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Research in the Field of Creativity in Mathematics: Directions and Perspectives on the International Scene

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ABSTRACT

Background: The field of studies on mathematical creativity is relatively new in Brazil. The first records of empirical research in this field are from the first decade of this century. As a way of contributing to the consolidation of this field, we present an overview of research on mathematical creativity in the international scenario, based on the productions published in the conference proceedings of the International Group for Mathematical Creativity and Giftedness. **Objectives:** The article seeks to answer the following questions: What elements have prevailed in the conceptualisation of mathematical creativity? What is the focus of research questions and/or research objectives? What methods/methodologies were used in the research? **Design**: Research mapping, with information extracted from a form structured by the researchers. **Settings and participants:** Were analysed the works published in the proceedings of the conferences promoted by The International Group for Mathematical Creativity and Giftedness, held in 2014, 2015, 2017, and 2019. **Data collection and analysis:** Thirty-five papers that met the following criteria: to be a research report, to be characterised as a complete work, and to have as an object of investigation the mathematical creativity at different levels of teaching and/or in teacher education were selected. **Results:** Different concepts for creativity in mathematics were identified, which vary according to the focus of the research, sometimes emphasising the creative person, and sometimes emphasising the creative process in mathematics. Most of the studies were developed with elementary and high school students. Different research methods/methodologies were also identified, with a predominance of qualitative approaches. **Conclusions:** The analysis carried out allows us to highlight the need for

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attention to new studies, especially in relation to correlational studies and longitudinal studies.
Keywords: Mathematical creativity; Creative thinking in mathematics; Creative process in mathematics.

A pesquisa no campo da criatividade em matemática: rumos e perspectivas no cenário internacional

RESUMO

Contexto: O campo de estudos sobre criatividade em matemática é relativamente novo no Brasil. Os primeiros registros de pesquisa empírica nesta seara são da primeira década deste século. Como forma de contribuição para a consolidação desse campo, apresentamos um panorama da pesquisa em criatividade em matemática no cenário internacional a partir das produções publicadas nos anais das conferências do International Group for Mathematical Creativity and Giftedness. **Objetivos**: Que elementos têm prevalecido na conceituação de criatividade em matemática? Qual o foco das questões de pesquisa e/ou objetivos das investigações? Que métodos/metodologias foram empregados nas pesquisas? **Design**: Mapeamento de pesquisas, com informações extraídas a partir de formulário estruturado pelos pesquisadores. **Ambiente e participantes**: Anais do International Group for Mathematical Creativity and Giftedness, edições de 2014, 2015, 2017 e 2019. **Coleta e análise de dados**: Foram selecionados relatos de experiência e trabalhos completos que tinham como objetivo a investigação em criatividade em matemática. **Resultados**: Identificou-se diferentes conceituações para criatividade em matemática, que variaram de acordo com o foco das pesquisas, ora enfatizando a pessoa criativa, ora enfatizando o processo criativo em matemática. A maioria dos estudos foi desenvolvida com estudantes de ensino fundamental e ensino médio. Também foram identificados diferentes métodos/metodologias de pesquisa, com predominância de abordagens qualitativas. **Conclusões**: A análise realizada permite destacar a necessidade de atenção a novos estudos, em especial, no que se relaciona a estudos correlacionais e estudos longitudinais.
Palavras-chave: Criatividade em matemática; Pensamento criativo em matemática; Processo criativo em matemática.

INTRODUCTION

Creativity is one of the human capabilities that has received great attention in recent times, being valued in the most diverse spaces. The term "creativity" has been used in abundance to refer to the search for solutions to global and local problems (Sriraman, 2019).

One example of the signs that the contemporary world must develop new skills can be found in the report of the World Economic Forum (World Economic Forum, 2018), indicating that creativity, originality, and initiative are the skills that occupy the third position in order of importance that workers should have in 2030. Some consulting companies in the people management field, such as the McKinsey Institute, have highlighted that among the skills employers most require, creativity was the one that grew the most between 2004 and 2019 (Bughin et al., 2018).

In the educational field, the Organization for Economic Cooperation and Development – OECD published the 2019 study *Fostering students' creativity and critical thinking: What it means in school, educational research and innovation*. The document highlights that in current times, critical and creative thinking becomes necessary for several reasons. Among those reasons is to contribute to the well-being of individuals and the proper functioning of democratic societies (Vincent-Lancrin et al., 2020). Moreover, educational researchers and policymakers nowadays recognise a link between creativity and economic and cultural prosperity (Beghetto, 2010).

Despite the importance given to the topic in recent years, research on creativity has been carried out for a long time. They gained momentum in the 1950s after Joy Paul Guilford's speech at the opening of the annual meeting of the American Psychological Association, when he highlighted the importance of promoting children's creative development to prepare them for a changing future, especially to face the challenges posed by the cold war and the space race, markers of those times (Beghetto, 2010). However, as Sriraman (2005, 2019) points out, many teachers still consider that stimulating creativity is a task in the field of educating students with high abilities/giftedness and that this is far from the regular classroom curricula.

