to Benitti (2012) and Trochim and Donnelly (2006) and presented statistical analysis in Fig. 5. Among the three research designs, true experimental research is considered as the most accurate form of experimental design, in that it attempts to suggest or disprove a hypothesis mathematically, through statistical analysis (Trochim & Donnelly, 2006). However, among the 20 papers, only 30% of them were classified as (true) experimental research design. Furthermore, 12 studies did not include rigorous comparison with a control group, thus the effect of the robot is not clear. On the whole, there is a lack of quasi-experimental or experimental research design of using robotics in mathematics education, which exposed the inherent limitations of existing studies. In the future, quasi-experimental or experimental research design with a control group may better explore the effectiveness of robotics treatment in mathematical learning.

The overall results reported in the 20 papers indicated students' positive learning outcomes, including the improvements in mathematical knowledge, attitudes, as well as skills. However, there are still many studies which reported inconclusive results of the role robot plays in mathematics education. Thus, future work should provide more empirical evidence on the potential of robotics in mathematics education.

Although having made significant inroads into many traditionally male-dominated fields (e.g. biology, chemistry), females remained underrepresented in fields related to STEM (Cheryan, Master, & Meltzoff, 2015; Master, Cheryan, & Meltzoff, 2016), and this gender disparities can be traced back to primary school (Ceci & Williams, 2010). For gender differences in robot-assisted mathematics education, contradictory results were reported in the 20 papers. On one hand, Keren et al. (2012), Keren and Fridin (2014), and Mitnik et al. (2008) concluded that there were no significant differences between the learning accomplished by boys and girls. On the other hand, Lindh and Holgersson (2007) and Shih et al. (2012) indicated that gender differences were found in strategies of learning the material, whereas no significant gender differences were found in the ability to build, program, and handle the LEGO material. It provided an evidence that like boys, girls have the same potential in STEM, but they do not follow the usual male image of speed, power, competition, and destruction (Johnson, 2003). The contradictory results on gender differences suggest that future research should further explore this important issue by conducting more rigorous research.

It is apparent from this review that there is a need for a formal evaluation of robot-assisted mathematics education. Self-designed measures, including observation, test/examination, questionnaire, and verbal interview are commonly used data collection methods in existing studies. However, these methods are summative in general, and lack of value for the development of education as well as students. One interesting finding is the utilization of sociograms in one paper (Mitnik et al., 2008). This method provides a new path to conduct "true" process evaluation. It can be applied to diagram the structure and patterns of group interactions, thus analyzing choices and preferences within a group. Since the use of sociograms in robot-assisted mathematics education is still in its infancy, future research can further explore the value of this method.

### Instructional Implications for Applying Robotics to Mathematics Education

The ultimate aim of educational research is to improve teaching and learning, yet previous literature reviews on robotics education (e.g. Benitti, 2012; Mubin, Stevens, Shahid, Al Mahmud, & Dong, 2013; Toh, Causo, Tzuo, Chen, & Yeo, 2016) rarely focused on this point. From this perspective, we made a comprehensive analysis of the 20 papers and presented instructional implications mentioned in these papers in the previous section.

Generally, these papers believed that the unique features of robotics activities (such as being multidisciplinary, hands-on, and integrated) provide the opportunity for students to bring their individual interests, perspectives, and areas of expertise together in order to work on real-world mathematics. For one thing, the interactive nature of robots can help students construct mathematical knowledge through hands-on experience (Adams & Cook, 2017; Brown & Howard, 2014; Keren & Fridin, 2014; Pinto et al., 2015). Specifically, when compared with virtual agents, real robots are considered as a more promising way to provide natural stealth education (Keren & Fridin, 2014). For another, learning through robotics activities means the transition of mathematics from an on-paper exercise to the real-world experience (Fernandes et al., 2009; Lindh & Holgersson, 2007). For many of the students, when applying their knowledge of math concepts solving real-world problems with the help of robots, they develop a lasting hands-on experience in a social context and a better attitude towards mathematics education (Shankar et al., 2013). Given this, future attempts to apply robotics in mathematics education should pay attention to the interactions between robots and learners, as well as the connections between abstract mathematics and the real-world experience.

On the practical level, the limited literature in this field would appear to indicate that the possibilities of robotics are not fully harnessed for teaching and learning mathematical knowledge. As Keren and Fridin (2014) mentioned that, without teacher's acceptance, robotics cannot hope to deliver whatever value it may be capable of in principle. That is to say, we should not expect the educational possibilities of robotics to be the key influence on learning, but rather whether teachers and learners are able to utilize those possibilities to positive effect. In fact, many teachers could appreciate the benefits of robotics, but they were just uncomfortable with the technology aspect. For the future of applying robotics to mathematics education, it will be necessary to know more about what supports teachers and learners need. For example, summer robotics workshop is a good program to provide opportunities for teachers to work with other like-minded individuals for integrating robotics into mathematics curriculum. Students also need additional opportunities to improve their ability to construct, design, and program robots, in order to flexibly use this tool in mathematical learning.

