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ORIGINAL ARTICLE

Creativity and mathematics education: the state of the art

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Abstract This paper draws connections between studies in general creativity and studies in mathematics education. Through analysis of the state of the art in the research in creativity as associated with mathematics education we review manuscripts included in this special issue. We consider definitions of creativity and the approaches to studying creativity as historically developed and as applied in studies presented in the current issue. We pay special attention to the relationship between creativity, high ability and giftedness. We analyze creative product, process, person and press as focal points chosen by researchers in order to analyze the role of mathematics education in the development of students' creativity. Finally we explore research methods that can be used when studying creativity and those used in studies presented in this special issue. We stress the importance of the advancement of research on creativity in mathematics education and consider this special issue as an important step in raising the awareness of the community of researchers in mathematics education of this intriguing personal and social trait.

Keywords Creativity · Mathematics creativity · Research methods and approaches

1 On the importance of research on creativity in mathematics education

Creativity is a personal and social trait that fosters human progress at all levels and at all points in history. Technological progress and inventions and the development of mathematics are interwoven: mathematical developments facilitate technological progress, while developments in technology and science require development of mathematics. Some of the ideas of ancient scientists and philosophers were realized only after meaningful progress was made in mathematics and science. We acknowledge that basics of creative thought are developed at earlier ages and during school years. The role of social and environmental factors is invaluable in the development of creative talent.

Historically speaking, creativity has been a long-neglected domain. Sternberg and Lubart (1999) reported that during the 20-year period between 1975 and 1994 a mere 5 % of the articles indexed in *Psychological Abstracts* were associated with creativity. Establishment of the *Journal of Creative Behavior* was directed predominantly at teaching people to be more creative. The need for empirical research on creativity led to the establishment of the *Creativity Research Journal*. In mathematics education only a late interest in creativity research can be observed. Since Haylock (1987) called for greater attention to be paid to creativity in the mathematics classroom and Silver (1997) suggested connecting problem posing and problem solving to Torrance's (1966) categories of creativity (see later in this section and in Leikin and Lev in this issue), very little research has been done on creativity in mathematics education. Haylock (1987), when reviewing educational literature from 1966 till 1985, demonstrated that the subject of creativity is neglected in mathematics education research. Two decades later Leikin (2009a) analyzed publications from 1999 till 2009 in seven leading research journals in mathematics education and seven leading journals in gifted education, and demonstrated that very few publications in mathematics education were devoted to

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creativity-related issues while research devoted to creativity within general psychology paid very little attention to mathematical creativity. Fortunately, the mathematics education community has been devoting more attention lately to this issue. Publications such as Leikin et al. (2009) and Sriraman et al. (2009) confirm this observation. Additionally, the new ICME-affiliated International Group for Mathematical Creativity and Giftedness (MCG) was established in 2010 (http://igmcg.org); the ICME-11 and ICME-12 conferences devoted work of discussion groups to this topic; and the ERME conference established a new Working Group (WG-7 'Mathematical potential, creativity and talent' at CERME 7 and CERME 8) whose purpose is to raise the mathematics education community's awareness of the fields of mathematical creativity, mathematical potential and mathematical giftedness. Nevertheless, only a small number of empirical studies on creativity associated with mathematics have been carried out.

This special issue aims to reflect current research on creativity in mathematics education and to encourage international exchange of ideas related to the empirical and theoretical research on creativity in mathematics and mathematics education and on creativity in teaching and learning mathematics. Researchers of mathematics education who have contributed to this special issue make use of the progress achieved in general creativity as well as advancement in mathematics education to study multifaceted phenomena of creativity in mathematics education.

In this introduction we provide an overview of research literature on creativity in general, with special emphasis on creativity in mathematics and creativity in mathematics education. Our aim is to highlight these fascinating fields within this special issue.

2 Creativity: definitions and approaches to the study of creativity

The research community's views on creativity have changed over time. These changing perspectives on what creativity is are reflected in the lack of a clear, widely accepted definition of creativity, and this is an impediment to the research on creativity (Mann 2006).