One of the problems faced in the creativity field research is the lack of consensus about this construct (Christou, 2017; Assmus & Fritzlar, 2017; Carvalho & Gontijo, 2017). However, a definition that encompasses much of the current thinking in the field of creativity considers it as the interaction between aptitude, process, and environment by which an individual or group produces something that is considered innovative and useful within a given social context (Plucker, Beghetto, & Dow, 2004).

Underlying almost all definitions of creativity is the notion that a creative product is new and has some kind of value (Lubart & Georgsdottir, 2004; Lubart & Guignard, 2004). Most researchers also recognise that creative achievement requires a combination of cognitive skills (ability to identify and solve problems, showing fluency, flexibility, originality, and elaboration of thinking), personality characteristics (high creative self-efficacy or belief in your ability to generate new and meaningful ideas; motivation, willingness to take intellectual risks, etc.), and environmental factors (external support or acceptance of new ideas, products, or ways of doing things) (Sternberg, 2006; Torrance, 1977).

A matter of debate in creativity is the specificity of the domain, i.e., the area in which creative ideas and products are developed. Creative outcomes (products, performances, and ideas) often exhibit domain specificity dependent on the knowledge and skill set unique to the field in which a creative solution is generated. Creativity is a domain-specific output resulting from domain-specific processes and domain-specific expert assessments (Baer, 1998; Han & Marvin, 2002).

In this article, we will discuss creativity in the mathematics field, with emphasis on the directions and perspectives of research in this area on the international scene. The literature on creativity in mathematics does not agree on a definition either (Mann, 2006; Pitta-Pantazi, Sophocleous & Christou, 2013; Carvalho & Gontijo, 2017). On the contrary, there are countless ways to conceptualise this phenomenon, reaching more than one hundred ways to conceptualise it (Mann, 2006; Savic et al., 2017).

Considering the field of creativity in mathematics, we developed a research mapping study (Fiorentini et al., 2016) based on those published in the proceedings of events promoted by the International Group for Mathematical Creativity and Giftedness - IGMCG. For this article, we analysed the works presented in the proceedings of the events held in 2014, 2015, 2017, and 2019. Previous events were not considered, as their respective proceedings are unavailable for consultation on the IGMCG website. The group began in 1999, when Hartwig Meissner organised an International Conference on Creativity and Mathematics Education in Münster, Germany. This group has already held 12 international conferences, including the conference of its creation.

The questions that motivated the research were:

1. What elements have prevailed in the concept of creativity in mathematics in the analysed works?
2. What is the focus of the research questions and/or objectives of the investigations?
3. What methods/methodologies were employed in the research?

CREATIVITY IN MATHEMATICS

Although it has been a recurring theme in various official documents that refer to education, and the number of studies and research has increased yearly, there is still no unique conceptualisation for creativity in mathematics. This can be evidenced by the different conceptualisations that have been elaborated over time by different researchers, including Laycock (1970), Krutetskii (1976), Haylock (1987), Ervynck (1991), Lee, Hwang & Seo (2003), Mann (2005) and Sriraman (2005), Livne and Milgran (2000, 2006), Gontijo (2007), Kattou et al. (2013), and Lev-Zamir and Leikin (2013).

For Laycock (1970), creativity in mathematics is the ability to analyse problems from different perspectives and agree to different responses. We believe that Ervynck (1991) complements this definition by saying that creativity in mathematics develops from combining the known and the unknown and does not develop arbitrarily and disconnected from the individual's reality/knowledge.

Creative thinking was associated as an integral part of doing mathematics by Aiken (1973) since the latter leads to the generation and combination of ideas and innovative approaches to solving problems. A similar argument was presented by Leikin and Pantazi (2013) when dealing with what they call relative creativity. The authors consider that students should act as professional mathematicians "relatively" to the school stage in which they are and to the learnings/knowledge constructed to engage in opportunities for research, study, and discussion about diverse mathematical objects, with available time to mature ideas, even if unconsciously, i.e., with time for incubation (Wallas, 1926). One of the difficulties in fostering creativity in mathematics in the classroom is the little time allocated for developing and improving ideas.

In the conceptual elaboration of creativity in mathematics, Haylock (1987) highlighted two aspects: (a) the need for knowledge in the area; and (b) flexible thinking. Without consistent mathematical knowledge, it is unlikely that one can build differentiated ideas for problem solving. It is broad knowledge that allows versatile thinking, which can produce multiple and varied mathematical ideas.

Throughout history, other conceptualisations have been proposed, and although they have some distinct elements, they somehow converge in their cores, in their essences. An example of a concept that encompassed aspects treated separately by other researchers was that presented by Gontijo (2007, p. 37), who proposed understanding creativity in mathematics as

> the ability to present several appropriate solution possibilities for a problem situation, in such a way that they focus on distinct aspects of the problem and/or differentiated ways of solving it, especially unusual forms. This ability can be employed both in situations that require the resolution and the development of problems and in situations that require the classification or organisation of objects and/or mathematical elements according to their properties and attributes, whether textually, numerically, graphically, or in the form of a sequence of actions.