## Conclusion

As robotics opens up new horizons, substantial studies have explored the role of robots in education. However, the existing studies mainly focused on the use of robotics to teach concepts that are closely related to the robotics field per se (e.g. programming, mechatronics) (Mitnik et al., 2008). In fact, robotics is flexible to teach students a range of topics in STEM area (Gomoll et al., 2016; Ponce et al., 2017). Based on the interdisciplinary nature of robotics and the abstraction of mathematical knowledge, this study proposes robotics as a tool for students' mathematical learning, that is, robot-assisted mathematics education. Currently, many studies have conducted exploratory experiments on the value of robotics in mathematics education. This increasing interest calls for a systematic review on the previous studies for the purpose of acting as a "pathfinder" for future research. After a systematic search in online bibliographic database by using a keyword search and a snowballing approach, this paper reviewed 20 empirical studies on the use of educational robotics in mathematics education. The aim of this study is to summarize relevant empirical evidence on applying robotics in mathematics education and to indicate future research perspectives of robot-assisted mathematics education.

The participants of the 20 papers aged between 3 and 33, and the largest sample groups were elementary school students and secondary school students. Nevertheless, 95% of the papers used less than 80 participants. With regard to the robot types used in these papers, the dominant position of LEGO is obvious (52.63%). The specific mathematical content knowledge involved in the 20 papers mainly includes three categories: graphics and geometry, number and algebra, and practice and synthesis application. In terms of the way robots and mathematics are integrated, three categories emerged: learning by interacting with robots, learning by programming robots, and learning by building and programming robots.

We classified the 20 papers into non-experimental, quasi-experimental, and experimental research design. As a result, 10 papers were classified as a non-experimental design, four papers adopted a quasi-experimental design, and six papers belonged to an experimental design. In general, there is a lack of rigorous research design in existing studies. On the whole, the results of the 20 papers suggested multiple learning gains through robot-assisted mathematics education. However, this is not always the case. Some selected papers found that the use of robotics has not brought significant improvement in student mathematical learning in some specific situations. Thus, future work should provide more empirical evidence under rigorous design to explore the potential of applying robotics in mathematics education. In order to evaluate the learning effects, seven data collection methods were found in the 20 papers: (1) observation, (2) test/examination, (3) questionnaire, (4) verbal interview, (5) evaluation of artifacts, (6) think-aloud protocol, and (7) sociograms. Among them, sociograms provide a new path to conduct "true" process evaluation. Future research can further explore the application of this method in robot-assisted mathematics education.

Because few instructional implications suggested in the previous literature reviews, we made a comprehensive analysis of the 20 papers and summarized the instructional implications mentioned in the 20 papers. We further divided these implications into four themes: human-robot interaction, connections between mathematics and real life, pedagogical suggestions, and facility conditions. In summary, we should not expect robotics per se to be the key influence on mathematical learning, but rather whether educators and learners are able to fully capitalize on the educational potentials of robotics, to focus and augment mathematical learning. Otherwise, robotics may only increase the cognitive load of students in mathematics activities, adding "seductive details" that distracted students.

Overall, this study describes a promising picture of applying educational robotics in mathematical learning. By raising the awareness of the educational possibilities of robotics in mathematics education, this paper aimed to support the successful use of robotics in mathematics, both now and in years to come. The outcomes of this study will make it easier for the people who are interested in robot-assisted mathematics education to find related works and guide their practice. This literature review also enables us to understand and forecast the trends of research on robot-assisted mathematics education.

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# Appendix

**Table 2** General information of the reviewed papers

| Paper | Participants | Age/level | Robot types | Mathematical knowledge | The way robots and mathematics are integrated |
|---|---|---|---|---|---|
| Adams and Cook (2017) | 3 | 10–14 | LEGO RCX | Measuring objects using non-standard units (e.g. straws, toothpicks) and then comparing and order-ing the objects using the resulting length measurement | Learning by programming robots |
| Brown and Howard (2014) | 24<br>20 | 18–33<br>15–16 | DARwIn-OP | N/A | Learning by interacting with robots |
| Fernandes et al. (2009) | 7 | 8th grade | Roverbot; Tank | Proportionality as a function | Learning by programming robots |
| Julià and Antolí (2016) | 21 | 12 | Fischertechnik | Spatial abilities: paper folding, card rotation, cube comparison, and perspective taking/spatial orientation | Learning by building and programming robots |
| Keren et al. (2012) | 9 | 3–4 | Nao | Geometric thinking: recognition, visual association, description/analysis, abstraction/relation, and formal axiomatic | Learning by interacting with robots |
| Keren and Fridin (2014) | 17 | 3–4 | Nao | Geometric thinking and metacognitive development | Learning by interacting with robots |
| La Paglia et al. (2017) | 60 | 10–12 | LEGO NXT | Mathematical and metacognitive skills: planning, reasoning, and problem solving | Learning by building and programming robots |
| Lindh and Holgersson (2007) | 696 | 12–16 | LEGO Dacta | The ability to solve mathematical and logical problems | Learning by building and programming robots |
| Mandin et al. (2017) | 28 | 1th–2th grade | Unknown robot | Choosing three numbers out of six, whose sum is a given target number | Learning by interacting with robots |
| Martin et al. (2006) | 18 | 4th grade | LEGO; Handy Cricket | Mathematical representation: permutations, binary representation, and | Learning by building and programming robots |

