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Mathematical Creativity: A Systematic Review of Current Research on Eye-Tracking Technology

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Abstract

Recent empirical research on mathematical creativity using eye-tracking (ET) technology has faced challenges in developing comprehensive overviews due to the diversity of tools, task types, ET data, and identification methods. Thus, this systematic review attempts to examine studies that focus on mathematical creativity and incorporate ET technology. Guided by Newman and Gough's seven-step approach, a Scopus database search covering publications up to 2024 identified five eligible empirical studies collected for this study. Of the 29 papers, 5 were selected, and their methodological validity was assessed using the Mixed Method Appraisal Tool (MMAT). The review reveals that researchers employed two primary types of eye trackers: mobile eye trackers, suitable for engaging in paper-and-pencil tasks while moving naturally, and screen-based eye trackers, preferable for computer-based creative tasks because they provide more precise gaze recordings without requiring wearable equipment. To stimulate creative thinking, these studies used tasks that encourage divergent exploration, such as multiple solution tasks (MSTs), multiple representation tasks (MRs), and creative problem-solving. The majority of studies utilized the geometry domain, which is considered particularly well-suited for ET-based research due to its visual representations. ET data included both quantitative data (e.g., fixations, saccades) and qualitative data (gaze-overlaid videos), which complemented each other. Two primary methods for investigating mathematical creativity were identified. Four studies combined eye-tracking (ET) with stimulated recall interviews (SRI) to directly capture the processes of mathematical creativity. In contrast, one study integrated ET with multimodal sensors such as skin conductance (SC) and electroencephalography (EEG), where creativity was first assessed from students' problem-solving products (fluency, flexibility, originality) and subsequently modeled by linking visual attention patterns and physiological responses to distinguish between high- and low-creativity groups. These findings emphasize the importance of cognitively challenging task design and data triangulation approaches in deepening our understanding of the dynamics of creativity in mathematical problem-solving.

Keywords: Eye-tracking; mathematical creativity; systematic review

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1. Introduction

Eye-tracking is a technology that measures a person's eye movements to determine where they look, what they see, and how long they stare at a given point. This technology is the only reliable method for accurately and objectively measuring and understanding visual attention. Furthermore, researchers have widely utilized eye-tracking technology to investigate human behavior (Santhoshikka et al., 2021). Eye movement measurements are commonly utilized in psychological research to study cognitive processes such as reading, perception, memory, and attention (Brand et al., 2021; Rayner, 2009). Additionally, Hu (2020) states that eye-tracking technology, also known as gaze tracking, employs various detection methods, including optical and mechanical, to determine the direction of a subject's gaze. Gaze is simply focusing on something or someone for a specific period with attention. Gaze information is also crucial because

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it provides cognitive information from eye movements during specific tasks. Therefore, knowing what someone is looking at provides valuable insights into cognitive processes.

Eye-tracking is a technique used to gather information about human eye fixation patterns. A person's fixation is related to what they pay attention to, and attention is a crucial component of human cognition (Duchowski, 2017). Rapid eye movements from one fixation point to another, known as saccades, are essential for constructing a complete visual representation. Saccades specifically reflect shifts of attention and indicate how visual information is explored. Eye-tracking allows researchers to obtain data on where participants allocate their attention, the duration of focused attention, and the gaze trajectories of eye movement behavior (Persaud & Eliot, 2014). Similarly, Wang et al. (2014) noted that collecting and recording information about eye movement behavior can provide an opportunity to observe subjects' cognitive processes through visualization directly. This reflects a shift in focus from output-based studies to those oriented toward visual cognitive processes (Schindler & Lilienthal, 2020; Schoenherr & Schukajlow, 2023).

Research examining the relationship between cognitive processes and eye movements is based on the "eye-mind" hypothesis proposed by Just & Carpenter (1980). This hypothesis assumes a relationship between what a person sees and what they think, meaning that what a person sees is what they think. Experts believe that when cognitive processes occur in the brain, the line of sight is focused on the position that triggers them. The corresponding fixation time and number of fixations increase. In this case, what a person sees is the focus of their cognitive processes, and eye movements are related to the trajectory of their attention and its shifts (Jang et al., 2014). Thus, eye-tracking technology can be used to comprehend how students think in terms of what they pay attention to when searching for solutions to problems.

The use of ET in mathematics education initially focused on observing how students read problems, understand mathematical arguments, or interpret diagrams (Strohmaier et al., 2020). However, more recently, ET has begun to be used to explore creative thinking in mathematics, examining how students construct alternative solutions, manage visual representations, and interact in collaborative contexts. Several recent studies have utilized ET to observe creative thinking processes in various types of mathematical tasks. For instance, Schindler & Lilienthal (2020) explored how students solved multiple-solution tasks and found that complex visual attention patterns were indicative of creative strategies. Another study by Schoenherr & Schukajlow (2023) examined how drawing activities helped students construct visual representations in modeling tasks. In contrast, Schindler & Lilienthal (2022) utilized dual eye-tracking to investigate collaborative creative processes.

