Fostering Students' Creativity via Educational Robotics: An Investigation of Teachers' Pedagogical Practices Based on Teacher Interviews

Yuqin Yang * Yanwen Long

Central China Normal University, China

Daner Sun

The Education University of Hong Kong, Hong Kong SAR, China

Jan van Aalst

University of Twente

Sanyin Cheng

Central China Normal University, China

Author Note

Contact details: yuqinyang0904@gmail.com

Yuqin Yang is an associate professor of the learning sciences at the School of Educational Information Technology in Central China Normal University. Her research interests include pedagogy and assessment of knowledge building, higher-order thinking, learning analytics, metacognition, and collaborative learning.

Yanwen Long is an undergraduate student at the School of Educational Information Technology in Central China Normal University. Her research efforts focusing on robotics education and collaborative inquiry.

Daner Sun is assistant professor at the Department of Mathematics and Information Technology, The Education University of Hong Kong. Her research interests are ICT-supported science learning, seamless learning, teacher education.

Jan van Aalst is a visiting scholar in the Department of Teacher Education, Faculty of Behavioural, Management and Social Sciences, University of Twente. His research interests include pedagogy and assessment of knowledge building and computer-supported collaborative learning.

Sanyin Cheng is an associate professor in Faculty of Education, Central China Normal University. Her research interests include educational psychology and special education.

Abstract

This study explored how educational robotics (ER) was implemented in classrooms to foster creativity among elementary school students and identified challenges associated with its implementation. Twenty-six teachers at different elementary schools were interviewed. In-depth teacher interviews and grounded theory were used to collect and analyze the interviews. We found that the intended creative learning outcome for students was mastery of the developmental process of creativity. The teachers generally reported using a four-phase instructional framework consisting of eight sub-phases and targeted teaching strategies to support students' learning outcomes. Challenges included insufficient appropriate learning materials, a lack of expansive learning activities and tasks, and limited opportunities to engage students in the process of design thinking and developing metacognitive abilities. The findings have practical implications for teachers and researchers who are interested in developing pedagogical practices (PP) incorporating ER to support students' creativity. The study also has theoretical value, offering insights into teachers' PP in implementing ER.

Keywords: Creativity, educational robotics, pedagogical practices, instructional framework

What is already known about this topic

- The development of students' creativity is an educational goal in many countries.
- Some previous studies have investigated the teaching of creativity via ER and relevant technologies and reported positive results.
- There is a lack of in-depth research focused on exploring teachers' common PP when implementing ER to develop students' creativity.

What this paper adds

- We identify an instructional framework that teachers can use to implement ER to develop students' creativity. The framework consists of four phases and eight sub-phases, with targeted teaching strategies in each sub-phase.
- The teachers use the instructional framework to help students achieve mastery of the developmental process of creativity.
- We also identify several challenges to implementing ER; finding answers to these issues should maximize the benefits of ER for supporting students' creativity.

Implications for practice and/or policy

- It is crucial to create a participatory and active culture and set expansive open-ended tasks to encourage students to explore more, to collaborate more, and to take risks.
- Scaffolding students to cope with and benefit from errors and failures, and respecting students' ideas, are crucial for students' development of creativity.
- Teachers should integrate metacognitive skills and teach those skills explicitly.

Fostering Students' Creativity via Educational Robotics: An Investigation of Teachers' Pedagogical Practices Based on Teacher Interviews

Creativity has been identified as a key future-ready skill, and many educators and policymakers have focused on the reform of schooling to help students develop creativity. For instance, the governments of South Korea (Ahn, 2012), Singapore (McWilliam, Tan, & Dawson, 2010), and China (Yang, Long, & Sun, 2019) have introduced policies that call for the development of creativity in schools. The pedagogical use of educational robotics (ER) has shown great potential in affording learning opportunities to engage students and help them develop creativity (Lieto et al., 2017; Denis & Hubert, 2001); however, few studies have examined the pedagogical practices (PP) in the use of ER to foster students' creativity. Here, we define ER as a powerful and flexible technological tool for teaching and learning that provides embodied and situated learning experiences (Ioannou & Makridou, 2018) and encourages students to think creatively, analyze situations, and apply critical thinking and problem solving to real-world problems (Angeli & Valanides, 2020; Bers, Flannery, Kazakoff, & Sullivan, 2014).

Increasingly, a variety of ER and platforms proposed for educational purposes are offered on the market and introduced in classrooms. However, simply introducing ER cannot guarantee that students' creativity will be fostered; ER is just another tool. PP (including instructional processes, strategies, and activities) that involve uses of ER are a critical factor in students' development of creativity.

In practice, various barriers exist to the implementation of ER. One major obstacle is the absence of effective PP for the use of ER in classrooms, a well-defined curriculum, and learning materials (Mubin et al., 2013). These barriers have led to a shortage of experienced and professional teachers in the productive use of ER. Moreover, few studies have provided in-depth investigations of teachers' PP to develop students' creativity via ER. Thus, our study, based on in-depth interviews with 26 teachers from 26 primary schools in Wuhan, China, aimed to investigate teachers' common PP in implementing ER with the purpose of nurturing creativity among elementary school students. The study also was intended to reveal the issues involved in the implementation of ER in classrooms.

