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Role of visual abilities in mathematics learning: An analysis of conceptual representation

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Abstract

Background: In mathematics education, the understanding of concepts is often influenced by students' visual abilities, making conceptual representation crucial in facilitating comprehension of the material.
Aim: This study aims to analyze the role of visual abilities in facilitating the understanding of mathematical concepts through conceptual representation.
Method: This research combines quantitative analysis with the use of attribute control diagrams to evaluate data obtained from tasks designed to test students' visual abilities in a mathematical context. These tasks include the manipulation of visual representations and problem-solving using geometric concepts.
Results: The findings indicate that 80% of the sample possessed visual abilities that did not meet the expected index, showing a wide variation in students' visual representation abilities. Additionally, most students (70%) were more likely to choose familiar geometric representations in problem-solving, despite difficulties in manipulating more complex concepts.
Conclusion: This study demonstrates that students often struggle to effectively utilize visual representations, preferring algebraic approaches that do not fully exploit the potential of conceptual representation. The findings suggest that an increased focus on developing visual abilities, especially in conceptual representation, could strengthen mathematical understanding. Further research is needed to develop intervention strategies that can help students overcome gaps in their visual abilities.

INTRODUCTION

The ability to visualize plays a pivotal role in mathematics education, not merely as a tool to elucidate abstract concepts (Nardi, 2014; Presmeg, 2020), but also as the primary bridge for understanding and internalizing mathematical knowledge (Andersen, 2014). The development of this skill within the school environment enables students to visualize and manipulate mathematical objects more effectively, from geometric figures to graphs and tables (Rif'at, 2018; Ziatdinov & Valles Jr, 2022). This directly impacts their ability to solve mathematical problems intuitively and creatively, underscoring the importance of incorporating visual skills into mathematics learning to enhance student comprehension and creativity (Bicer, 2021; Vale et al., 2018).

Through mathematics education, the enhancement of visual skills is vital for grasping conceptual representations, essential for establishing robust mathematical knowledge (Rif'at, 2014; Sriadhi et al., 2018). These representations reveal the myriad ways mathematical concepts can be depicted, encompassing symbolic, numeric, verbal, and visual formats, thus providing learners with access to mathematical insights from varied viewpoints (Goldin, 2020;

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Thomas, 2008). Proficient visual skills enable students to fluidly move between these conceptual representations, enriching their grasp of mathematical notions and their proficiency in employing such knowledge across different contexts (Amir et al., 2021). This illustrates that enhancing visual skills not only aids in understanding abstract notions but also amplifies students' capabilities in creatively and efficiently interpreting and utilizing these concepts.

Therefore, the integration of visual abilities with conceptual representations becomes crucial in enriching the mathematics learning process (Fauziyah et al., 2024; Wang et al., 2020). Learning that develops visual abilities and utilizes them to explore conceptual representations provides students with the tools they need to understand mathematical concepts intuitively and apply them in diverse contexts (Hutagaol, 2013). This not only enables students to internalize mathematical knowledge but also enhances their capacity to use that knowledge creatively (Rahmawati et al., 2022), making the development of visual abilities and the use of conceptual representations essential steps in educating competent students (Mainali, 2021; Permatasari et al., 2021; Saputri et al., 2021). This will undoubtedly support students' success in mathematics learning by leveraging the full potential of their visual abilities.

Previous research has underscored the importance of evaluating visual skills in the context of mathematics education. The study by Azmidar et al. (2021) reveals that adopting a Concrete-Pictorial-Abstract strategy boosts the ability of students to represent mathematical concepts, particularly through visual and symbolic forms. Additionally, Bani & Abdullah (2021) investigated how strategic thinking and approaches to visual representation affect students' performance, their metacognitive awareness, and their disposition towards mathematical word problem solving, highlighting the crucial role of visual strategies in the educational process. Priyadi (2023) assessed the effect of the contextual teaching and learning (CTL) model, integrated with outdoor activities, on enhancing students' abilities to represent mathematical ideas, pointing out the vital contribution of contextual learning methods to improving visual comprehension and stressing the importance of various representations in mathematics education (Sinambela, 2021).