Initially, creative ideas were considered to be generated mystically (Sternberg and Lubart 1999). Subsequently, the mystical approach to creativity was replaced by a pragmatic approach which was mainly engaged in the ways of developing creativity. These techniques for developing creativity included brainstorming (Osborn 1953), analogy-based thinking (Gordon 1961) and role play (von Oech 1986). However, these methods were not proved to be productive, since there were no available tools for the evaluation of creativity.

The need to evaluate creativity led to the development of psychometric approaches. In 1950 in his seminal APA address, Guilford (1967) proposed that psychometric tools should be applied to evaluate creativity in all individuals, and introduced instruments of "divergent thinking" for the evaluation of creativity. To evaluate divergent thinking he suggested implementing "many uses" tasks in which subjects were asked to pose as many uses as possible for certain ordinary objects. Following Guilford, Torrance (1966, p. 6) defined creativity as "a process of becoming sensitive to problems, deficiencies, gaps in knowledge, missing elements, disharmonies, and so on; identifying the difficulty; searching for solutions, making guesses, or formulating hypotheses about the deficiencies: testing and retesting these hypotheses and possibly modifying and retesting them; and finally communicating the results". Torrance (1966) designed a Test of Creative Thinking. The test requires performance on verbal and figural tasks that can be evaluated by fluency (total number of appropriate responses), flexibility (the number of different categories of responses), originality (rarity of responses) and elaboration (amount of detail used in the responses). However, there is a debate as to whether this evaluation captures the essence of creativity. In our special issue a number of authors base their evaluation schemes on Torrance's categories. Studies by Kattou, Kontoyianni, Pitta-Pantazi and Christou (this issue), Leikin and Lev (this issue), Pitta-Pantazi, Sophocleous and Christou (this issue), Tabach and Friedlander (this issue) and Voica and Singer (this issue) assess the level of creativity of participants in terms of fluency, flexibility and originality of mathematical reasoning associated with problem solving and problem posing.

Cognitive approaches to the study of creativity have been directed at the analysis of cognitive processes associated with creative reasoning (Sternberg and Davidson 1995). These studies consider mental processes underlying human creativity including use of different representations, constructing mental connections between different objects and providing explanations and justifications, and solving problems of different kinds. As such, these studies analyze cognitive processes acting on the knowledge already stored in the memory of the individual that lead to creative products. These studies, for example, pay attention to illumination. In this issue Peter Liljedahl presents his study, which makes use of questions from Hadamard's seminal survey (1945), in which 25 prominent research mathematicians responded regarding their experiences with discovery, creativity and invention in general, and illumination in particular. Based on the findings of previous studies, Liljedahl (this issue) assumed that the phenomenon of illumination is a cognitive transformation—a leap in understanding. However, this assumption was not supported by his study with preservice mathematics teachers.

Further examination with a different population group might lead to better understanding of illumination as an integral part of invention.

Social-personality approaches to creativity emphasize affective creativity-related factors, as well as socio-cultural characteristics, as sources of creativity (Sternberg and Lubart 1999). According to Sawyer (1995), a creative process from the social perspective can be considered as a collaborative improvisation in which creativity emerges from a complex interactional process. Among other personality characteristics that were identified as being related to creativity, Shani-Zinovich and Zeidner (2009) critically review what is known about the personal and affective development of gifted students. They first consider developmental issues followed by personality facets, social processes, and a discussion of the implications of the personality profile for mental health and well being of gifted adolescents. The authors address broad dimensions of personality (i.e. openness, conscientiousness, extroversion, agreeableness and neuroticism) and the two narrow-band personality variables (self-concept and anxiety) and argue that both types of personality variables influence to a great extent the realization of intellectual talents. The models of Subotnik et al. (2009) include personal-psychological attributes among the factors that influence talent development, including "teachability", self-evaluation, responsiveness to extrinsic rewards, mathematical inclination, self-promotion, and the ability to learn how to play the game. They also stress risk taking as being one of the personality traits that promote innovation. Csikszentmihalyi (1988) argues that "creativity is a process that can be observed only in the intersection where individuals, domains, and fields interact" (p. 314). Creative ideas are those that are considered by the reference social group as new and meaningful in a particular field.