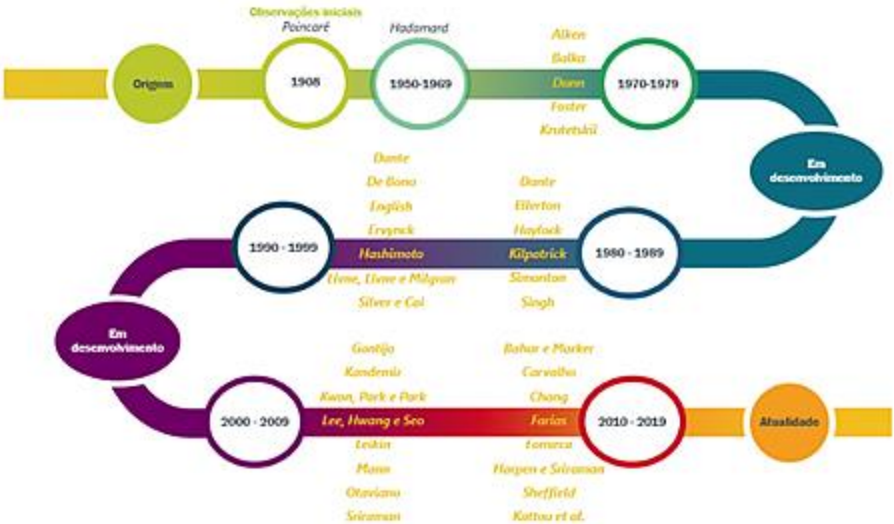
Since creativity in mathematics is a specific type of creativity (Sak et al., 2017) but with similarities with the descriptions of other psychological theories about creativity in a general context, we emphasise that it must also present fluency, flexibility, and originality of thinking, which are characteristics of creative thinking and which can be identified in productions in different areas of knowledge. Regarding those characteristics, Gontijo (2007, p. 37) says that creative production in mathematics is constituted:

> by the abundance or amount of different ideas produced on the same subject (fluency), by the ability to change thinking or to conceive different categories of responses (flexibility), by presenting infrequent or unusual responses (originality), and by presenting a large amount of detail in an idea (development).

Considering researchers' efforts in theoretical and empirical production on creativity in mathematics, several works were produced over time, with emphasis on the years from 1950 onwards. The following illustration seeks to present a chronology of some of those works.

Figure 1

A chronology of research on creativity in mathematics (Gontijo et al., 2021, p.12)



Thus, given the multiple concepts and relevance that have been seen by researchers and institutions, creativity in mathematics has reached its own space for discussion, such as the International Congress on Mathematical Education (ICME), which is preparing to hold its 15th edition in 2024; Psychology of Mathematics Education (PME), which hold its 45th edition in 2022; and the International Conference on Mathematical Creativity and Giftedness (MCG), holding its 12th edition in 2022.

While the first two have discussion groups that involve mathematics and creativity, the MCG is an event focused on creativity and giftedness in mathematics, which is why the number of specific works increases significantly, coming from different countries.

METHODOLOGY

The present work is a research mapping, which, according to Fiorentini et al. (2016, p. 18), is

> a systematic process of surveying and describing information about research produced in a specific field of study, covering a certain space (place) and time. This information concerns the physical aspects of this production (describing where, when, and how many studies were produced in the period, and who were the authors and participants of this production), as well as its theoretical-methodological and thematic aspects.

Establishing clear criteria was necessary to determine whether the scientific production found would or would not be part of the set of texts to be analysed. This process was based on Heitink et al. (2016), whose work resulted in the construction of an electronic form to facilitate the extraction of information that would be analysed.

Electronic forms were chosen due to the ease of storage, access (portability), and authors' interaction. The choice fell on Google Forms due to its user-friendly interface, ability to be edited by several users regardless of permission, diversity of tools, and being free, cross-platform, dynamic, and interactive.

For a work to be included in the analysis, it should be: a research report, a complete work, and have as an object of investigation the creativity in mathematics at different levels of education and teacher education. Given the focus of the events, we chose to exclude works on creativity in mathematics developed in the field of high skills/giftedness. This choice is due to the interest in analysing productions whose results refer to broader educational contexts, and that can be applied/adapted to most students.

We analysed 35 papers, three of which were published in the proceedings of the 2014 event, ten in 2015, ten in 2017, and 12 in 2019. We observed a growth in the number of papers at each event edition, revealing an increased interest in the topic. We observed that the works were from 15 countries, whose occurrences are informed along with the places of origin: USA (8), Germany (5), Brazil (4), Canada (2), Cyprus (2), Greece (2), Israel (2), Romania (2), Turkey (2), Netherlands (1), India (1), Czech Republic (1), Serbia (1), Sweden (1) and one article with no identified origin.

RESULTS AND DISCUSSION

In the following topics, we present the results obtained from the analysis of the consulted texts, after which we discuss the findings regarding the studied construct. The results were structured to answer the research questions that motivated the present study. For this reason, initially, we present the characterising elements of creativity in mathematics, with definitions of the construct being addressed as the focus given to the studies. In the following topic, we display the research questions and/or objectives investigated in the papers. The third topic of this section allows us to highlight the methods/methodologies used in the analysed studies.

The analysis of the works revealed a diversity of ways of understanding the phenomenon of creativity in mathematics, resulting from the methodological choices that guide the research, which allows us to categorise the concepts presented according to the directions that the researchers took when undertaking their investigation. However, it was not always possible to identify an explicit or implicit definition referred to by the authors.