This study emphasizes the importance of students' visual abilities. Integrating visuals into teaching methodologies can enhance conceptual understanding and students' mathematical representation skills. Although the significance of visual abilities and conceptual representation in mathematics education is recognized, there is a scarcity of research explicitly exploring the interaction between these two aspects. This gap presents an opportunity for innovative research aimed at developing a pedagogical framework. This framework would guide the development of learning strategies that maximize the potential of students' visual abilities in understanding mathematical concepts.

This research aims to bridge the knowledge gap by investigating how the integration of visual abilities and conceptual representation can support a more effective learning process. The study seeks not only to fill the existing void but also to make a practical contribution to teaching. Its goal is to analyze the role of visual abilities in facilitating the understanding of mathematical concepts through conceptual representation, thereby aiding students in visualizing and processing mathematical information more effectively.

METHODS

This research adopts an experimental approach to enhance the visual abilities of students in the realm of mathematics learning, emphasizing the cognitive practices of calculation and the incorporation of conceptual analysis via visual representations. The study's participants consist of students, faculty members, and researchers, spanning the last decade and encompassing subjects such as trigonometry, linear algebra, calculus, and geometry. Tools for this research included notes from instructors, written diagnostic assessments, observations within the classroom setting, and the creation of tests by the researchers to evaluate visual and spatial capabilities, specifically designed around visual representations in mathematical competency (Prayitno et al., 2021).

Lecturers' notes and student-provided problem solutions, as well as classroom activities and written tests. The research was divided into two main phases: classroom observation and direct experimentation, where the research team attended classes and collected lecturers' notes and documentation of student activities, especially in solving mathematical problems. Data were analyzed using a qualitative approach to explain the identified categories and statistically through attribute control charts to evaluate conformity or non-conformity based on the assessed attributes.

Furthermore, this study documented the visual conceptual guidance and support provided to students, investigating their ability to use visual representations, and highlighting the challenges encountered during the learning process. Therefore, the research focused not only on enhancing students' understanding of geometric concepts but also on developing their visual skills, which are crucial for comprehending and solving mathematical problems from various perspectives (Fathani, 2016; Lesh & Yoon, 2017) and integrating algebraic and geometric capabilities.

RESULTS AND DISCUSSION

Result

Along four times teaching and learning for each of eight different classes, the researcher gives ten same visual problems. Those are ideas of visual senses and thinking about the problems using visual framework. The ideas are not seen as comprehensive, but it may add another visual perspective to solve or explain the problems.

The relational model recognized as mathematical identity development presented highlighted issues of more algebraic works, particularly related to the visual representations and the identities of lecturers and students. That based on imagery experiences consistent with the nature of learning mathematics. That is essential aspect of the learning well-developed personal identities. The problems were presented in order below.

Problem 1

Given a visual of a ball with a mass m that pulled by *F* horizontally as Figure 1.

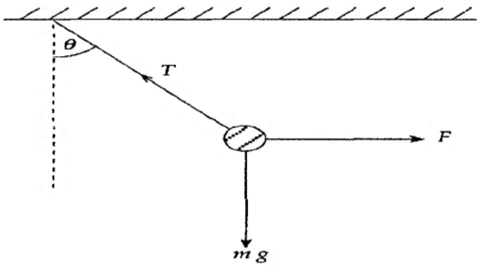

Figure 1. Visualization of a Ball of Mass m Pulled Horizontally by a Force F

Most of the students' (47%) belief the equation is $F + mg = T$. They do not use the angle Θ in their heuristic perception. The other (26%) write that $mg = F$, so $F = ½\ T$. They look the visual situation algebraically. In the case, the researcher builds their visual image in the teaching by completing the visual to get lines or ropes using angle Θ.

Problem 2

The following figure 2 is a graph of the function *sin x* and the results of the graph reflect the straight line through the point (0, 0) and point (π / 2, 1). The orthonormal line X^1 is the result of mirroring the *X*-axis to the line passing through the two points. The students ask to determine *sin α*.

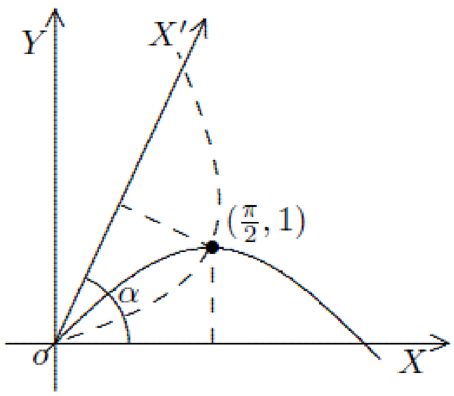

Figure 2. Graph of the Sin x Function and Straight Line Through Points (0, 0) and (π/2, 1)

The students illustrate the visual by a simple one as intermediary in Figure 3.