Literature Review

Creativity and Teaching for Creativity

Interest in creativity in education has grown exponentially in recent decades (Craft, 2005; Huang et al., 2019). This interest underlies the assumptions that creativity can be developed and that educational contexts are suitable environments for the development of creativity in students (Hernández-Torrano & Ibrayeva, 2020; Mourgues, Barbot, Tan, & Grigorenko, 2014). Creativity is a broad term that involves multiple dimensions; therefore, it is difficult to provide a universally recognized definition. In psychology research, creativity is typically defined as the process that leads to the generation of products that are original and useful (Runco & Jaeger, 2012), and most definitions follow the "bipartite standard definition," (Runco & Jaeger, 2012) in which creativity includes originality and usefulness (e.g., Gajda, Beghetto, & Karwowski, 2017; Sternberg & Lubart, 1995). *Originality* relates to novelty, uniqueness, infrequency, and newness; and *usefulness* refers to utility, effectiveness, appropriateness, or value (Gube & Lajoie, 2020; Hernández-Torrano & Ibrayeva, 2020). The definition proposed by Runco and Jaeger (2012) primarily addresses the features of a creative product, and does not capture other aspects.

Kaufman and Beghetto (2009) proposed a “four C” creativity framework to differentiate levels of creative magnitude. “big-C” is a characteristic of “big-time,” genius-level creativity and implies an achievement that only a select few will reach in their lives; “little-C” is related to everyday creativity and accounts for expressions that are accessible to most people; “pro-C” refers to professional creativity and denotes the creative expressions of experts or experienced people who influence a specific domain; and “mini-C” describes the creativity inherent in the learning process and is particularly related to students’ development of knowledge and understanding in a social-cultural context. At this level, students’ creations are novel, meaningful, and useful to them, though they may not be revolutionary (Hernández-Torrano & Ibrayeva, 2020).

In this study we focused on “mini-C” creativity, which involves the development of students’ ability to engage in tasks by which they could develop new perspectives and meaningful interpretations within a given social context and further generate flexible and fluent ideas and workable solutions. We explored teachers’ PP that involved the development of this mental process in students and engagement in social activities within the normal classroom interaction.

In education, studies of PP that aim to foster students’ creativity have contributed some productive strategies and principles. After a systematic review, Davies et al. (2013) found that designs for creative learning were characterized as flexible use of time, space and outdoor environments; the availability of appropriate resources; respectful teacher-student relationships; and collaboration opportunities. The terms ‘creative learning’ and ‘creativity’ are sometimes used interchangeably (Lucas & Anderson, 2015), but creative learning has a particular focus on individual needs and abilities (Agbowuro et al., 2017) and usually involves an environment that fosters students' habits of challenging and questioning, making connections, exploring diverse ideas and open-ended options, envisaging what might be, and critically reflecting on ideas, outcomes, and actions (Gomez, 2007). In a meta-analysis of 62 empirical articles on teaching creativity in art and design courses, Sawyer (2017) reported that the course teachers created an open-ended environment in which students were encouraged to make decisions, experiment, take risks, and occasionally fail, and they used formative assessment to involve students in creative learning. These designs, though different, primarily involved students in questioning, inquiry, investigation, risk-taking, innovation, divergent and convergent thinking, agency, and metacognition and engage them in a developmental process.

Fostering creativity among students via ER requires context-specific PP; these PP consist of teaching stages and accompanying strategies for each stage in the use of ER. However, few studies have examined the common PP regarding the use of ER to support and promote students' creativity. In this study we aimed to address this gap.

Fostering Creativity via Educational Robotics

ER has attracted much interest from practitioners and researchers in recent years. ER is a multidisciplinary that integrates computer science with mechanical, electrical, and electronic engineering (Nemiro et al., 2015). ER provides students opportunities to work with peers and conduct hands-on projects such as assembling their own robots, and therefore creates a fun and exciting learning experience (Eguchi, 2014). This type of experience is crucial for intense concentration and absorption, and thus generating further creativity (Schutte & Malouff, 2020). Therefore, ER has potential as an effective tool for cultivation of students' creativity. Furthermore, students can gain greater interest and develop new perspectives for thinking (Alimisis, 2013; Bers et al., 2014; Leonard et al., 2016). All of these competencies are critical to the development of creativity in students. The productive PP designed for ER use may allow students to develop their creativity by working with ER to generating original solutions to authentic problems. To embrace this new form of learning, the Chinese government has recently initiated various policies and projects to introduce ER in many schools and to establish courses related to the design, manufacture, and programming of robots in primary and secondary education.

ER is, in fact, increasingly used to develop students' creativity. Leonard et al. (2016) developed creativity in secondary school students with robotic and game design strategies. Bers et al. (2014) facilitated students' development of creativity by providing authentic learning environments, and by encouraging students to implement abstractions to authentic transitional strategies in a figurative way. Berland and Wilensky (2015) fostered students' creativity by providing them with authentic and virtual robotic systems that allow them to apply their acquired knowledge and skills and make innovations. The research and practice of helping students develop creativity via ER has captured the interest of researchers and teachers (Benitti, 2012; Eguchi, 2016; Nemiro et al., 2015). However, the use of ER and research in this area both remain at a stage of inception. Very few studies have examined PP regarding the use of ER to develop creativity in students, particularly primary school students.