**Table 2** (continued)

| Paper | Participants | Age/level | Robot types | Mathematical knowledge | The way robots and mathematics are integrated |
|---|---|---|---|---|---|
| | | | | Boolean algebra. Mathematical analysis. Mathematical thinking | |
| Mitnik et al. (2008) | 18<br>29<br>23 | 7th grade<br>10th grade<br>10th grade | Palm Pilot Robot Kit; ER1 robot | Geometric concepts, such as distances, lengths, relative positions, angles, and vectors. The construction and interpretation of 2D graphs. Diverse kinematics concepts | Learning by interacting with robots |
| Nickels and Cullen (2017) | 1 | 14 | LEGO EV3 | Numeracy and the relationship between diameter and circumference. Turns and angles. Using ratios to describe proportional relationships and to determine if the relationship between time and distance was linear. The algebraic relationship between speed and number of teeth on the gears. Measurement. Functions. Probability | Learning by building and programming robots |
| Padayachee, Gouws, and Lemmer (2015) | 40 | 4th grade | LEGO League | Standardized mathematics tests for numeracy and literacy. Mathematical problem-solving skills | Learning by building and programming robots |
| Pinto et al. (2015) | 30 | 11–14 | NAO | The classification of 2D and 3D geometrical figures | Learning by interacting with robots |
| Ponce et al. (2017) | 80 | Elementary grades | LEGO | Geometry issues focus on angles. Distance, fractions, and conversion (cm-inches). Using the wheel parameters, diameter, perimeter to calculate the distance that the robot can reach | Learning by interacting with robots |

**Table 2** (continued)

| Paper | Participants | Age/level | Robot types | Mathematical knowledge | The way robots and mathematics are integrated |
|---|---|---|---|---|---|
| | | | | using the number of wheel turns | |
| Rhine and Martin (2008) | 32 | High school | iRobot Create | Using base number systems to communicate with low-level robot software, using analytic geometry to understand robot's motion patterns, normalizing sensor values for motor power control, and using graphing and algebraic analysis to model sensor performance | Learning by programming robots |
| Shankar et al. (2013) | 17 | 9th grade | Arduino | Using robot to draw geometric art on a large (6′ × 6′) canvas. Using robotic geometric art to solve math equations and word problems | Learning by building and programming robots |
| Shih et al. (2012) | 49 | 11–12 | LEGO NXT | Speed, time, distance, graph, diminution, enlarge, square, and measure | Learning by building and programming robots |
| Walker et al. (2016) | 35 | 4th–6th grade | LEGO NXT | Coordinate geometry problems | Learning by interacting with robots |
| Wei et al. (2011) | 47 | 2th grade | LEGO NXT | Mathematical multiplication | Learning by interacting with robots |