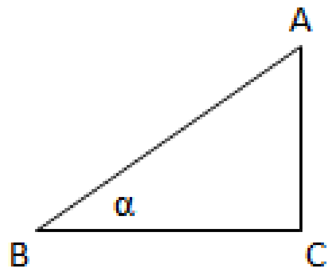

Figure 3. Simple Illustration for Determining sin α

From the illustration in Figure 3, all of them did not use the visual situations, but solve it algebraically. The solution arranged to get *AC* by Pythagorean and find *sin α* as *BC/AC*. It is the problem to simply the representation using symbols as an algebraic thinking.

Problem 3

Starting with a square of side 1, a regular hexagon is constructed, concentric with the square as presented in Figure 4. Determine the area of the intersection of both figure 4.

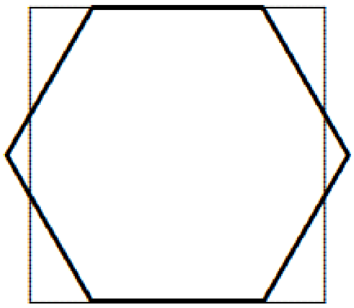

Figure 4. An Intersection of a Square and a Regular Hexagon

There are 37 students come in the teaching at the third semester. All of the students answer it algebraically, using formula recognized in geometry course. The answers presented in Table 1.

Table 1. The kinds of the students' solutions

Formula Used	Visual or Algebra Interpretation	Determining Value
Area of regular hexagon (Ah) = $\{(3\sqrt{3})/2\}\ S^2$, where *S* is the length of the side Area of square (As) = S^2	Area of the intersection = Ah-As	The side of the hexagon $S = 1/3$
Using Pythagorean for *BC*	Not recognizable in their visual	Each of right triangle sides is 0.25 and 0.5
Only for the area of hexagon	Algebraic without looking at the visual The same side length of hexagon and the square	Using variable for the side of hexagon but no solution
The area of hexagon and the square	Regular octagon Not intersection area Varies of algebraic expressions	Not discovered
The relation of the side of hexagon and the area of the square	Algebraic thinking, i.e., the side of the hexagon = ½ the square area Varies equations of some different variables	No relation for getting the intersection area No certain value at all

	Visual perception	The side of the hexagon $S = 2/3$
Using circumference of the hexagon	The side equal to 1/6 of the circumference	Not discovered
	Come to quadratic equation	No value, only the variable

Results from the solution of the problems show that most students had a weak background of visual ability or the thinking. The basic performance of geometry concept also reflects the same problem, and some errors on the complete visual representation to the solution of visual problem situation. The students also seem to have difficulties with analytic concepts. The students learn more when information is presented in a variety of algebraic expressions than the visual representations. E.g. the visual representation to be explained using the algebraic methods and a visual description not to develop the solution from the intuitive to the visual level.

The different of representations are useful as an aid in constructing understanding and communicating information. That is also show that misconceptions are an understanding of the basic themes of geometry like the no change law of an area in the representation. The researcher also obtained that some difficulties and misconceptions in algebra were a result of teaching approach that emphasizes to a large extend procedural aspects and neglects a solid grounding in the underpinnings of visual representation. For some of these findings algebraic-analytic representation should be developed early in a mathematics course.

Based on the result of needs analysis, it can be stated that the purpose of the students to learn the visual represented problems varies, ranging from the range of educators. The 100% students said they wanted to master visual solution skills. Furthermore, visual competence (100%) states that it requires mastery of spatial ability material, representation connected to visual thinking (92.3%) and visual literary (92.3%).

In relation to the foundation of the development of visual ability materials, it states (100%) the need for exercises and learning support the elements and in accordance with the needs of the students, universities, and department. For visual literary, students (69%) claimed that need geometry competency and spatial ability (46%). The cultural effect of the students (69%) needs algebraic thinking and the procedural knowledge (46%).