Whereas the few previous studies on ER focused on a single teacher or class, in this study we were interested in common PP in the use of ER to develop students' creativity with a broader range of teachers, classes and schools. We aimed to explore how ER was generally implemented in real classrooms to foster students' creativity and to identify challenge in its implementation. We analyzed teachers' PP based on in-depth teacher interviews with the aim of answering the following two research questions.

1. Which, if any, creative learning outcomes are evident when using ER to foster students' creativity?
2. How was ER generally implemented in real classrooms to foster students' creativity, and what were the issues that emerged during the implementation?

Methods

Grounded Theory Approach

This is qualitative study adopting grounded theory (GT) methods. GT is an inductive and interpretive approach to collecting and analyzing data to develop understanding and theories of human behavior patterns in social contexts, rather than basing them on existing paradigms and theories (Glaser, 1992; Glaser & Strauss, 1967). Thus, GT is a suitable approach for investigating phenomena for which limited prior research exists. The study used GT to investigate the fundamental teaching processes and strategies involved in using ER and their learning outcomes. GT assumes that people actively shape the world in which they live through a process of symbolic interactionism, and that this way of living is characterized by change, complexity, and its processual nature (Glaser, 1992).

Research Context and Participants

The study was conducted in two administrative districts of Wuhan, Hubei Province, China. Wuhan was one of the first cities that introduced a variety of ER and platforms into classrooms to help students develop creativity and computational thinking, and that launched a few teacher training programs and encouraged collaboration between companies and schools to improve the ER implementation. Twenty-six teachers who all taught at 26 different elementary schools participated in the study. The 26 elementary schools were chosen based on recommendation of the local Education Bureau because they were performing relatively better than 100 other elementary schools in the districts in using ER. In these schools, ER was used in extracurricular activities, generally in one class of 25–40 students per school. Students in Grades 4–6 were encouraged to take part. Most of the teachers involved (70.8%) were male. Most (79.2%) had a Bachelor degree in computer science or a related field, and 12% of teachers had a Master's degree. The teachers had varying amounts of teaching experience, ranging from one to 20 years; and the majority (78.3%) had taught with ER between one and six years.

Data Collection

Semi-structured interviews were used to investigate the teachers' PP related to teaching creativity via ER. Most interviews were conducted in the teachers' schools and the remainder (5 teachers) were conducted by telephone. All the interviews were conducted individually, and completed over a period of about five months; each interview lasted approximately one and half hours. Teachers were de-identified and their data was traced by labels such as T1 throughout the analysis. Details of the teachers' demographic information are presented in Table S1 in the Supplementary File.

To obtain data with good quality that were characterized by fairness, ontological, educative, catalytic and tactical authenticity (Lincoln & Guba, 2013), we followed the following measures to conduct interviews. All interviews were audio recorded and conducted by two researchers. One researcher interviewed the participating teacher following a pre-designed interview outline, and the other took notes of the key information. We transcribed verbatim each interview once we finished it, and returned the transcripts and the key notes to the teacher interviewed for participant check. In addition, we persistently observed the teaching of four experienced teachers for 3 months to gain better understanding of the ER activities and practices and further to get better interpretations of the teachers' interviews.

The teacher interviewees were asked to give explicit instructional examples to illustrate their answers to the questions in the interview protocol. The interview protocol (S1 in the Supplementary File) was developed based on research on creativity (Sawyer, 2017, 2018), creativity fostering teacher behavior (Soh, 2017), and educational robotics (Kim et al., 2015; Xia & Zhong, 2018). It consisted of five questions each of which targeted the teachers' perceptions of the effect of ER on creativity, how to teach, methods used, how to motivate students and assessment and reflection conducted.

Data Analysis

We used grounded-theory methods "to interpret participants' tacit meanings" and to identify connecting relationships among these meanings in an emergent framework (Charmaz, 2014, p. 114–15). We used an iterative three-stage constant comparative method to identify themes in the interview data (Glaser & Strauss, 1967). The iterative process concluded when the analysis reached saturation (Charmaz, 2014; Corbin & Strauss, 2008);

that mean no new themes emerged in the interview data.

Stage 1: We conducted a thorough analysis of the interview transcript. All meaning units related to teachers' practices in using ER to support students' creativity were coded, and an initial list of themes was generated. We wrote a brief description or keywords for each theme. This process resulted in a teaching framework with 50 codes.

Stage 2: We reanalyzed all 26 transcripts and compared descriptions related to these initial codes, resulting in 24 themes. Sixteen themes were found across all of the teachers and eight were found for only three teachers.

Stage 3: The stage also involved constant comparison. We recoded the full transcribed data set, dividing and merging the initial themes as follows: (a) themes that were overly narrow in definition were merged with a related theme, and the newly merged theme was given a broader definition that incorporated both; and (b) themes that were overly broad in definition—those that coded a large number of meaning units and seemed to encompass two distinct themes—were divided.