The relationship between fixation patterns and creativity can be better understood by integrating theoretical perspectives with empirical findings. From a theoretical standpoint, the eye-mind hypothesis suggests that eye movements reflect ongoing cognitive processes, while mathematical creativity is often characterized through fluency, flexibility, and originality (Silver, 1997), as well as the interplay of divergent and convergent thinking (Guilford, 1967). Combining these perspectives implies that eye-tracking metrics can provide indirect indicators of creative engagement. Empirically, studies have begun to support this link. For example, Muldner & Burleson (2015) found that students with higher creativity showed significantly longer saccade lengths and higher saccade speeds, suggesting a more divergent and holistic exploration of geometric representations. In contrast, students with lower creativity displayed shorter saccade and slower saccade speeds, which may reflect more local thinking and cognitive fatigue. These findings provide initial evidence that fixation patterns and gaze dynamics may serve as meaningful markers of creative thinking processes, though further research is needed to establish stronger theoretical and empirical connections.

Investigating the creative process, Schindler et al. (2016) found that gaze-overlaid videos could offer fine-grained access to what students are paying attention to and focusing on. Analysis of gaze-overlaid videos offers insight into how students reconstruct new creative ideas, select complex approaches through written or pictorial descriptions, and assess the level of elaboration in their approaches. These results suggest the potential that eye-tracking can offer for investigating students' creative processes in mathematics (Schindler & Lilienthal, 2017b). Eye-tracking can help understand the creative process in its fluid nature, where students compare information, jump back and forth, or jump to other ideas or approaches (Schindler & Lilienthal, 2020).

Although the use of eye-tracking technology in mathematics education research is increasing, its application in the study of mathematical creativity remains relatively recent, and the number of studies incorporating this approach is still limited. Furthermore, no systematic review has specifically examined how eye-tracking is used to investigate mathematical creativity, in terms of the type of ET technology used, the variety of mathematical tasks given, as well as the patterns of visual attention observed as indicators of creativity. These four aspects are crucial for understanding the role of eye-tracking in comprehensively uncovering the dynamics of mathematical creativity. To address this gap, this article aims to conduct a systematic review of studies that use eye-tracking technology in the context of mathematical creativity. Specifically, this review is designed to answer the following research questions (RQ):

RQ1: What types of eye-tracking technology have been used in research to study mathematical creativity?
RQ2: What types of mathematical tasks are designed for mathematical creativity through eye-tracking?
RQ3: What types of eye-tracking data have been used to interpret mathematical creativity?
RQ4: How do we investigate mathematical creativity using eye-tracking?

The findings of this review are expected to provide a more comprehensive understanding of how students' visual attention and cognitive processes in mathematical creative thinking can be analyzed through an eye-tracking technology-based approach. Furthermore, the study is expected to provide a foundation for the development of learning designs, further research, and the use of technology in mathematics education.

2. Method

This study employed a systematic review approach to answer the previously formulated research questions. The systematic review was conducted following the procedures proposed by Newman & Gough (2020). In general, the review process consisted of the following seven stages:

Stage 1: Formulating Research Questions and Conceptual Framework. The research questions developed focused on identifying the type of eye-tracking (ET) technology used, the characteristics of the mathematical tasks designed in the study, the metrics and visual attention patterns observed as indicators of mathematical creativity, and the methods used to analyze this creativity, as described in the introduction. The conceptual framework in this study was built on the assumption that mathematical creative thinking processes can be observed and understood through visual attention patterns recorded using eye-tracking technology. Visual attention patterns, such as fixations and saccades are viewed as representations of cognitive strategies and may reflect the idea generation processes underlying creativity. Furthermore, this framework also includes the relationship between the type of ET technology utilized (e.g., screen-based or mobile), the design of mathematical tasks (e.g., problem-solving or open-ended), and the ET data analysis method (e.g., quantitative analysis of ET metrics or triangulation with interviews), which contribute to a more comprehensive understanding of mathematical creativity. This framework serves as the basis for designing inclusion criteria, search strategies, and data synthesis, aiming to provide a comprehensive overview of how eye-tracking technology is utilized to explore creativity in mathematics learning contexts.

Stage 2: Determining Inclusion and Exclusion Criteria. To ensure transparency in the study selection process, specific inclusion and exclusion criteria were applied during article screening. The inclusion criteria used in study selection were: (1) articles were sourced from the Scopus database and published up to 2024; (2) studies focused on aspects of mathematical creativity identified using eye-tracking technology; (3) articles were written in English; and (4) were available in full-text. Studies were excluded from the review if: (1) they did not focus on aspects of creativity that directly utilized ET data; (2) they were only reviews or non-empirical summaries; (3) articles were written in languages other than English; or (4) were not available in full-text.

Stage 3: Developing a Search Strategy. The search for previous studies was conducted using the Scopus database search engine. The keywords used included: [("eye-tracking" OR "eye tracking" OR "eye movement") AND ("creativity" OR "creative") AND math*]. These keywords were selected to capture all potential studies linking ET to mathematical creativity.

Stage 4: Study Selection. The keyword search yielded 19 documents. The documents were then selected, and documents from conference reviews and errata (7 documents) were removed, resulting in 12 papers. Screening was then conducted based on the research theme and objectives by identifying articles discussing the process of mathematical creative thinking. From this process, five articles were obtained. Finally, there were five articles that met all full-text and accessible criteria after further screening. We acknowledge that the number of articles analyzed in this study is relatively small and limited to only five articles. This limitation may impact the validity and generalizability of the findings. Therefore, the results of this study should be understood as preliminary conclusions (descriptive-exploratory) rather than generalizing conclusions. Several studies also used only five studies in their reviews (Cirrin et al., 2010; Feenstra et al., 2014; Sweeney et al., 2025), suggesting that small-scope reviews can still be a useful starting point for future research. The search and article selection process is presented in Figure 1.