The analyses led us to conclude that ten works (about 29%) did not present a definition of creativity in mathematics, either by choice, by negligence, or by applying a definition of creativity as a general domain to the specific field of mathematics.

For a field of research like this, which is at the same time relatively new (Carvalho, 2019) and characterised by the multiplicity of concepts (Emre-Akdoğan; Yazgan-Sağ, 2015), we consider it essential to state what is understood by the term creativity in mathematics. It is necessary to highlight the perspective from which the phenomenon is analysed so that the research design can compose a coherent and clear whole for those seeking information in the literature.

The other studies (71%) have definitions in their texts that shed light on the concepts that outline their studies, explicitly or implicitly presenting a concept about creativity in mathematics. We categorise those concepts according to the focus of the research, noting whether they focused on the creative process or creative product, or both. The creative product refers to students' and/or teachers' productions, materialised in problem solving protocols or the construction of mathematical objects and teaching methodologies. The creative process is related to how mathematical productions were carried out, observing the individuals' attitudes, their motivation, and the steps they followed to complete their tasks. Some studies sought to analyse the product associated with the process.

As for the focus: product, processes or both

The concepts present in the research works focus on the product or process; in some, they can present a concept with both focuses. In the next paragraphs, we describe the characteristics of those studies and show some definitions of creativity in mathematics.

Focus on the product

We found eight studies centred on the product (23% of the total number of texts). They have in common the fact that they state, in the concept they use, criteria with which they evaluate the creativity of the answers presented by research participants to questions of a mathematical nature. Those criteria are related to fluency, flexibility, and originality (or novelty, as some call it) of thinking.

Manuel (2014) says that creativity in mathematics is defined by fluency, flexibility, and originality of solutions to a mathematical problem. Thus, he conceptualises each of those criteria, defining fluency as the number of correct answers or problems created, flexibility as the number of varied appropriate strategies used to solve a problem, and originality as the correct answers and strategies used less often in the sample space.

Five studies focused on the product used those criteria to assess creativity in mathematics. However, contrary to the trend in the area of using mainly the criteria of fluency, flexibility, and originality, Shiakalli and Zacharos (2017) include a fourth factor in their analysis: elaboration. Thus, they define this factor as the ability to describe, extend, and develop an idea. On the other hand, Voica and Singer (2019) only consider flexibility as a conceptual element to establish relationships between creativity and problem solving. For the authors, students demonstrate cognitive flexibility when they generate new proposals that diverge from the initial problem (cognitive novelty), when they present new different problems based on a given context (that is, cognitive variety), and can change their mental structure when solving problems or identifying/discovering new ones (i.e., change in cognitive framing).

Based on Sririman (2005, 2009), Savic et al. (2014), and Assmus and Fritzlar (2017) treated creativity in mathematics as the presentation of new (unusual) or useful solutions for problems posed. Savic et al. (2014) adopt the definition presented by Sriraman (2005), who considers creativity in mathematics as: (a) the process that results in unusual (new) and/or insightful solutions to a given problem or analogous problems; and/or (b) the formulation of new questions and/or possibilities that allow an old problem to be considered from a new perspective that requires imagination. Assmus and Fritzlar (2017) cite Sriraman (2009) and define creativity in mathematics as the ability to engage in non-algorithmic decision-making or generate new and useful solutions to problems.

Focus on the process

Most of the analysed studies (40%) are based on concepts focused on the creative process. The focus of the 14 texts in this category is divided into a) describing the stages in which the creative process in mathematics occurs, b) pointing out resources needed to foster this ability, c) addressing perceptions of students and teachers about what can favour creativity in mathematics, d) listing sub-processes in which creative thinking in mathematics takes place, and e) choosing sociocultural approaches to explain the creative process that emerges from social interactions.

The works that propose a concept defining creativity in mathematics as a stage-composed process are based on the theoretical contributions disseminated almost a hundred years ago by Graham Wallas, who proposed a four-stage model to explain creativity: preparation, incubation, illumination (described by some as an insight or aha! moment) and verification. The studies by Czarnocha and Baker (2015) and Schindler and Lilienthal (2017) address those stages, although they focus only on the so-called aha! moment (illumination). Czarnocha and Baker (2015) resort to Koestler's contributions, who bring the term bisociation to distinguish the ordinary thinking skills on a single plane and the creative act that always operates on multiple planes of thinking. Thus, the authors understand that the top of the creative act occurs in spontaneous moments of insight, meaning that the idea arises in the mind of the creative subject as a connection of distinct routine experiences that result in new and valuable ideas and/or products.

Schindler and Lilienthal (2017) are interested in understanding how original ideas or ideas that lead to insight (illumination) arise when students work with the so-called multiple-solution task (MST), i.e., activities that lead students to come up with multiple solutions to mathematical problems. Therefore, the authors seek to analyse the moments in which ideas emerge while students produce solutions.

Another work that addressed the stages in which the creative process occurs is Kattou, Christou, and Pitta-Pantazi's (2015). In their theoretical foundation, the authors presented not only the stages described by Wallas but also addressed a heuristic model presented by Sheffield (2009), indicating that the creative process during problem solving can occur through five non-sequential stages: investigating, relating, creating, evaluating, and communicating.