Wallas (1926), in his seminal work *The Art of Thought*, suggested a four-stage Gestalt problem solving model that included: preparation, incubation, illumination and verification. Understanding details of such stages and sequences yielding creative productions is a central issue for creativity research. Lately neuroscience has contributed to the understanding of insight (illumination-based) mechanisms. For example, Dehaene et al. (1999) demonstrate that mathematical intuition is an interplay between spatial imagination, abstraction and approximate reasoning on the one hand, and analytical reasoning or visual–spatial and linguistic thinking on the other.

Viewing creativity as a social-personal concept leads to a distinction between different types of creativity with respect to their contribution to the scientific fields and to the arts. A paper by Leikin and Lev (this issue) following Leikin (2009b) considers creativity in school students as relative creativity since this creativity is usually considered with respect to their own educational history and in comparison with other students. Students' ability to produce mathematical ideas/solutions in a new situation (to a new mathematical problem that was not learned previously) or to produce original solutions to previously learned problems is usually considered to be an indicator of relative creativity. This is in contrast to absolute creativity which is evaluated in terms of high achievements in the creator's field and whose significance is evaluated by the professional community that regards it as a meaningful creation from an historical perspective. Such an example can be seen in discoveries of Nobel Prize laureates in different fields and recipients of the Abel Prize in mathematics.

Most of the studies presented in this issue examine relative mathematical creativity. The different methods of assessing creativity indicate that the authors approach the concept of creativity in different ways. In particular, the cross-cultural work by Leikin and colleagues follows a socio-cultural approach, in order to reveal similarities and differences among six studied countries. A socio-cultural approach was also implemented in the studies of Lev-Zamir and Leikin, Sinclair, de Freitas and Ferrara, and Sarrazy and Novotná. These studies aimed to reveal whether several educational settings influence students' creative ability. Liljedahl follows a cognitive approach, that is, an attempt to understand the mental representations and processes underlying creative thought in an effort to investigate the phase of illumination. He finds that affective characteristics are more prominent than cognitive ones in subjects' reflections on illuminations that they experience. Additionally, a psychometric approach is applied in this issue by the following researchers: Pitta-Pantazi et al., Kattou et al., Tabach and Friedlander, Leikin and Lev, and Voica and Singer. In these studies creativity is explored through a variety of tests which are used to measure mathematical creativity (fluency, flexibility, originality) or its perceived correlates such as cognitive styles, mathematical ability and personality traits.

3 Relationship between creativity and giftedness

A literature review reveals complexity regarding the relationship between creativity and giftedness. As shown below, some researchers claim that creativity is a specific type of giftedness, others feel that creativity is an essential component of giftedness, and still other researchers suggest that these are two independent characteristics of human beings (Leikin 2009a). Researchers suggest a variety of models that express the relationship between creativity and giftedness and the development of creativity. Some of these models are outlined below.

Renzulli's (1978) "three-ring" model of giftedness considers creativity among three factors important for the development of gifted behavior: above average ability, creativity and task commitment. By creativity Renzulli understands the fluency, flexibility and originality of thought, openness to experience, sensitivity to stimuli, and a willingness to take risks. The above average abilities include processing information, integrating experiences and abstract thinking as well as a capacity to acquire knowledge and perform an activity. Task commitment, without which, according to Renzulli, high achievement is simply not possible, is based on motivation turned into action. Renzulli (2006) places an emphasis on the background factors including personality traits and environmental conditions.

The Triarchic Theory of Intelligence comprises analytical, creative and practical abilities that jointly enable individuals to achieve success within particular socio-cultural contexts (Cianciolo and Sternberg 2004; Sternberg 2005). The model adds the aspects of usefulness and adaptation to the definition of creativity, defining it as "the ability to produce unexpected, original work that is useful and adaptive". The model further suggests that creativity is one of the central components of intelligent human behavior.