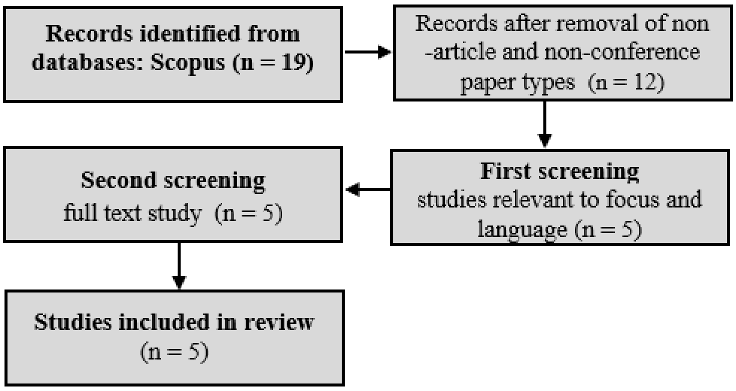

Fig. 1. Flow Diagram of study selection process

Stage 5. Study Coding. Articles selected in the selection stage were then coded based on four main aspects: the type of ET technology used, the type or context of the mathematical task given, the types of ET data to analyze and interpret mathematical creativity, and the methods for investigating mathematical creativity. Coding was performed by conducting a content analysis of each article.

Stage 6. Study Quality Assessment. At this stage, each study selected in the systematic review was assessed for quality to ensure its alignment with the research question, the quality of the method implementation, and its relevance to the study's focus. To assess the overall quality of each selected paper, we used the Mixed Method Appraisal Tool (MMAT) criteria, a well-established tool for assessing the methodological quality of five study design categories: qualitative design, quantitative randomized controlled trials, quantitative non-randomized, quantitative descriptive, and mixed methods (Hong et al., 2018). This quality assessment tool was used considering the diversity of study types included in this review. The assessment was conducted with two initial screening questions followed by five core criteria for each category. Each quality criterion consists of questions with “Yes,” “No,” and “Can’t tell” responses. A “Yes” response correlated with a score of 1, and a “No” or “Can’t tell” response correlated with a score of 0. Studies scoring 0–2 were classified as of low quality, those scoring 3–4 were classified as of moderate quality, and those scoring 5 were classified as of high quality. All selected papers met the initial screening criteria, which considered whether the study had a clear research question and sufficient data to support it. The results of the quality analysis of the selected papers are presented in Table 1 (column 2).

Stage 7. Synthesis of Findings. The synthesis was conducted in a configurative manner by organizing and interpreting the findings based on the four main focuses previously formulated. This process yielded a comprehensive understanding of the interrelationships between eye-tracking technology, mathematical task context, types of ET data, and methods for investigating mathematical creativity. The results of this synthesis will be presented in detail in the results and discussion section.

3. Result & Discussion

Following the search, selection, and validation process based on inclusion and exclusion criteria, five articles were identified that were relevant to the focus of this systematic review, specifically studies that utilized eye-tracking technology (ET) to analyze mathematical creativity. Table 1 summarizes the results of the content analysis, focusing on the quality of the paper and four main aspects corresponding to the research questions: type of eye tracker (RQ1), type of mathematical task (RQ2), types of ET data (RQ3), and methods for investigating mathematical creativity (RQ4).

The quality scores of the selected papers indicated that four studies were classified as high-quality and one as moderate-quality. Quality ratings were not used to include or exclude studies, but rather to describe the overall quality of evidence from the included studies (Nyanchoka et al., 2022).

3.1 Types of Eye Trackers Used in Mathematical Creativity Studies

To understand how eye-tracking technologies support the investigation of mathematical creativity, it is important to examine the types of devices used across studies and the rationale for selecting them. The specific types of eye trackers, models, and the purposes for which they were selected are presented in Table 2.

Table 1. Content Analysis of Selected Articles

Author	Quality of Paper (MMAT)	RQ1	RQ2	RQ3	RQ4
Bicer & Bicer (2023)	5	GS	MRs	Eye-tracking videos, fixation measures	ET and SRI
Schoenherr & Schukajlow (2023)	5	GS	PS	Fixation, AOI sequence, eye-tracking videos	ET and SRI
Schindler & Lilienthal (2022)	5	GS	MST	Eye-tracking videos	ET and SRI
Schindler & Lilienthal (2020)	5	GS	MST	Eye-tracking videos	DUET and SRI
Muldner & Burleson (2015)	3	SB	PS	Fixations, saccades, and pupil size	ET, EEG dan SC

Note. GS:Glasses; SB: Screen-based; MRs: Multiple Representation, PS: Problem-Solving; MST: Multiple Solution Tasks ; ET: Eye-tracking, DUET: Dual Eye-tracking, SRI: Stimulated Recall Interview, EEG: Electroencephalography, SC: Skin Conductance