Three studies are concerned with understanding which resources and ways of fostering creativity can enhance that capacity. Through Sternberg and Lubart's (1995) investment theory, whose maxim is 'buy low and sell high,' Shen and Edwards (2014) define creativity as an ability that requires intellectual skills, thinking styles, personality, motivation, knowledge, and a conducive environment to develop.

Beck (2015) takes creativity in mathematics as individual, mathematically differentiated activities produced by kindergarten-age children when they participate in games or exploration situations. On the other hand, Cilli-Turner et al. (2019) see creativity in mathematics as a process of offering unexpected solutions or ideas in relation to the student who produces them, regarding their mathematical background or the problems they have already seen. Concerned with how creativity in mathematics develops, the authors focus their attention on the student's creative process, listing some problems and actions that can foster this ability: multiple solution tasks (a term coined by Leikin in 2009), generation of examples by students, open problems, and creation of new mathematical definitions.

With a similar look to the previous one, two surveys address the perceptions of both students and teachers about what can favour creativity in the field of mathematics. While Vela et al. (2019) focus on students' beliefs about how activities in science, technology, engineering, and mathematics - STEM can develop creativity, Zioga and Desli (2019) take as research subjects teachers and their perceptions about creativity in mathematics after going through a continuing education program. Both studies adopt a definition of creativity in mathematics as the production of a new way to solve a problem, even if the novelty is only for the subject who produced it and even if other people already know it.

Some studies list sub-processes in which creativity occurs, such as the text by Pitta-Pantazi and Sophocleous (2017), proposing the theory of higher-order thinking in mathematics, a combination of basic, critical, creative, and complex thinking processes. Referring specifically to the creative thinking process, the authors point out that it goes beyond what is already known, the reorganisation of existing knowledge and the generation of new knowledge. As sought in the Iowa Department of Education (1989) guidelines, creative thinking includes subprocesses such as analogical thinking and abilities to summarise, hypothesise, plan, imagine, synthesise, and elaborate. Other studies that analyse creativity in mathematics through subprocesses emphasise that this process requires different modes of thinking (Savic et al., 2017) and involves divergent thinking and actions that allow expanding possibilities (Aljarrah & Towers, 2019).

Finally, contributions that choose sociocultural approaches to explain the creative process seek to interpret the influences of social interactions on creative processes, even though these interactions occur between different peoples and times. Those works view creativity beyond the individual dimension and understand it as a social, collective process. Fritzlar, Kötters, and Richter (2017) resort to Sternberg and Lubart's (1991, 1999) investment theory and to ethnomathematics to understand how cultural aspects and mathematical contexts (in different places and times) can relate to creativity in mathematics or favour the development of this skill. From another perspective, Carvalho and Gontijo (2017) use 'shared creativity in mathematics' to define how interacting people can share knowledge and affection in the collective production of mathematical ideas.

Focus on product and process

Some studies have understood that there are ways to integrate more than one focus so that creativity in mathematics is understood as a phenomenon that needs a holistic approach, seeking to ascertain the various aspects that can be observed in the phenomenon and interrelate them. This does not mean that all studies with this multiplicity of focal points have actually interrelated such aspects (process and product), but rather that they adopt a concept about creativity in mathematics that present elements both related to the evaluation of the creative product and related to the analysis of the process in which creativity takes place in this field of knowledge.

We identified three studies by the same group of authors with these characteristics. In this sense, all studies share the same definition of creativity in mathematics (Gontijo, 2007). They consider it to be the ability to present several appropriate solutions to a problem (fluency) so that they impact different aspects of the problem and/or different ways of solving it (flexibility), especially unusual ways (originality). This ability can be used in situations that require problem elaboration and solving and in situations that require classification or organisation of objects and/or mathematical elements according to their properties and attributes, in textual, numerical, or graphic format or in a sequence of actions.

This definition is a construction that involves both aspects related to the evaluation of the creative product (fluency, flexibility, and originality) and aspects that refer to the creative process (requiring resolution and elaboration of the problem, classification or organisation of objects and/or mathematical elements) and, also, the way creative thinking is manifested (which may occur through texts, numbers, graphics or in a sequence of actions). Carvalho and Gontijo (2017) seek to analyse both the products (production of mathematical knowledge) and the process of creative sharing in mathematics when students interact in mathematical activities. Fonseca, Gontijo, Zanetti, and Carvalho (2019) study how creativity workshops in mathematics can stimulate the development of students' motivation in mathematics. Gontijo, Fonseca, and Zanetti (2019) seek to present the validation of a workshop that aims to develop critical and creative thinking in mathematics with teachers.

By categorising the concepts of the construct discussed here as to the focus of analysis, we seek to provide theoretical bases for those interested in the subject, teachers concerned with advancing their students' knowledge development levels, and beginners in this area to know what is understood in the various existing approaches about creativity in mathematics.

Research questions and/or objectives that were investigated

Twenty-nine works considered in this investigation explicitly presented their research questions and/or objectives, while six did not present this information explicitly.

Among the works that explicitly presented their questions and/or research objectives, we can verify the occurrence of four categories: (a) development of students' creativity in mathematics; (b) creativity in mathematics at work and teachers' continuing education; (c) correlational research involving creativity and; (d) bibliographical and/or theoretical research in the field of creativity in mathematics.