A comprehensive model of giftedness (Milgram and Hong 2009) considers creative talent as one of two distinct types: expert talent and creative talent. While these share different types of abilities, expert talent involves more analytical or intelligent thinking ability than creative thinking ability. According to Milgram and Hong (2009, p. 152), expert talent is based on "logical, systematic thinking ability that utilizes pattern matching based on the massive knowledge base from years of learning and work experiences". Creative talent reflects the ability "to produce ideas that are imaginative, clever, elegant, or surprising, beyond analytical thinking, required as part of creative process" (p. 152). Different people possess different combinations of creative and analytical talents which can appear at different levels. According to this view creative mathematicians use both analytical and creative thinking abilities at different levels of accomplishment. Milgram and Hong (2009) stress that personal-psychological attributes and environment-social factors are crucial for talent development.

An additional view on creativity is expressed in the Actiotope Model which focuses on creative actions (Ziegler 2005). The Actiotope Model and the ideas of Csikszentmihalyi and Wolfe (2000) suggest that the location of creativity is not limited to an individual's mind; but rather creativity is also embedded in a system where an individual interacts with a cultural domain and with a social field. The Actiotope Model (Ziegler 2005) matches the conceptions of creativity and argues that the development of excellence and of innovative and creative actions is part of the permanent extensions of a person's action repertoire.

In spite of the differences between the models and the impact they make on different factors that contribute to talent development, all researchers agree that interaction between personality traits and environmental factors determine, to a great extent, the realization of creative talent. In this volume special attention to the learning environment and the development of creativity is given in Sinclair et al. Moreover, their study is performed in line with Vygotsky's (1930/1984) view on creativity as one of the basic mechanisms that facilitate development of new knowledge. Sinclair et al. demonstrate that primary school students construct mathematical knowledge individually through interaction with the appropriate learning environment.

Three publications in this issue examine the relationship between creativity and ability. Kattou et al. find that mathematical creativity is a predictor of mathematical ability. Pitta-Pantazi et al. demonstrate that visual cognitive styles are statistically significant predictors of participants' creative abilities in mathematics. Leikin and Lev demonstrate that general giftedness increases the success of mathematically excelling students in performing insight-based solutions to mathematical problems; that is, general giftedness supports mathematical creativity.

4 Creative product, process, person and press

Through a review of the literature there appear to be some "useful" definitions that have a specific focus. The focus is either on the creative person, the creative processes, the creative product or the creative environment (Rhodes 1961, 1987; Runco 2004).

Research studies which concentrate on the creative person deal with individuals' cognitive and personality traits. For instance, researchers in the domain of general creativity, such as Runco (2007), Kleiman (2005), Sternberg and O'Hara (1999) and Sternberg and Lubart (1996), as well as researchers in the domain of mathematical creativity, such as Freiman and Sriraman (2011) and Klavir and Gorodetsky (2009), referred to characteristics that describe the creative personality or investigate cognitive-related traits. Conciseness, curiosity, intuition, tolerance for ambiguity, perseverance, openness to experience, broad interests, independence and open-mindedness are some of the commonly accepted characteristics of creative individuals.

In regard to the creative process, several research studies have investigated the way in which creative pieces of work are produced. In this framework, a number of studies proposed several stages to describe the process of creation. For instance, as mentioned earlier, Wallas (1926) proposed a four-stage model. Treffinger (1995) defined the stages leading to creative problem solving. These were: understanding the problem (question finding, data finding and problem finding), generating ideas (idea finding, elaboration of ideas and evaluation of ideas) and planning for action (solution finding and acceptance finding). Furthermore, Torrance's (1966) categories—fluency, flexibility, originality and elaboration—characterize students' creative process.