Table 2. Types of Eye Trackers

Type	Model	Description	Author
Mobile eye trackers (glasses-based)	Pupil Pro/Pupil Core	Used to study the creative thinking processes of elementary school students in visual representation tasks. It was chosen because it can capture a high-definition video stream of a person's eye movements, is very affordable and easy to use, and is relatively unobtrusive due to its light weight.	Bicer & Bicer (2023)
	Tobii Pro Glasses 3	Used to investigate the role of drawing in mathematical creativity. It was chosen because it allows students to work naturally with paper and pencil and move their heads freely.	Schoenherr & Schukajlow (2023)
	Tobii Pro Glasses 2	Used to study collaborative creative thinking processes in Multiple Solution Tasks. It was chosen because it is relatively unobtrusive due to its light weight, ease of operation, high-resolution camera, and synchronized voice recording microphone.	Schindler & Lilienthal (2022)
	Pupil Pro/Pupil Core	Used to observe creative thinking processes in MST. It was chosen because it is relatively easy to install and operate, relatively unobtrusive, and allows students to work naturally (paper-and-pen-based) without restricting body and head movements.	Schindler & Lilienthal (2020)
Screen-based eye trackers	Tobii TX60	Used to record student gaze patterns during geometry proof generation in a digital geometry application. It was chosen because its self-contained eye tracker does not restrict head movement or participant movement and can record gaze and all user actions in the digital application.	Muldner & Burleson (2015)

Based on the five studies reviewed, four used mobile eye trackers to identify mathematical creative thinking processes, while one used a screen-based eye tracker to model levels of creativity. This indicates that both types of eye trackers have been effectively applied to investigate mathematical creativity, each contributing unique methodological strengths. Schindler & Lilienthal (2017b) emphasize that both screen-based and mobile eye trackers are suitable for examining mathematical creativity, although each type offers distinct advantages and limitations. Mobile eye trackers, such as the Pupil Pro/Pupil Core and Tobii Pro, are widely used in the creative thinking process for their ability to record detailed eye movements without disrupting participants' natural activities. These devices are generally lightweight, easy to install and operate, and allow users to move freely and work with writing instruments naturally. Furthermore, features like high-resolution cameras, synchronized audio recording (Tobii Pro), and user-friendliness make them ideal for studying creative thinking processes. As noted by Schindler & Lilienthal (2017b), mobile eye trackers enable the recording of eye movements at close range and support natural head and body movement, making them particularly suitable for paper-and-pencil tasks and activities requiring mobility.

In contrast, screen-based eye trackers offer the advantage of recording user interactions with digital environments more precisely. Screen-based eye trackers such as the Tobii TX60 were chosen because they are standalone eye trackers that do not restrict head movement and can record gaze direction and all user actions on the screen (Muldner & Burleson, 2015), making them highly effective for examining creative thinking processes in computer-based contexts. These tools are mounted on a screen, typically located below or near the computer, and require the user to sit in front of the screen (Gunawardena et al., 2022). These devices do not require participants to wear any equipment (Farnsworth, 2017), making them relatively unobtrusive (Poole & Ball, 2006).

These findings demonstrate that the choice of eye tracker type is closely aligned with the characteristics of the mathematical task and the form of creativity being investigated. Therefore, future research should consider not only technical aspects such as price and convenience of the eye tracker, but also the need for holistic data collection to obtain more comprehensive insights into students' mathematical creativity.

3.2 Mathematical Tasks to Foster Creativity

Mathematical tasks play a central role in eliciting students' mathematical creativity. In studies employing eye-tracking methodologies, task design becomes critical because the structure and cognitive demands of a task directly influence visual attention and the diversity of solution approaches. Table 3 summarizes the characteristics of tasks used in previous mathematical creativity studies, including the types of mathematical tasks, domain, the participants/subjects, and a brief description of each task.

Table 3. Task Types Used to Foster Mathematical Creativity

Task Type	Domain	Subject	Description	Author
Multiple Solution Tasks	Geometry	High School Student	The assignment asks students to solve a problem by generating as many possible solutions as possible.	Schindler & Lilienthal (2020)
Multiple Solution Tasks	Geometry	Graduate Students	The assignment asks two students to work collaboratively to solve a problem by generating as many possible solutions as possible.	Schindler & Lilienthal (2022)
Multiple Representation	Numbers and Algebra	Elementary Students	The assignment asks students to generate various representations (visual patterns, area models, number lines, subitizing) for a single problem.	Bicer & Bicer (2023)
Problem-Solving	Geometry	University Students	The assignment involves geometric proofs, requiring students to generate as many proof strategies as possible.	Muldner & Burleson (2015)
Problem-Solving	Geometry	High School Student	The assignment involves solving mathematical modeling problems, requiring students to create drawings to construct mathematical models and evaluate realistic parameters.	Schoenherr & Schukajlow (2023)

Based on an analysis of the five reviewed studies, the mathematical tasks used in eye-tracking research included multiple solution tasks (2 studies), problem-solving tasks (2 studies), and multiple representation (MRs) tasks (1 study). Schindler & Lilienthal (2020) utilized geometry-based multiple solution tasks that allowed students to generate multiple solution strategies. These tasks provided opportunities for divergent thinking, exploration of various approaches, and strategic decision-making in selecting the most appropriate solution. MSTs also allowed participants to explore solution strategies both independently (Schindler & Lilienthal, 2020) and collaboratively (Schindler & Lilienthal, 2022). These tasks stimulate creativity by encouraging students to explore multiple solution paths, characterized by steps such as information seeking, idea/intuition, working further step by step, and finding a solution. In particular, MRs tasks, as implemented by Bicer & Bicer (2023), can be considered a specific form of MSTs, as they required elementary students (grades 1–3) to generate multiple representations of numbers and operations, and grade 5 students to do so for algebra. By producing visual patterns, area models, number lines, and subitizing representations, students were encouraged to explore alternative approaches and representations, fostering creativity in mathematical thinking. Schoenherr & Schukajlow (2023) used a problem-solving task that emphasized solving mathematical modeling problems to stimulate students' creativity through the use of diagrams. Meanwhile, Muldner & Burleson (2015) used a creative problem-solving task to generate multiple geometric proof strategies in a digital environment. Overall, the tasks used in the studies were highly varied and designed to facilitate the exploration of ideas.