This multistage comparative method resulted in the identification of twelve emergent themes, which are described in the next section.

The trustworthiness of the analysis was enhanced through consistent observation, and rigorous coding. We observed four teachers' classrooms for approximately 3 months. We presented the preliminary findings to three experienced teachers interviewed, our whole research team, and two international peer-review conferences, and used their comments and feedback to improve the analysis.

Findings and Discussion

Creative Learning Outcomes of Using ER

RQ1: Which, if any, creative learning outcomes are evident when using ER to foster students' creativity?

This question focused on the primarily intended creative learning outcomes among students who use ER. One primarily creative learning outcome was identified.

Mastery of the developmental process of creativity. We found that the most significant outcome was mastery of the developmental process of creativity. In the interviews, some teachers said that the more things students touch, the more they think and reflect, and the more ideas they then can generate (T20, T22, T25, T26). When counseled by teachers, the students could gradually develop their own new ideas and generate new and workable solutions (T16, T17, T18, T20, T22). T22 mentioned that "students' creative thinking skills develop along with the degree of complexity involved in building models and in programming." T6 pointed out, "sparking creativity is vital in implementing ER. With no drawings or templates to constrain students, they can use their imaginations and create spontaneously. We as teachers need to give students enough space to build and create." These statements suggest that teachers believe that the development of creativity is a non-linear iterative process that is aided by constant articulation of the process and reflection on how the process is unfolding. Therefore, teachers should provide students with appropriate scaffolding to guide their developmental process of creativity (Dennen, 2004; Sawyer, 2018; Yang et al., 2019).

The study finds that the primary creative learning outcome in using ER is the mastery of the developmental process of creativity. The findings concur with prior research on the effects of ER on creative learning outcomes (Bers et al., 2014; Leonard et al., 2016; Xia & Zhong, 2018). The findings are also consistent with prior research on creativity (Hernández-Torrano & Ibrayeva, 2020; Sawyer, 2018; Yang et al., 2016), according to which creativity, developed from curiosity, motivation, and engagement, is a deliberate process that can be taught and learned. In addition, the findings are consistent with research suggesting that creativity development requires the gradual acquisition of discipline-specific knowledge and skills (Qian, Plucker, & Yang, 2019).

Pedagogical Practices (PP) Related to Instructional Phases and Accompanying Strategies in Implementing ER and Issues Emerged

RQ2: How was ER generally implemented in real classrooms to foster students' creativity, and what were the issues that emerged during the implementation?

The question focused on the PP designed to help students develop their creativity in classrooms. Specifically, we examined the general instructional phases used when implementing ER, the teaching strategies designed to foster students' creativity in each phase, and the issues that emerged during ER implementation.

We identified four instructional phases, each of which had two subphases, and the strategies teachers used in implementing ER in each phase. The four phases with eight subphases and targeted teaching strategies constituted an instructional framework (Figure 1) for implementing ER. Details of the teaching strategies are presented in Table S2 in the Supplementary File. We also identified the issues that emerged in implementing ER. In the following sections, we report and discuss the findings in detail.