*N/A* not available

**Table 3** Study design and major findings

| Paper | Intervention | Study type[a] | Measurement instruments | Major findings |
|---|---|---|---|---|
| Adams and Cook (2017) | Non-experimental: Math measurement lessons taught by a special education teacher | O X O | Observation; verbal interview; test/examination | Having access to both speech-generating device and a robot gave students multiple ways to show their understanding of the mea surement concepts |
| Brown and Howard (2014) | Experimental: EG: socially interactive robotic tutor; CG: no agent | R X O<br>R X O | Test/examination; questionnaire; verbal interview | Verbal engagement is ideal for decreasing boredom and, ultimately, enhancing test performance in robot-based education |
| Fernandes et al. (2009) | Non-experimental: situated learning; activity theory | X O | Observation | The use of robots to study proportionality as a function aided and supported student learning. |
| Julià and Antolí (2016) | Experimental: EG: robotics course; CG: no activity | R O X O<br>R O X O | Test/examination; observation; evaluation of artifacts | The positive change in spatial ability of the participants in the robotics course (EG) was greater than change evident in the students who did not join the course (CG) |
| Keren et al. (2012) | Non-experimental: "Four Seasons Procedure" conducted by social assistive robotics | X O | Observation | Children's performances on a spatial task were improved while they "played" with robot |
| Keren and Fridin (2014) | Non-experimental: "Four Seasons Procedure" conducted by social assistive robotics | X O | Observation | Children's performances on geometric thinking and metacognitive tasks were improved while they "played" with the robot |
| La Paglia et al. (2017) | Experimental: EG: extra-curricular robotics activities; CG: no activity | R O X O<br>R O X O | Questionnaire; observation | Using robot kits improves students' attitude towards mathematics and it also increases the attitude to reflect on themselves and on their own learning, and higher-level control components |
| Lindh and Holgersson (2007) | Experimental: EG: robotics activities; CG: no activity | R O X O<br>R O X O | Observation; verbal interview; questionnaire; test/examination | There is no obvious over-all effect of LEGO, though there are significant positive effects of LEGO for sub groups of pupils |
| Mandin et al. (2017) | Non-experimental: Robot moves as tangible feedback in a mathematical game | O X O | Observation; verbal interview; think-aloud protocol | Some aspects of the moves of the robot, like its position, are perceived as a form of help and not as a threat, even if they are only partially understood |
| Martin et al. (2006) | Non-experimental: robotic jewelry project | X O | Evaluation of artifacts; observation | Children saw the design unfold over the course of the project, were involved at multiple levels, and became intellectual and practical owners of the resulting system |

**Table 3** (continued)

| Paper | Intervention | Study type[a] | Measurement instruments | Major findings |
|---|---|---|---|---|
| Mitnik et al. (2008) | Quasi-experimental: EG: See-You-There/ Graph-Plotter learning activity; CG: Paper-based/ Computer-based simulation activity | N O X O<br>N O X O | Test/examination; observation; questionnaire; sociograms | A novel use of robots as mediators that autonomously guide an educational activity using a collaborative and constructivist learning approach |
| Nickels and Cullen (2017) | Non-experimental: semi-structured robotics task-based interviews | O X O | Test/examination; verbal interview; observation | This study found evidence of the robotics supporting the devolution of a fundamental situation to a didactic situation of mathematics in each robotics task and evidence of 4 key features (thick authenticity, feedback enabling autonomy, connectivity, and competence) of robotics play that support this devolution |
| Padayachee et al. (2015) | Quasi-experimental: EG: LEGO robotics training; CG: no activity | N O X O<br>N O X O | Observation; verbal interview; test/examination | LEGO robotics training does have a positive effect on mathematical ability and attitude |
| Pinto et al. (2015) | Quasi-experimental: EG1: less interaction group; EG2: high interaction group | N X1 O<br>N X2 O | Test/examination; questionnaire | This study suggests that a high interaction robot is a significant manner to help teachers, motivating children to study at home to defeat the robot in game |
| Ponce et al. (2017) | Non-experimental: A math tutor based on LEGO robots and LabVIEW programs | O X O | Test/examination | The results confirm that the platform helps to increase the kid's motivation about math and it opens new possibilities for teaching mathematics. The kids learn at the same time different topics and skills such as robotics, computer science, mechanical systems, teamwork, and leadership |
| Rhine and Martin (2008) | Non-experimental: Advanced high school-level robotics course called Interactive Robotics | X O | Observation | As much as possible, this study has encouraged students to develop their own mathematical analysis to explain the robot behavior |
| Shankar et al. (2013) | Non-experimental: An elective robotics course on mechatronics | X O | Verbal interview; evaluation of artifacts | This study explicitly shows how students used the robotic art approach to better conceptualize and solve math problems |
| Shih et al. (2012) | Experimental: EG: LEGO NXT supporting mathematics learning system; CG: no activity | R O X O<br>R O X O | Questionnaire; test/examination; observation | The approach used in this study can improve the users' mathematical achievements and strengthen the users' intention to use |
| Walker et al. (2016) | Experimental: EG1: robo-Tangible Activities for Geometry system; | R O X1 O<br>R O X2 O<br>R O X3 O | Test/examination; questionnaire; self-report | While there are no significant learning differences between conditions, students' |

**Table 3** (continued)

| Paper | Intervention | Study type[a] | Measurement instruments | Major findings |
|---|---|---|---|---|
| | EG2: embodied teachable agent condition; EG3: virtual teachable agent condition | | | perceptions of the agent are influenced by condition and prior knowledge |
| Wei et al. (2011) | Quasi-experimental: EG: Joyful classroom learning system; CG: Traditional learning method by using the blackboard | N X1 O<br>N X2 O | Observation; questionnaire; verbal interview | Joyful classroom learning system can provide learners with more opportunities for hands-on exercises and deepening their impressions about the learning contents |

*N*, nonequivalent group; *O*, measures/evidence; *R*, random assignment; *X*, treatment; *EG*, experimental group; *CG*, control group; *N/A*, not available

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