This study shows that four articles discussing mathematical creativity through ET used the geometry domain. Interestingly, Schindler et al. (2025) stated that geometry is the second most researched domain in ET studies in mathematics education, after numbers and operations. Geometry problems typically involve visual diagrams that combine spatial information with written descriptions (Lin & Lin, 2014). Similarly, Gal & Linchevski (2010) emphasized that every geometry task always contains a visualization process, either explicitly or implicitly. Therefore, geometry is considered a suitable topic for the application of ET technology. Schindler & Lilienthal (2017a) emphasized that ET is effective for observing visual-based cognitive tasks, where eye movements can be associated with mental operations. By integrating ET into observations of students' problem-solving processes, researchers can record their visual attention (Rayner, 1998). ET enables researchers to capture students' gaze patterns as they engage in visual tasks, providing insight into how they process visual information during problem-solving. In the context of geometry tasks, students can solve problems through various strategies, such as reading text, drawing additional diagrams, searching for familiar patterns, recalling relevant information, and drawing conclusions (Epelboim & Suppes, 2001). Therefore, the visual–spatial nature of geometry makes it a highly relevant and informative domain for studying with ET technology.

The participants in this study ranged from elementary school students to graduate students, providing insight into how task complexity and type interact with students' developmental level and problem-solving abilities. Specifically, elementary school students engaged more in multiple representation tasks, while high school and university students engaged more in multiple solution and problem-solving tasks, reflecting increased cognitive demands and the need for more sophisticated problem-solving strategies.

3.3 Eye-tracking Data for Interpreting Mathematical Creativity

Eye-tracking data produces quantitative (eye movement metrics, such as fixations and saccades) and qualitative (eye-tracking videos) data, which provide researchers with the opportunity to detect and interpret mathematical task-solving strategies (Andrzejewska et al., 2016). Olmsted-Hawala et al. (2014) mention common measures used in many eye movement studies, namely fixations, saccades, Area of Interest (AOIs), heatmaps, and gaze plots. Regarding eye movement measures used in creative problem solving, Muldner & Burleson (2015) employ fixations (number of fixations, total fixation time, and duration), saccades (distance, length, and speed), and pupil size. Fixation data is used to determine the extent to which students focus their attention on specific elements in a task, where the number and duration of fixations serve as indicators of the level of cognitive focus. Longer fixation durations may indicate more specific information processing, allowing for a deeper understanding of the information (Pei et al., 2024). Saccades are rapid eye movements from one fixation to another. Specifically, fixations indicate attention and cognitive processing of information, while saccades indicate shifts in attention. Meanwhile, pupil size indicates cognitive load and attention level. A larger pupil size can indicate a higher cognitive load or greater attention to specific information (Pei et al., 2024).

In the context of mathematical creativity, fixation can be understood as the basis for how students emphasize important information, filter details, and lay the foundation for new ideas. Saccades can be interpreted as students' attempts to explore the problem space, marking transitions from one approach to another, or revealing unexpected relationships between pieces of information. Variations in saccades length and speed can indicate flexibility of thinking, while short and repetitive saccades indicate limited exploration. Muldner & Burleson (2015) stated that highly creative students tend to have longer and faster saccades than less creative students, perhaps because their thinking is more divergent. Meanwhile, less creative students have significantly shorter saccades lengths, suggesting they may be more locally focused when solving problems. Furthermore, pupil size and the number of peaks of pupil size change were also examined as indicators of cognitive load and affective state, although no significant differences were found between creative and less creative students (Muldner & Burleson, 2015). Overall, these findings suggest that more dynamic and diffuse visual attention patterns (saccades) may be an important marker of students' mathematical creativity in solving mathematical problems. However, while these quantitative indicators are useful for mapping the focus and dynamics of visual attention, they cannot fully explain how creative ideas are formed. Therefore, quantitative analysis is often complemented by qualitative approaches (Andrzejewska et al., 2016).

One commonly used qualitative approach is eye-tracking videos analysis, which enables researchers to identify creative processes in a more contextualized manner. Eye-tracking videos or gaze-overlaid videos are recordings of students' activities that display the trajectory of their gaze directly over their work, allowing researchers to observe how visual attention moves from one element of the problem to another. This data may provide an opportunity to reconstruct the journey of ideas, from initial exploration and idea discovery, to forming connections between representations, strengthening ideas, verification, and ultimately, a mature solution. Although not directly revealing the contents of students' thoughts, this visual data can still be interpreted as traces of cognitive processes that shape the construction of mathematical creativity. Schindler et al. (2016) stated that gaze-overlaid videos offer access to what students notice and focus on while completing tasks. This suggests that eye-tracking videos contribute to describing the approaches used by students and how new creative ideas develop (Schindler & Lilienthal, 2017b).