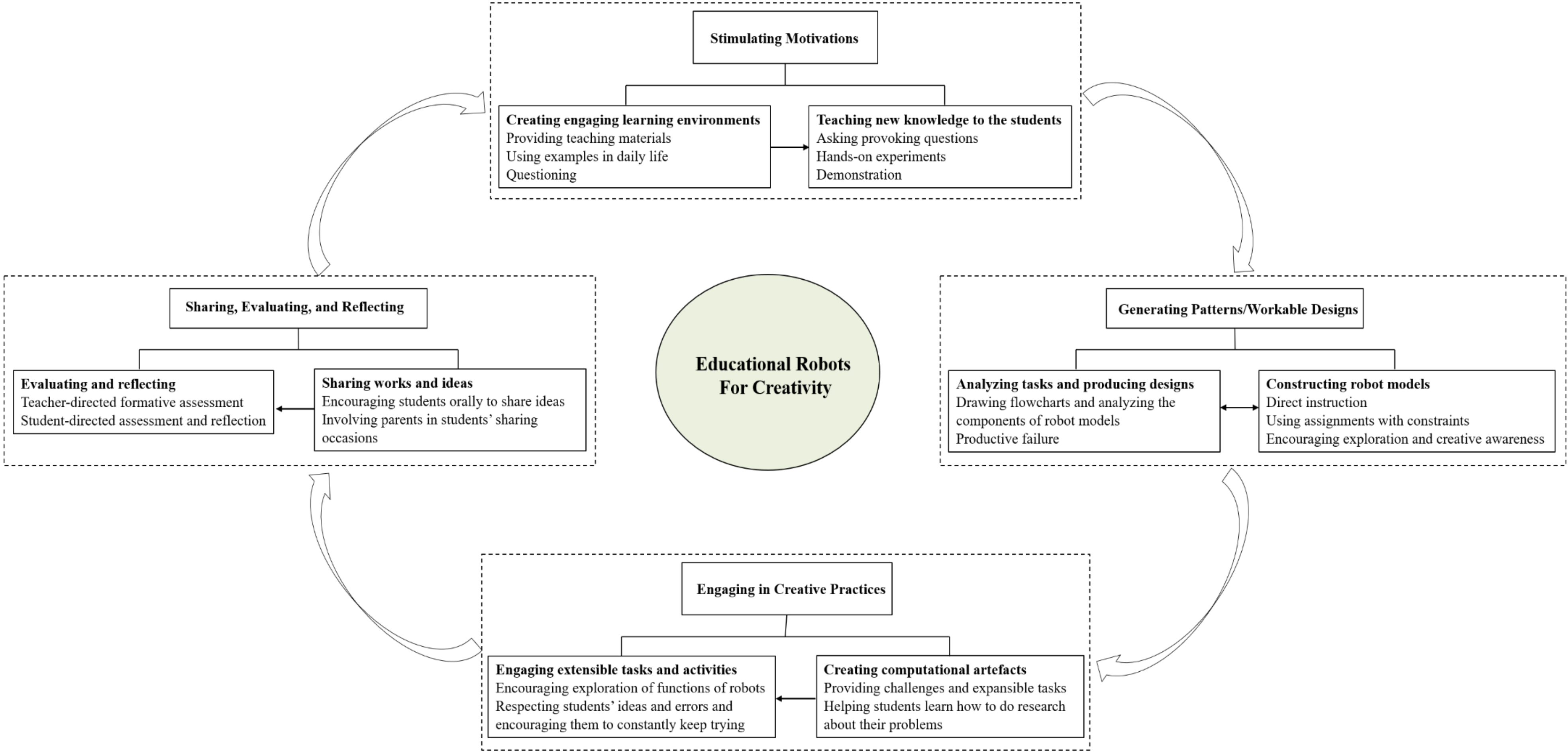

Figure 1. Instructional framework for teaching creativity via educational robotics

Stimulating Motivation to Be Creative

Stimulating motivation to be creative was the first phase of the instructional framework. The focus of this phase was promoting students' curiosity and motivation, eliciting their prior knowledge, and helping them engage in new concepts. This phase included the following two subphases.

Creating an engaging learning environment

This subphase aimed to design appropriate learning context to motivate students to be creative and engage them in the learning tasks and activities. During this subphase, three main types of teaching strategies were adopted. The first strategy was providing teaching materials with rich and well-tailored resources (T20, T18, T7, T14). The teachers provided resources that fully considered students' characteristics and learning habits. These resources included the use of vivid language (T20), visualizations (i.e., images and animations) (T18), and multimedia resources (i.e., videos) related to the topics (T7, T14). T14 mentioned, "the videos targeted at boys and girls are different in their colors and design style, as girls prefer a more vivacious style. Moreover, age is another factor to be considered."

The second strategy was using examples from daily life to help students generate questions and find possible alternative solutions (T15, T23, T14, T22). For example, when T15 mentioned that the anti-pinch function of the lift door was controlled by an infrared sensor, some students used a robot vacuum cleaner as another example of integrating infrared sensors to avoid obstacles.

Teaching new knowledge to the students

In this subphase, the teachers introduced new concepts or technological or scientific explanations to the students in a direct, formal, and explicit manner.

In this subphase, the main methods used by the teachers were asking provoking questions (T1, T8, T14, T15), hands-on experiments (T8, T9, T18), and demonstration (T14, T15, T16). In particular, when implementing ER in classrooms, helping students to construct a robot was an important part of the lesson. Therefore, the teachers used different ways to help students understand the core elements, principles, and structures of robot models. For example, some teachers provided students with pictures of different viewpoints of a model (T5, T14, T18, T19), and some teachers guided students to identify and elaborate on certain principles in the models, such as symmetry or the stability of triangles (e.g., T15) and the lever principle and gear occlusion (T23).

In the teacher interviews, we found that nearly one third of the teachers did not mention this subphase. Some teachers reported difficulties in teaching new knowledge for the following reasons: the concepts were too abstract to be taught (T15, T17, T18, T20); the scientific/technological explanations or other knowledge taught was dull (T1, T10, T15); it was difficult to choose appropriate scenarios related to the new knowledge (T13, T15); and an appropriate curriculum was lacking (T2, T5, T13, T15).

Motivation is a major element that considerably influences creativity; it helps with full engagement in creative learning (Hennessey, 2010; Mackinnon, 1965). Creating an engaging learning environment promotes cognitive disequilibrium in the students. Teaching new knowledge to the students gives them a baseline understanding of the knowledge and skills related to their learning tasks. These two subphases help students get ready for the subsequent phase of generating patterns. However, issues such as the lack of a flexible school curriculum, a lack of appropriate teaching materials, and old methods of teaching and learning were identified and need to be addressed.

Generating Patterns/Workable Designs

Developing students' creativity via ER requires students to operate robots and computers. This phase, the second phase of the instructional framework (Figure 1), was to help students get involved in mental and concrete design and hands-on activities that could help them conceive and refine designs, construct robot models, and develop design thinking, all of which are important for developing their creativity. Design thinking is characterized by an iterative loop of divergent-convergent thinking, uncertainty handling, and decision making (Dym, Agogino, Eris, Frey, & Leifer, 2005). This phase included the following two sub-phases.