It is commonly believed that in order to recognize a creative behavior one has to discern the existence of a creative outcome. Research studies that concentrate on the creative product focus on ideas translated into tangible forms. For instance, Sternberg and Lubart (1999) defined creativity as the ability to produce unexpected, original, appropriate and useful pieces of work.

At first glance, studies by Kattou et al., Leikin and Lev, Pitta-Pantazi et al., Tabach and Friedlander, and Voica and Singer presented in this special issue all have as their focus the creative product. These studies deal with the creative products which are presented in participants' responses. However, the scoring schemes that these studies utilize in data analysis allow evaluating the flexibility of the problem solving process as well as the fluency, flexibility and originality of participants' reasoning and, as such, these studies evaluate the creative process and the creative person.

Additionally, four research papers in this issue deal with cognitive properties and personality traits of creative individuals in an effort to answer their research questions. In particular, Kattou et al. investigate the way in which students' mathematical ability is correlated with mathematical creativity. Pitta-Pantazi et al. examine the influence of cognitive styles on mathematical creativity. Leikin and Lev analyze the relationship between students' ability level and their mathematical creativity. Finally, Leikin et al. investigate several personality traits of creative teachers and students and their relation to mathematical creativity.

Explicit attention to the creative process is given in studies performed by Liljedahl, Voica and Singer, and Sinclair et al. In his paper Peter Liljedahl gives evidence of the AHA! experience and the way in which the illumination phase contributes to mathematics learning. Part of the research by Voica and Singer examines the way students act to provide coherent and consistent proposals in changing a given problem. Sinclair et al. demonstrate that embodied cognition expressed in students' gestures is part of the creative process associated with new knowledge construction.

The fourth strand refers to the creative press, which is the relationship between human beings and their environment. In educational settings, the characteristics and specifications of the educational environment where the creative person acts, where the creative process takes place and where the creative product appears are investigated. Among others, aspects such as the design of lessons, the selection of appropriate tasks (Goldin 2002), the assessment (Kleiman 2005) and the integration of technology (Yerushalmy 2009) have been identified as factors that may facilitate or inhibit the appearance of creative activity. Such studies were conducted in mathematics education by Ervynck (1991) and Sheffield (2009). Ervynck (1991) suggested certain conditions that yield creative products. He claimed that a preliminary technical stage is needed for technical or practical application of mathematical rules and procedures, followed by an algorithmic activity essential to the performance of mathematical techniques, in order to reach the creative activity stage. In order to encourage learners to think as creative mathematicians, Sheffield (2009) proposed a non-linear heuristic approach. In this approach she claimed that creating, relating, investigating, communicating and evaluating may be applied, in an effort to propose an original and creative solution.

In this issue three studies deal with the environment in which the creative act takes place. Lev-Zamir and Leikin focus on teachers' conceptions and conceptions-in-action that are expressed through their teaching. Sinclair et al. approach the concept of creative environment through the integration of new technologies. They analyze technology-based environments that allow young students to be involved in creative activity and become creators of their own mathematical knowledge. Sarrazy and Novotná investigate opportunities opened for students' creativity in different didactical situations. The same task was assigned to students in four different situations. The task apparently involves an unusual use of multiplication, not common in school practice, and the students have to use their knowledge to discover that the task does not actually involve this multiplication. In all these studies the authors not only demonstrate that the situations are effective learning environments that promote creativity but also analyze mechanisms underlying development of students' creativity.

It is important to note that the four strands (creative person, creative process, creative product and creative environment) in research studies are often interrelated, and it is difficult to compartmentalize them. In this special issue mutual relationships amongst the four strands can be found in the cross-cultural research article by Leikin et al. Apart from the key issue of personality traits of creative individuals, the authors investigate the ways in which creativity is related to various cultural frameworks. Moreover, Leikin and Lev incorporate issues related to the creative product and the creative person, since they examine differences in mathematical creativity across students of different ability levels and the impact of mathematical instruction on these students. In the same paper it can be argued that the creative environment is also discussed since the difference amongst students appears to be task dependent.