Developing students’ creativity in mathematics

Research with students involved testing activities, workshops or formative programs to stimulate creativity in mathematics at different stages of schooling, from early childhood education to higher education. Also, some studies have used procedures for evaluating students’ creative thinking in mathematics, applying tests of a psychometric nature.

A group of works investigated creative skills in mathematics with students in school years compatible with Brazilian elementary education. In this group are the works of Beck (2015), Carvalho and Gontijo (2017), Carvalho, Gontijo and Fonseca (2019), Karadag, Martinovic and Birni (2015) Kattou, Christou and Pitta-Pantazi (2015), Mihajlović and Dejić (2015), and Pitta-Pantazi and Sophocleous (2017). Prusak (2015), Schoevers and Kroesbergen (2017), Shen and Edwards (2014), Slezakova and Swoboda (2015).

Beck’s (2015) work aimed to analyse how preschool children’s mathematically creative activities can be identified and described. Prusak (2015) investigated students’ perception of the influence that written riddles have on their mathematical creativity. He also sought to analyse teachers’ perceptions of those enigmas, confronting them with students’ perceptions. Kattou, Christou, and Pitta-Pantazi (2015) investigated the process followed by students during the resolution of multiple solution mathematical creativity tasks, concluding that this process can be described in five non-sequential sub-processes: investigating, relating, creating, evaluating, and communicating and that this varied among students with different degrees of mathematical creativity.

Carvalho and Gontijo (2017) analysed the immersion process of creativity in mathematics in a group of students. They presented a strategy for developing collective creativity in which everyone can contribute by presenting solutions to the proposed problems or improving or judging their peers’ solutions. In another work, Carvalho, Gontijo, and Fonseca (2019) investigated whether creativity can be treated as a collective phenomenon, whether there are differences between individual and collective work in the production of ideas and, if so, what the nature of this difference is, in addition to investigating whether power relations between students can influence creative and collective work in classrooms.

Pitta-Pantazi and Sophocleous’s (2017) study analyses students’ performance in tasks that combine basic knowledge, critical thinking, creative thinking, and complex thinking processes. The authors present a model to validate the combination of those elements, which they call higher-order thinking.

We also found research conducted with students in school years compatible with Brazilian high schools by Alexe et al. (2015), Fonseca et al. (2019), Lee et al. (2019), and Vela et al. (2019).

Alexe et al. (2015) reported an investigation in which they introduced manipulative materials in mathematics classes to promote creativity, visual perception, and mathematical thinking in a geometric context. Fonseca et al. (2019) analyse the use of mathematical creativity workshops as a strategy to stimulate mathematical motivation among high school students, while Lee et al. (2019) investigated the development of students' conceptions of critical and creative thinking in mathematics through science, technology, engineering and mathematics (STEM) activities in project-based learning (PBL) context. Finally, Vela et al. (2019) analysed how students' beliefs about mathematics, their interest in applying mathematics, and their beliefs about creativity in science, technology, engineering, and mathematics (STEM) fields predict students' interest in applying creativity in those areas.

Investigations involving university students were produced by Singer, Pelczer, and Voica (2015) and Cilli-Turner et al. (2019). In Singer, Pelczer, and Voica (2015), some questions refer to the type of tools that could provide information about the mathematical creativity of university students in problem-solving contexts and how creativity could be assessed in this case. Cilli-Turner et al. (2019) developed a study to answer how this mathematical creativity is promoted in higher education.

Although mathematicians and mathematics educators agree that students should be exposed to the creativity inherent in mathematics, there is still a need for more research to show how this can be done in mathematics in higher education. The small number of studies involving this educational level points to this field as a fruitful space for further investigations.

Creativity in mathematics at work and in the continuing education of teachers

Our research revealed works which directed their investigation questions and/or objectives to the phenomenon of creativity in the teaching work or teacher continuing education. These were the works by Emre-Akdoğan and Yazgan-sağ (2015, 2019), Savic et al. (2017), Schoevers and Kroesbergen (2017), Shen and Edwards (2014), Voica and Singer (2019), and Zioga and Desli (2019).

Emre-Akdoğan and Yazgan-sağ (2015, 2019) presented works from the same perspective, investigating teachers' views on creativity considering the characteristics and practices of a creative teacher and the characteristics of a creative student. Savic et al. (2017) also had a similar concern, seeking to investigate whether teaching actions or practices can foster students' perception of mathematical creativity. Zioga and Desli's (2019) concerns also focused on the analysis of activities that teachers develop in the classroom and their relationship with creativity in mathematics. They also investigated whether the types of activities used and those teachers' conceptions were changed after participating in a training program on creativity in mathematics. Shen and Edwards (2014) show a model to explain how teachers understand creativity in mathematics learning and how they promote or fail to promote it in the classroom.

Two other studies analysed the effects of continuing education programs on teaching practices to promote creativity in mathematics. Schoevers and Kroesbergen (2017) evaluated the effects of a teaching sequence and a teacher professional development program in the practice of a group of teachers. Voica and Singer (2019) analysed teachers' productions in the context of a course on problem solving, verifying whether they transferred more subtle elements of a problem, such as implicit indications of resolution, or whether they remained in a superficial analogical transference and the implications of those transferences in the creative production.