Analyzing tasks and producing designs

In this subphase, the students were required to analyze the tasks and generate designs for constructing robots after they learned the basic knowledge and skills. Generally, the students spent limited time on the design of their robot models. Two types of teaching strategies emerged in this phase. One was encouraging students to decompose tasks and explore more with scaffolding, which was used by 80% of the teachers. The common methods used in this strategy were drawing flowcharts, analyzing the components of robot models, and realizing their functions (T5, T8, T9, T10, T19, T18, T22, T23, T26). T18 suggested, “it is useful to provide different stereoscopic representations of the models to students for observing and taking notes, with the purpose of identifying the components and parts of these models and getting more insight into how these parts connect with each other.” After helping the students understand the basic procedures, the teachers encouraged the students to explore more.

The other strategy was *productive failure*—teachers first encouraged the students to explore multiple possible solutions to solve the problems and then guided them to consolidate the final solutions (Kapur, 2008; Kapur & Bielaczyc, 2012). When using productive failure, emphasis was placed on students’ inquiry (individual or collaborative) into the structure and function of the robot models. T8 said, “students should constantly try to revise their ideas in practice. They should have ideas, but not unrealistic ones. By doing so, they can find problems, solve problems, and possibly create innovations.” T12 mentioned that he guided students to think about different ways to make an induction lamp, for example, through sound control, light control, an infrared sensor or distance sensor, and he said that “in this way, students can choose from different angles and improve creativity subtly.” These quotes illustrated that the teacher valued students’ solutions and diverse ideas that may did not work at the beginning and thought this failure was important for students’ final successful solution. Learning to deal with errors and failure is critical for students’ learning and creativity (King et al., 2017).

Constructing robot models

In this subphase, the students engaged in constructing the robots, which took most of the time. The most frequently used strategy was direct instruction. Almost 80% of the teachers provided direct instruction to the students via video demonstration, visualizations, or guidelines.

The second strategy was using assignments with constraints to enhance students’ creative learning (T2, T3, T13, T15). T13 said, “Teachers need to consider the open-ended nature and expansibility of the tasks… We put forward the *basic requirement*, and the students continue to diverge…For example, when the students can control the car to move, the teacher then introduces the use of sensors and puts forward the requirement that the car should be controlled. Students need divergent thinking for better installment and for using sensors to meet the requirement.” The constraints helped students to avoid becoming directionless and to make choices about where to focus; these constraints were critical for the creative process (Sawyer, 2018).

The third strategy was encouraging students to explore more and emphasizing their awareness of creativity. Many teachers *created exploratory opportunities* for the students to encourage them to construct robots by relying on their own imagination and creativity (T1, T2, T3, T7, T8, T9, T10, T12, T13, T14, T15, T16, T18, T19, T20, T22, T23), and some of the teachers did not provide any drawings or templates to constrain the students (T15, T20). Some teachers directed students' creative awareness by encouraging new ideas (T1, T3, T7, T9, T15, T18, T19, T23, T26). T1 mentioned, "when I evaluate models that the students have constructed, I prefer to give A+ grades for the robots of helicopters that may go far beyond the typical model in the instructions by extending the length of the empennage and adding more wheels, [whereas I give an] A to those models that carefully follow the instructions." This excerpt suggested that A was given to students whose robots just meet the basic requirement and A+ to students who generated new and useful solutions to promote diverse and new ideas.

In sum, the PP reported in the phase of generating workable designs suggest that some teachers helped the students to cope with frustration/failure and learn from failure, provided assignments with constraints to guide students' creative learning, and created exploratory opportunities to encourage students to generate multiple models that might be creative. These results are consistent with prior research on creativity (Nathan & Sawyer, 2014; Sawyer, 2017, 2018; Yang et al., 2019). However, in this phase, the students spent most of their time constructing robots, with less time spent on producing designs for constructing robots; indeed, the students in some teachers' classes even constructed models without conceiving designs. Involvement in the process of conceiving designs considerably contributed to the students' development of creativity (Dym et al., 2005; Yang et al., 2019).

Engaging in Creative Practices

In this phase, the third phase of the instructional framework (Figure 1), the students engaged in programming, testing, and debugging to generate creative artefacts that could be a prototype of something or a model or simulation that would eventually become a physical artefact. During this process, students gradually developed their logical thinking and programming abilities, which are critical components of creativity in ER practices.

Creating computational artefacts

Programming, testing, and debugging constituted one of the key subphases mentioned by 88% of the teachers, as coding is extremely important in ER activities. Programming itself is a creative process, which produces computational artefacts (Grover & Pea, 2013). In this subphase, the teachers used two main strategies. The first one was providing students with challenges and expansible and open-ended tasks that encourage them to make creative choices about how to proceed and then guiding them to act creatively and independently. In the interviews, T1 mentioned, "[o]ur teachers can't simply give directions to students because the purpose of the class is to help the students develop their own creative problem-solving skills.… [T]he teachers ideally guide students to reflect on why they made mistakes." The second was helping students learn how to do research about their problems. In this method, the teachers encourage the students to first engage in creative learning (e.g., solving problems, making artifacts, and following their own path) and then ask them to observe the results, evaluate what had caused the present results, and decide what to do next (T6, T8, T15, T16). It is critical for students to be able to analyze and reflect on the decisions they have made (Yang et al., 2019; Yang et al., 2016). T15 mentioned, "We can't simply give solutions; it is meaningless when students don't think deeply in the problem-solving process. Therefore, when students have problems, the teacher ideally guides them to *reflect* on why they make these mistakes."