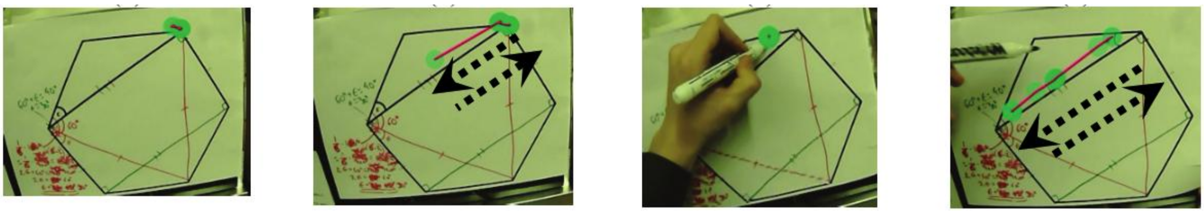

Fig. 2. Screenshot of eye-tracking videos (Schindler et al., 2016)

Table 4. Data ET Used to Investigate Mathematical Creativity

Data	Description
Gaze-overlaid videos	Video recordings displaying visualizations of participants' eye movements while performing a task. Used to analyze visual sequences, problem-solving strategies, and reconstruct the process of creative idea generation.
Fixation	A stable point of gaze on a specific element indicates attentional focus and cognitive processing of information. Used to measure attentional focus, depth of information processing, and the generation of new ideas.
Saccade	A rapid movement between fixations. A long, fast saccade tends to indicate divergent and holistic visual exploration (creative), while a short trajectory indicates a local focus (less creative).
AOI Sequence	A sequence of fixations on AOIs that shows the path of visual exploration. This data can be used to interpret how ideas are constructed through shifting between representations and solution reinforcement.
Pupil size	Changes in pupil size serve as indicators of cognitive load, attention, and affective engagement that accompany the processes of searching for, processing, and consolidating creative ideas. In particular, pupil dilation (larger pupil size) may indicate an increased cognitive load or more intense engagement in creative problem-solving.

Gaze-overlaid videos directly displays participants' gaze trajectories across the observed stimuli, allowing researchers to study visual sequences and problem-solving strategies in a contextualized manner, while also supporting SRI reflective interviews to explore how creative ideas emerge and develop (Schindler & Lilienthal, 2020, 2022). Schindler & Lilienthal (2020) reconstructed the phases of a single student's creative process in a Multiple Solution Task (MST) using eye-tracking videos and SRI. A follow-up study by Schindler & Lilienthal (2022) extended this design to a collaborative context, utilizing dual eye-tracking, which enabled researchers to track the synchronization or divergence of visual focus between students during collaborative work. Schoenherr & Schukajlow (2023) used three main types of eye-tracking data to interpret mathematical creativity: (1) fixation data within defined Areas of Interest (AOIs) to identify phases of image construction and use, (2) AOIs sequence charts to visualize the sequence and duration of fixations across problem representations. AOIs' sequences are sequences of gazes between AOIs, showing visual exploration paths. These data can be used to understand how ideas are constructed through the switching of representations, repeated gazes at key elements, and the establishment of visual associations that support solutions. Thus, in the construction of mathematical creativity, these sequence patterns can be interpreted as maps of the idea-building process: as students explore multiple visual paths, attempt to connect different representations, and return to relevant areas to strengthen solutions, and (3) gaze-overlaid videos used in stimulated recall interviews to link visual attention to students' reflections on originality, fluency, and usefulness. Similarly, Bicer & Bicer (2023) combined eye-tracking video recordings with SRI to reveal gaze shifts between representations that corresponded to the moment of original idea emergence in elementary school students. In their study, Bicer & Bicer (2023) also conducted a quantitative analysis of fixation measures to identify aspects of students' focus during SRI, and compared this to their attention when solving problems. This combined data approach allows researchers to interpret the relationship between visual attention patterns and the dynamics of participants' creativity holistically, providing a deeper understanding of how creative thinking processes occur in the context of mathematical problem-solving.

Thus, ET metrics enable the quantitative identification of creativity through differences in visual attention patterns, while gaze-overlaid video emphasizes the qualitative aspects by tracing the dynamics of the creative process. In other words, these two approaches complement each other. To summarize the above, Table 4 presents the types of ET data used in these studies along with a description of their role in identifying mathematical creativity.

3.4 Methods for Investigating Mathematical Creativity

Recent studies have employed two main approaches to investigate mathematical creativity using ET technology. Most studies emphasizing internal processes use a combination of eye-tracking and stimulated recall interviews (SRI). On the other hand, one study used multimodal sensor methods as a quantitative method focused on predictive modeling. The multimodal sensors in question are a combination of ET with other sensors such as Skin Conductance (SC) and Electroencephalography (EEG). Table 5 summarizes the types of methods used in the five studies.