Mathematics creativity in correlational studies

The research in this category refers to correlational studies between creativity in mathematics and motivation, creativity in mathematics and academic performance, and creativity in mathematics and intelligence. Two works present those characteristics.

Kattou and Christou's (2017) work aimed to investigate whether mathematical creativity and intelligence constructs are correlated and to examine whether this correlation was different between students with different scores on intelligence tests. Specifically, they investigated: a) whether mathematical intelligence and creativity are correlated; and b) how this correlation differs between students who have different scores on intelligence tests. Sophocleous and Pitta-Pantazi's (2017) work investigated whether there is a correlation between performance in activities that require critical thinking in mathematics and problem-solving tasks and whether critical mathematical thinking is a predictor of fluency and flexibility, and originality, characteristics of creative thinking.

Creativity in mathematics in research of a bibliographical nature and/or theoretical essay

Only one of the works related to this category was classified as a literature review study: Joklitschke, Baumanns, and Rott's (2019) study, which investigated the types and quantity of articles published in journals that dealt with the relationship between formulating mathematical problems and mathematical creativity and how this relationship was conceptualised. The other works have different characteristics, as described below.

Manuel's work (2014) investigated the mathematical problems published on the *Communauté d'Apprentissages Multidisciplinary Interactifs* - CAMI website, evaluating the creativity of the solutions to the problems presented and verifying the potential of those problems to stimulate creativity in mathematics. Savic et al. (2014) present a rubric to assess creativity in mathematics in problems that require a proving - creativity-in-proof rubric (CPR). Karadag, Martinovic, and Birni (2015) discuss the opportunities that dynamic and interactive mathematics learning environments (DIMLE) and their resources can provide teachers to foster students' mathematical creativity.

Regarding Mihajlović and Dejić's work, (2015), the objective was to point out the importance of using open problems and problem representation activities in elementary mathematics classrooms. Also, the article brings the application of concrete examples with a brief reflection on their roles and benefits for the development of students' creativity and mathematical thinking.

Three theoretical essays address themes related to creativity in mathematics, presenting elements ready for debate. In Sriraman (2019), the role of uncertainty in the dynamics of insights/constraints as catalysts of creativity is explored. Nair and Ramasubramanian (2019) discuss the importance of exploring unknown territories to nurture students' mathematical creativity at school, and Czarnocha and Baker (2015) discuss the importance of democratising stimulus programmes for the development of creativity for all students, because, according to the authors, in many places, those programmes are only available to students with high abilities/giftedness.

Methods/methodologies employed in research

The first analysed item refers to the methods employed in the research. Most of the articles brought some description of the method, reporting theories and approaches, for example. However, about 28% either did not make the description in a single section or the information had to be inferred throughout the work.

Besides the number of works that did not properly describe the method used, a greater number of authors, 86% of the sample, did not defend or explain the choice for the type of research and methodology used. In a way, the methodology description presented the path only but not based on the epistemological assumptions that justified the choices made.

Another investigated scenario was the research approach: qualitative, quantitative, or mixed. We verified the predominance of the qualitative approach. This predominance can be explained by different factors, such as the interest in analysing either students' written and/or verbal production during school activities or the information contained in guiding documents of education systems to stimulate creativity in mathematics. However, it should be considered that mixed approaches (Alexe et al., 2015; Carvalho & Gontijo, 2017; Schoevers & Kroesbergen, 2017; Shen & Edwards, 2014; Singer, Pelczer & Voica, 2015) and quantitative approaches (Carvalho, Gontijo & Fonseca, 2019; Fonseca, Gontijo, Zanetti & Carvalho, 2019; Gontijo, Zanetti & Fonseca, 2019; Kattou & Christou, 2017; Lee et al., 2019; Manuel, 2014; Pitta-Pantazi & Sophocleous, 2017; Sophocleous & Pitta -Pantazi, 2017; Vela et al., 2019), together, reached 43% of the total works, which may indicate a certain balance with studies that also used quantitative approaches in their analyses, which are characterised especially by the treatment of data obtained from tests and scales applied to measure creativity in mathematics.

Regarding the classification of research objectives, most of the works (74.3%) did not present a specification, but 20% said that their investigations were, from the point of view of the objectives, exploratory (Czarnocha & Baker, 2015; Emre-Akdoğan & Yazgan-Sağ, 2015; Fonseca, Gontijo, Zanetti & Carvalho, 2019; Manuel, 2014; Singer, Pelczer & Voica, 2015; Savic et al. 2017; Shen & Edwards, 2014), and 5.7% reported that their research was descriptive (Aljarrah & Towers, 2019; Joklitschke, Baumanns, & Rott, 2019). This lack of explanation regarding the type of research also occurred about the procedures, as 57% of the studies did not bring this information. The remaining 43% were divided into: 9% bibliographical or documentary (Czarnocha & Baker, 2015; Joklitschke, Baumanns, & Rott, 2019; Sriraman, 2019); 14%

survey or data collection (Alexe et al., 2015; Kattou, Christou, & Pitta-Pantazi, 2015; Manuel, 2014; Shen & Edwards, 2014; Singer, Pelczer, & Voica, 2015); 3% experimental (Fonseca, Gontijo, Zanetti, & Carvalho, 2019), and 17% case study (Aljarrah & Towers, 2019; Assmus & Fritzlar, 2017; Beck, 2015; Savic et al., 2017; Slezakova & Swoboda, 2015; Zioga & Desli, 2019).