5 Research methods on creativity

The researchers publishing their work in this issue used a wide range of tools to collect data and employed diverse methods for recording, managing and analyzing it. The methodologies used can be grouped into three categories: quantitative, qualitative and mixed.

Quantitative research methods in this issue are used by Leikin et al. and Kattou et al. In particular, Leikin et al. collected their data through a Likert-scale questionnaire which measured teachers' conceptions about the characteristics of a creative student in mathematics, a creative mathematics teacher, a creative person and the relationship of the mathematical creativity and culture. To analyze these data and identify the similarities and differences across countries the researchers applied descriptive methods and exploratory statistical techniques. Kattou et al. gathered their data through two tests: one assessing mathematical abilities using multiple choice tasks and one measuring mathematical creative abilities using open-ended multiple-solution mathematical tasks. Confirmatory, mixture growth and exploratory analyses were used by the authors to analyze their data.

Qualitative research methods both for collecting and analyzing data were used in this issue in four studies: Liljedahl, Lev-Zamir and Leikin, Sinclair et al., and Voica and Singer. In order to answer their research questions the researchers used interviews (Lev-Zamir and Leikin; Voica and Singer), lesson observations (Lev-Zamir and Leikin; Sinclair et al.), self-report assignments (Liljedahl) and problem posing tasks (Voica and Singer). In Liljedahl's paper two studies are described: one study examined undergraduate students' answers on a reflective writing assignment upon an AHA! experience, while the other one aimed to elicit mathematicians' reflections on mathematical creativity, using some of the questions applied by Hadamard (1945). An analytic inductive coding method was used to interpret the answers provided by the participants in these two studies. Lev-Zamir and Leikin conducted individual interviews with two teachers before and after their observed lessons. They also analyzed their lessons in order to compare both teachers' views on creativity versus their actual teaching using a content analysis approach. Sinclair et al. describe two episodes of two interventions where digital technologies were used. Voica and Singer investigated the links between problem posing and flexibility by asking high achievers to pose mathematical problems. Students' answers were categorized and analyzed. Additionally, students' ability to pose and modify problems was investigated through individual interviews.

Mixed methods, in this issue, were applied by Leikin and Lev, Pitta-Pantazi et al., Tabach and Friedlander, and Sarrazy and Novotná. The first three studies measured mathematical creativity through multiple solution tasks and rated the responses based on fluency, flexibility and originality whereas Sarrazy and Novotná used "pseudo-multiplicative" problems. The four research teams used both quantitative and qualitative methods to analyze their data. In particular, Leikin and Lev used descriptive and exploratory methods to specify the differences in mathematical creativity comparing three different groups of students according to their ability level (IQ) and level of mathematical instruction. They also used grounded theory techniques to provide information about the different kinds of solutions produced by participants. Pitta-Pantazi et al. used exploratory statistical techniques to identify the relationship between cognitive styles and mathematical creativity and grounded theory techniques to provide information about the strategies employed by participants with different cognitive styles in creative mathematical tasks. Tabach and Friedlander applied descriptive methods and grounded theory techniques in order to present students' mathematical creativity, as expressed in their solution methods. Sarrazy and Novotná applied descriptive methods and factor analysis of correspondence in order to analyze the quantitative data. Further, qualitative methods were employed for data gathered through interviews.

6 Summary

This special issue devolves a set of empirical studies dealing with creativity in school mathematics to a broad audience of readers: mathematicians, mathematics educators and educational researchers. The researchers accept developmental perspectives on creativity and discuss various issues, such as the relationship between mathematical creativity and mathematical ability, effective learning environments for the development of creative thinking and teachers' conceptions of creativity in school mathematics. A variety of research approaches are integrated in the studies which lead to diverse findings and insights about creativity in school mathematics. Besides merely answering research questions, the authors in this special issue ask new research questions which their studies help to raise. We hope that our readers will find this collection interesting and creative, useful and encouraging for the performance of new and original research on creativity in mathematics education.

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