Engaging extensible tasks and activities

The subphase was to help students engage in extensible and open-ended tasks that are crucial for the development of creativity. In this subphase, one of the teaching strategies was encouraging students to explore various functions of the robot models to inspire their creativity (T14, T15, T19, T20, T26). T15 described an example: "If I want my students to be creative with a model car, I will inspire them by showing the car's potential for diverse uses such as transportation, emergency services, and engineering. The students will then work on their own designs.… I help my students through realization of these specific structures and functions." These expansive explorations may benefit students when they complete a creative project that integrates diverse things: students can think and play freely.

The other strategy was respecting students' ideas and errors and encouraging them to constantly keep trying. When students were in trouble, the teachers respected the students' ideas and choices (T1, T2, T5, T6, T7, T8, T10, T11, T12, T13, T15, T16, T17, T19, T20, T22, T23, T26). T26 mentioned, "As teachers, we should look at their [students] problems from a higher angle and analyze the reasons; it is not [about] imposing directions on them. [For example, we could] just tell them that they may encounter obstacles when they go left, [but] students can choose by themselves."

The PP reported in the phase of creative practices suggest that some teachers used a learner-centered, open-ended pedagogy to encourage their students to get involved in creative learning and acted as facilitators who "lead, elicit, guide, and encourage" (Billings & Akkach, 1992, p. 441). These PP show alignment with recent research on creativity (Nathan & Sawyer, 2014; Sawyer, 2017, 2018; Yang et al., 2019). However, many students have limited opportunities to engage in extensible tasks and activities, which are critical for developing creativity, because of the time limit imposed on each lesson.

Sharing, Evaluating, and Reflecting

In this phase, the forth phase of the instructional framework (Figure 1), the teachers encouraged the students to share their ideas and work with peers, to assess and reflect their understanding and abilities, and to eventually extend their understanding. However, only a few teachers involved their students in sharing, assessment, and reflection. This phase included the following two subphases.

Sharing work and ideas

After the students had generated computational artefacts, some of the teachers gave them opportunities to share their ideas and encouraged them to voice their own various ideas. We found that one third of the 26 teachers encouraged students to share their works in class. The most common approach was encouraging students to orally share their ideas on their robot construction, coding process, logistic thinking, and operational experiences (T6, T14, T18, T23). For example, T18 asked students to explain the knowledge they had learned and the reasons for their design and construction, as well as the key aspects of and difficulties they faced during their work. Another approach was involving parents in students' sharing occasions. In the interviews, some teachers pointed out that some of the more mature and capable students were highly motivated by the course itself and by the interactions with their teachers and parents (T1, T2, T6, T9, T20). T6 commented, "recognition of the students' accomplishments by the teachers and parents is the most effective [incentive]." Therefore, some teachers invited the students' parents to participate in the students' sharing of artefacts (T18, T20).

Evaluating and reflecting

In this subphase, teachers and students assessed and reflected on their learning. The predominant assessment method was teacher-directed formative assessment. In the classrooms, some teachers frequently praised their students verbally. T15 commented, "In front of the students, encouragement is the main thing. Every child may do something unique and has his or her own strengths. We as teachers need to recognize the students' uniqueness and make them know that we appreciate this uniqueness." After being praised more, the students may become more involved in accomplishing the task with confidence and enthusiasm. Gradually, the students may build a sense of achievement, particularly when their designs and programming operations run normally.

Another assessment method was student-directed assessment and reflection. When working with ER, students were required to reflect on the knowledge they had learned and the ideas that indicated creativity, difficulties, and functions in constructing models and programming (T5, T8, T10, T14, T19, T22, T23, T25). For example, T8 mentioned, “Students need to clarify the operation principles of the gate, and they have to show the running effect and programming process of the finished product.” Generally, different teachers asked students to value different aspects in self- and peer assessment and reflection. Some teachers valued the enhancement of knowledge and skills in coding (e.g., T6); some appreciated the optimization of the works and the smoothness of the program (T10, T11); and some emphasized the development of students’ creativity (T6, T8, T9, T18). For example, T18 mentioned, “there should be no standardized assessment, as this will depress students’ creativity.” T9 commented, “the learning goal of ER is not the final product but students’ interest, sense of achievement, and creativity.” These findings suggest that the teachers had different views on what should be assessed, which had an important influence on the students’ development of creativity.

Sharing, evaluating, and reflecting provide an important opportunity for students to use the skills they have acquired, evaluate their understanding (Taylor & Gardner, 2006). These methods can help students to take agency (Yang et al., 2019) and are critical for their development of creativity when working with ER. Most importantly, sharing, evaluating, and reflecting enable students to develop metacognitive skills (such as planning, reflecting, evaluating, and regulating) and thus learn how to learn (White & Frederiksen, 1998; Yang, 2019; Yang et al., 2016). However, very limited PP related to sharing, assessment, and reflection have been developed. Only a few of the teachers in this study sought to create opportunities for students’ informal sharing and assessment.