Analysing those who explicitly presented their type of research in terms of objectives, we have a greater concentration of exploratory research – which, according to Gil (2008, p. 27), "aims to develop, clarify, and modify concepts and ideas, to formulate more precise problems or researchable hypotheses for further studies", i.e., a "first" step to propose other and more in-depth research on the subject. For the author, this type of research is characterised, most of the time, by bibliographical/documental research and case studies. It is worth mentioning that studies with these two procedures add up, in our investigation, to 67% of the works.

Concerning data collection techniques, we identified that in 37% of the works the researchers used tests, scales, or questionnaires (Alexe et al., 2015; Carvalho & Gontijo, 2017; Carvalho, Gontijo, & Fonseca, 2019; Fonseca, Gontijo, Zanetti, & Carvalho, 2019; Gontijo, Zanetti, & Fonseca, 2019; Kattou & Christou, 2017; Lee et al., 2019; Pitta-Pantazi & Sophocleous, 2017; Savic et al., 2014; Schoevers & Kroesbergen, 2017; Singer, Pelczer, & Voica, 2015; Sophocleous & Pitta-Pantazi, 2017; Vela et al., 2019), while about 23% resorted to the use of individual or collective interviews (Aljarrah & Towers, 2019; Cilli-Turner et al., 2019; Emre-Akdoğan & Yazgan-Sağ, 2015; Kattou, Christou, & Pitta-Pantazi, 2015; Prusak, 2015; Savic et al., 2017; Shen & Edwards, 2014; Zioga & Desli, 2019), and 23% resorted to qualitative analysis of students' production (Assmus & Fritzlar, 2017; Beck, 2015; Karadag; Martinovic & Birni, 2015; Manuel, 2014; Nair & Ramasubramanian, 2019; Schindler & Lilien tal, 2017; Slezakova & Swoboda, 2015; Voica & Singer, 2019). Finally, 6% used document analysis (Joklitschke, Baumanns, & Rott, 2019; Sriraman, 2019) and that 11% of the analysed articles did not collect data.

Among those who used tests, scales, and questionnaires, 51% employed their own instruments for data collection. However, only 9% indicated how to validate those instruments.

With regard to the participants' selection –another variable necessary for understanding the context, the results of the research, and possible biases that could compromise the conclusions– we identified that about 25% made an explicit presentation, against 60% who kept this information implied. In 15%

of the studies, this type of characterisation was not applied due to the type of investigation carried out.

We emphasise that describing the method/methodology, the type of research approach, data collection techniques, selection criteria for participants, and explanation of types of research objectives and data analysis procedures, among other elements, are factors that enable replication of research. From our analyses, we registered that about 25% of the works did not give this information clearly, while the vast majority made it possible, even partially, to replicate it.

CONCLUSIONS

The analysis of the works showed that few researchers presented the limitations of their experiments. Only about 20% of the works did so. We consider such information relevant for the construction of the research field, as it offers clues for the development of further investigation. As important as pointing out the limitations of the study is to indicate research that may result from the investigations carried out. This type of information, unfortunately, was not found in the analysed studies. It is noteworthy, however, that the formatting of papers in terms of the number of pages does not provide conditions for all desirable information to be included in the texts.

Based on the analyses and other experiences in the field of research on creativity in mathematics, we present some elements that may be relevant for future research. We draw attention, especially, to the development of correlational studies and longitudinal studies. Regarding the first, only two of the 35 analysed papers examined correlations between performance on tests of creativity in mathematics and on intelligence tests, and between performance on tests that assess critical thinking and on tests that assess creativity in mathematics. We consider that many variables favour or hinder the development of creativity in mathematics, for example, those indicated in research that involved issues of gender, motivation, affectivity, classroom climate for creativity, assessments, and teacher-student relationship, among others. Investigating the effects of these variables on the development of creativity may subside the organisation of pedagogical work with mathematics.

About longitudinal studies, we emphasise that they are vital to verify to what extent the results of actions developed to stimulate students' creativity are maintained over time and whether other actions are necessary for creative thinking to remain active throughout students' development.

In addition to these two aspects mentioned, other questions still remain open in the research field of creativity in mathematics, despite the many answers already found for them. Thus, the following questions still need to be explored: What are the characteristics of creative students in mathematics? How can teachers promote and encourage mathematical creativity? How does the brain function during activities that require creativity in mathematics? What relationships can be established between theories in the field of mathematics didactics and theories about creativity in mathematics? We hope that such open questions can inspire future scholars to dedicate themselves to understanding the phenomenon of creativity, thus contributing to the advancement of this area of research.

AUTHORSHIP CONTRIBUTION STATEMENT

All authors, C. H. G; M. G. F.; A. T. de C.; and W. W. V. B contributed equally to the development of the instrument, data collection, and writing of the article.

DATA AVAILABILITY DECLARATION

The data supporting the results of this study will be made available by the corresponding author, C. H. G., upon reasonable request.

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