Table 5. Methods for Investigating Mathematical Creativity

Method	Description	Author
ET & SRI	Creativity was identified through eye-tracking video combined with interviews from gaze-overlaid videos recordings (SRI). This method triangulates visual attention with participants' reflective verbal reports to capture their creative thinking processes.	Schindler & Lilienthal (2020; 2022), Bicer & Bicer (2023) and Schoenherr & Schukajlow (2023)
Multimodal Sensor (ET, SC, and EEG)	Creativity was first assessed through students' problem-solving products (fluency, flexibility, originality) and then modeled with sensor data (ET, SC, and EEG). ET captured visual attention patterns, SC provided signals that change around affectively or cognitively charged events, and EEG data were mapped into affective and cognitive states (excitement, frustration, engagement, meditation). This method enables the identification of differences in visual attention patterns and affective and cognitive measures between participants with high and low creativity.	Muldner & Burleson (2015)

a. ET and SRI

Four studies (Schindler & Lilienthal, 2020, 2022; Schoenherr & Schukajlow, 2023; Bicer & Bicer, 2023) combined ET with SRI to identify mathematical creativity. This approach allows researchers to not only observe students' visual data but also gain direct verbal insights from participants regarding the meaning of their attention patterns. SRI provides an opportunity for students to reflect on their actions after the task has been completed, using gaze-overlaid videos as a stimulus to recall their thought processes. This method is considered most effective in capturing the complexity of creative thinking because it combines objective and subjective evidence (student reflections) in a contextualized manner. SRI is also conducted by synchronizing eye gaze recordings with participants' verbal narratives, allowing researchers to explore cognitive processes in greater depth (Schindler & Lilienthal, 2020). However, SRI interview questions do not alter the cognitive processes used at the time of the event (Dempsey, 2010). Furthermore, SRI helps uncover non-linear aspects of creative thinking, such as strategy changes and the formation of new ideas, which are not always apparent from quantitative data alone. Therefore, the use of ET and SRI is considered most effective in uncovering mathematical creative thinking processes because this combination allows for data triangulation between visual behavior and participants' cognitive interpretations. As noted by Bicer & Bicer (2023), using ET without interviews to stimulate reflection is less effective in explaining the meaning behind the recorded visual patterns. Therefore, integrating quantitative and qualitative approaches is significant for obtaining a more comprehensive understanding of the dynamics of students' mathematical creativity.

In the eye-tracking process, a calibration stage was initially performed to ensure the accuracy of eye-tracking and the subject's gaze position. Afterward, the subject was given a mathematical creativity task. While working on the task, the eyes moved rapidly and stopped for a period to take in information before moving onto another area (Copeland, 2016). This movement indicated an initial search for important information, such as numbers or keywords (Schindler & Lilienthal, 2020). After reviewing all the information, the subject's gaze tended to focus on a specific section to gain a deeper understanding of the problem. Repeated scanpath patterns indicated attempts to connect the information with the problem, form mental images, and search for data connections. At this stage, the subject began to generate ideas, explore possible solutions, and connect new ideas with existing ones. Next, the subject selected one idea. Longer fixations on related elements indicated focus and in-depth information processing as part of planning (Rayner, 2009). Shorter saccades and repeated visits to specific areas indicated a structured approach to planning. During the implementation phase, subjects executed the plan, focusing intently on relevant parts of the problem and formulas. The alternating gaze demonstrated double-checking of steps and verification of calculation results. If a solution was deemed inappropriate, the scanpath pattern shifted to search for alternatives. When a solution was found, fixations focused on key elements to verify the answer through short saccades. In a more extended approach, as the subject's eyes explored a specific area, they attempted to look around and expand their gaze to discover new aspects worthy of investigation (Schindler & Lilienthal, 2020). This aligns with findings by Muldner & Burleson (2015) that highly creative participants tended to have longer saccades on average, likely due to their extensive thinking. If the subject was confident in the final solution, the entire creative thinking process, recorded through eye-tracking, was considered complete.

The gaze-overlaid videos obtained during eye-tracking then served as the basis for the SRI. Other authors have also conducted quantitative analyses of fixation measures (Bicer & Bicer, 2023) and fixations within Areas of Interest (AOIs) and AOI sequence charts (Schoenherr & Schukajlow, 2023), which are to be validated through SRI. Prior to the SRI, the interviewer explains how participants can identify their gaze in the video and the SRI process itself. During the session, the interviewer can pause, rewind, or fast-forward the video to clarify any needed information. The activity begins with the interviewer and subject watching a video recording of the subject's gaze-overlaid. At specific eye movements, the video is paused, and the interviewer asks questions about the reasoning behind the eye movement. The subject's eye movements are certainly related to the subject's creative solution to the idea. The subject is then invited to answer questions to describe the strategy used and the creative solution or idea created. When the gaze-overlaid image ends and there are no further questions from the interviewer, the SRI activity is complete. Thus, gaze-overlaid videos help students recall their deliberations during tasks, providing insights into the creative process that are not reflected in written notes (Schoenherr & Schukajlow, 2023). However, eye movements need to be interpreted with caution, as they reflect, among other things, affective arousal in addition to cognitive processes (Thomaneck et al., 2022).

b. Multimodal Sensor (ET, SC, and EEG)

Muldner & Burleson (2015) employed a multimodal approach combining ET, skin conductance (SC) sensors, and electroencephalography (EEG) to model mathematical creativity. While working on a geometric proof task, participants' eye movements were recorded using an eye tracker, while electrodermal activity and brain signals were recorded using a wrist-shaped SC sensor and an EEG device. ET was used to record visual attention patterns, such as the number and duration of fixations, saccade length and speed, and pupil size, which reflect participants' focus, attention shifts, and exploration strategies. Data from the SC and EEG supplemented this information by capturing physiological responses related to arousal, mental engagement, and emotional fluctuations that may be associated with moments of insight.