Teaching creativity via ER requires PP characterized by authenticity of tasks, student agency and metacognition, flexibility, the encouragement of creativity, and openness to novelty (Alimisis & Moro, 2016). The PP developed around the instructional framework (Figure 1) in our study are participative, active, and flexible, encourage students to take agency in questioning, identifying issues, building models, taking risks, conducting experiments, programming creatively, and coping with and further benefiting from errors and failures, and engage students in evaluating and reflecting in order to engage in creative processes. The PP demonstrate the above characteristics, and share substantial similarities with many of the key learning-science principles, including authentic learning environments for participation, discovery and inquiry, metacognitive assessment and reflection, student agency, and learning from errors and failures. These principles have been shown to be effective for developing students' creativity and other higher-order skills (e.g., collaboration, knowledge creation) (Brown, 1997; Navarrete, 2013; Yang et al., 2019, Yang et al., 2016). Therefore, our instructional framework should be able to foster students' creativity. Additionally, we identified several issues that emerged during ER implementation; these issues stimulate opportunities for further investigation

Conclusion and Implications

This study addresses the important problem of providing an instructional framework (Figure 1) for implementing ER in classrooms to help students develop their creativity. The small number of existing studies focused on a single teacher or class. This is the first study to explore common PP for using ER based on in-depth interviews with a broad range of teachers, classes and schools. We directly investigated how ER is implemented in classrooms to foster students' creativity and identified the challenges of implementing ER.

This study contributes to research on teaching creativity via ER by proposing a pedagogical framework that consists of four phases and eight sub-phases, along with targeted teaching strategies. In many cases, teaching creativity via ER is merely reinforcing old ways of teaching and learning, such as step-by-step recipe-style guides to assemble "amazing robots." However, the PP developed around the instructional framework in our study revealed the characteristics of student agency and metacognition, authenticity and flexibility of learning environments and tasks, inquiry and discovery, learning from errors and failures, openness to novelty, and encouragement of creativity gradually; these characteristics are critical for fostering students' creativity (Brown, 1997; Navarrete, 2013; Sawyer, 2017, 2018; Yang et al., 2019). Our framework should be capable of helping students develop creativity. Although this framework was generated for ER activities, it should be applicable to other subjects and disciplines that involve mental and hands-on activities as well as higher-order skills.

This study also contributes to research on implementing ER by identifying several issues for further investigation. These issues include how to design learning materials and a flexible school curriculum, how to engage students in conceiving designs for constructing models, how to create expansive and open-ended tasks to engage students in creative practices, and how to design metacognitive opportunities (e.g., assessment and reflection) and scaffolding to support students' agency and metacognition. Finding and applying the answers to these questions might guarantee the benefits of integrating ER into learning.

In sum, this study offers insights into teachers' common PP in implementing ER to foster students' creativity. The findings also have practical implications for teachers and researchers who are interested in developing productive PP using ER to support students' development of creativity.

Implications for Educational Practices

The findings of this study have several implications for teaching creativity via ER. First, it is important for teachers to hold beliefs that creativity is a working process; that is, it is iterative and involves risk-taking, errors and failures, issue identification, model construction, progressive investigation and experimentation, and problem solving. Second, it is crucial to create a participatory and active culture and set expansive open-ended tasks to encourage students to participate more, to explore more, to collaborate more, and to take risks. Such a culture can be enabled by gradually fostering a sense of epistemic agency and guiding students to inquire, collaborate and reflect, individually as well as collaboratively. Third, scaffolding students to cope with and benefit from errors and failures, and respecting students' ideas, are crucial for students' development of creativity. Teachers can use strategies such as providing choices, accepting students as they are, and boosting their self-confidence. Fourth, teachers should integrate metacognitive skills such as assessment and reflection into the creative learning process and teach those skills explicitly. This can be achieved through creating reflection opportunities opportunistically and designing appropriate scaffolding to guide students' assessment and reflection.

Limitations and Future Directions

This study has some limitations. First, we relied primarily on in-depth interviews with teachers to explore PP in implementing ER. We did not conduct persistent and systematic observations of and prolonged engagement with the majority of the teachers' classes (Lincoln & Guba, 2013), which are crucial to generate accurate findings and interpretations. Therefore, future studies are needed to examine teachers' PP through both in-depth interviews and familiarity with their practices based on observation and engagement. Furthermore, interviews with teachers from different districts are needed to refine the understanding of common PP identified in this study.

Second, this study focuses on teaching rather than students' learning. We identified an instructional framework for implementing ER, based on what the teachers perceived to be effective for fostering students' creativity. However, very few empirical studies have been conducted to identify the causal relationships between teachers' PP and students' development of creativity. Further research is needed to examine whether these practices lead to the development of creativity.

Statements on open data, ethics and conflict of interest

a. Requests for data may be made to the corresponding author.
b. This project was conducted with full ethical approval from the Central China Normal University
c. The authors do not report any conflicts of interest.

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