Before analyzing the sensor data, participants' creativity levels were first determined based on their solutions. Each student was asked to produce as many geometric proofs as possible, and then their solutions were analyzed using three dimensions of creativity: fluency (the number of unique solutions), flexibility (the variety of strategies used by a single participant), and originality (the uniqueness of solutions across participants). These three dimensions are summed to produce a creativity score, which is then used to categorize students into High Creativity (HC) and Low Creativity (LC) groups. After grouping, the sensor data is processed through cleaning (removal of invalid data), normalization, and feature extraction relevant to the task. From ET data, visual metrics are obtained; from the SC, peak detection reflecting physiological arousal was obtained; and from the EEG, cognitive-affective indicators such as short-term excitement, engagement, frustration, and meditation were extracted. These multimodal features were then either compared between the HC and LC groups or used to train classification models in order to detect distinctive patterns associated with creativity. Thus, in this method, creativity was first operationalized and scored based on students' mathematical solutions, and subsequently, the sensor data were employed to model and predict differences between students with high and low levels of creativity.

The combination of eye-tracking (ET) with stimulated recall interviews (SRI) integrates objective data, such as eye gaze patterns, with subjective data derived from students' verbal reflections. This method yields qualitatively rich insights, enabling researchers to capture the dynamics of creative thinking that may not be evident through quantitative data alone. However, it is time-intensive, difficult to apply with large samples, and vulnerable to retrospective bias or inaccurate recall. In contrast, combining ET with electroencephalography (EEG) and skin conductance (SC) provides objective, real-time multimodal data that is less influenced by subjective bias. Yet, this method relies on costly equipment, has technical limitations, generates noisy raw data, and presents complex processing and interpretation challenges because physiological responses are not always specific to creativity, but can also be triggered by other factors, such as stress or fatigue. These findings emphasize that studies aiming to explore students' thinking processes in depth should consider combining ET with reflective approaches such as SRI. Eye-tracking should be regarded not only as a tool for monitoring visual attention but also as a means of modeling thought processes in mathematical problem-solving. Therefore, the use of additional technologies and multimodal data beyond eye-tracking has the potential to provide richer and more holistic information, not only regarding mathematical creativity but also other aspects of mathematics learning, such as strategies, representations, and conceptual understandingSchindler et al. (2025) identified nine types of complementary data to eye-tracking, including SRI, think-aloud interviews, observations, tests, questionnaires, and online measures.

This systematic review makes a significant contribution to the application of eye-tracking in the investigation of mathematical creativity. However, this review still has several limitations. First, the review relied solely on articles indexed in Scopus, which may have excluded relevant studies published in other databases such as Web of Science, ERIC, or Google Scholar. Second, the number of eligible studies was relatively small, which restricts the ability to draw broader generalizations about how eye-tracking has been used across diverse mathematical domains and participant populations. As a result, the scope of the findings related to the four research questions may not have been fully captured in this review. Third, the quality assessment was conducted by a single reviewer, which increased the risk of subjective interpretation and may have affected the consistency of the study appraisal. These limitations should therefore be considered when interpreting the overall trends and conclusions of this review. Future research should expand database coverage, involve multiple reviewers to minimize bias, and include a broader range of mathematical domains and participant groups. Overall, the findings underscore the potential of eye-tracking not only as a tool for assessing visual attention but also for investigating students' creative processes, providing valuable insights for future research and practice in mathematics education.

4. Conclusion

Based on the analysis of the five studies reviewed in this study, it was found that mobile eye trackers and screen-based eye trackers can be used to identify mathematical creativity. To stimulate creative thinking, the reviewed studies implemented tasks designed that allowed for the exploration of divergent strategies and solutions such as multiple solution tasks (both individual and collaborative), multiple representations, and problem-solving. Eye-tracking produces two main types of data: quantitative (eye movement metrics, such as fixations and saccades) and qualitative (eye-tracking videos). Both serve as complementary approaches to uncover how participants process information, construct ideas, and realize creative solutions when solving mathematical problems. In terms of identification methods, studies focusing on internal processes have shown high effectiveness when using a combination of eye-tracking and stimulated recall interviews. This approach enables triangulation between quantitative data ET and verbal reflective data SRI, providing a more comprehensive understanding of the dynamics of creative thinking. In contrast, another approach integrated ET with skin conductance and electroencephalography. In this method, creativity was first assessed from students' problem-solving products (fluency, flexibility, originality) and then modeled by linking visual attention patterns and physiological responses, allowing researchers to distinguish between high-and low-creativity groups.

The results of this review have several practical implications for mathematics educators. First, the use of geometry-based open-ended tasks appears effective in stimulating creativity due to their visual nature and the possibility of diverse solution strategies. Teachers can utilize this type of task to encourage students' exploration of ideas and divergent thinking, while expanding into other mathematical domains such as algebra or arithmetic, rather than being limited to geometry. Second, the findings regarding the integration of eye-tracking with reflective interviews emphasize the importance of understanding students' thinking processes, not just the final product. This combinative approach not only provides information about what students pay attention to when completing tasks, but also why they make certain decisions. Therefore, even though ET technology may not be available in the classroom, a similar approach can be adapted through think-aloud or interview, allowing teachers to gain insight into students' creative thinking processes.

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