For course materials, the students and lecturers alike to declare experiencing obstacles in classic mathematics contained in the course. The material needed should use visual problems, mainly the application that is easy to be understood by students and lecturers. It is aligned with the competence of visual problems which has been studied.

For visual thinking material, 76.9% of students stated that they need problems presented visually and 61.5% need geometry material, like ancient Greek. The students (69.2%) need visual construction material and 76.9% need geometry comprehension material and activity. For the form of the material used by the students, (53.8%) need of discourse visual representation, (84.6%) need activity material. It is concluded that the visual representation used in every course material.

For the teaching material and evaluation based on needs analysis, concluded that 70% need practical materials of visual problems, and the skills, as much as 16% desperately need visual literary materials and 14% desperately need cultural material. So the type of exercise used by 85% of students claimed to require classroom practice, and 65% of students claimed to need a variety of visual tasks. Regarding the exercise will be adapted to the contextual learning guide, and used to improve students' visual thinking.

In terms of technical drawing of most students feel the task of groups and individuals no difference of difficulty but should be done and studied in class. For the problems, the visual ability evaluation will be more emphasized by the representation of varies of geometry objects. For 65% of the students need a comprehensive evaluation, 80% need the algebraic, 60% need a combination of the algebraic and visual based thinking and 70% require varies between geometry and algebra. For 69% student test techniques requiring class activity, 61% require group and 65% varying between individuals and groups. For the time of the test, 46% of the students stated that to answer the problem is needed at the end of the lesson theme, 23% after the two courses (algebra and geometry), and 38% stated that the problem is needed when all courses are integrated.

Discussion

All of the answers, there is a visual ability problem - in understanding the intersection of the representation and the visual representation belief is incorrect. The students based on their work for algebraic equations, taking from the visual partially. They also used a value (predicted by perception) for the solution or final activity toward the problem. Most of the solutions (52%) can't be recognize because: (1) no relationship; (2) no exact drawing; (3) using more than one variable in single equation; (4) using formula but not in relation to the visual situation; and (5) do not need a complete visual that constructed on.

While students demonstrate with visual representation, the quality toward the solution cannot be the determinant regarding their mathematical understanding. Numerous dimensions of the representation in the mathematical learning suggest association with the visual. The association is far from being understood as causational. It means the visual representation cannot be interpreted as connoting mathematical understanding, independent of knowing more about the learner.

A reason from algebraic representation remains unanswered. It cannot yet be determined if the visual ability leads to mathematical performance or if the ability leads to increase the visual thinking. The parallels between the role of mathematical proficiency in the representation and the algebraic proficiency suggest that research into the similarities and differences between the two cognitive processes may yield important insights into both types.

While associations were made between levels of the geometry knowledge, geometry and algebra (symbol), types of connections in transformation, and visual representation is unclear if mathematical instruction should emphasize the levels of algebra in order to enhance visual thinking or focus on the representation to enhance student activity. Some studies of algebraic level have suggested that may represent a system of "symbolic grammar". It might be possible that the visual ability evolves into a hybrid representation. Geometry and trigonometry are more prone to visual ability than others topics. The students mimic the visual representation they see used by their educators. There is a different perspective with interests in visual perception and thinking. The overall result the visual thinking is evidence operate in the imagery. On the perception, the students demonstrated a more visual activity for directed attention in geometric ability.

This research is to specify how different aspects of the two types of thinking operate in detail, using evidence from the visual representations and the combination. The researcher emphasizes the variation of the representations by the problems, sometimes over trials on an available one, but in a limitation. The limitation is in constructing more visual representation in the problem. This limitation is also important in a number of varies representations, but also not much. That is no adding geometry figures, so the students met some difficulties to solve the problems. However, the methods will be required in order to answer questions about how the visual representation comes about on the constructions, as well as the suggestion that the visual thinking is designated for having priority for the solution. Despite the limitations of the methods, the researcher suggests provided insights for a multi representation of the visual. Attending to a visual representation creates a model of solution but vulnerable to interference when the visual is perceived. That is for an observation that the problem is typically the activity followed by the thinking.

The researcher attributes the visualization is as successive stimuli. The visual interference involves the progressive of geometric objects as an explanation for the solution. That is to reactivate the representations and involve the solution features. The experiment indicates the partition between algebra and geometry information. The results suggested that the visual thinking or ability increases the probability of solution having the encoded visual, not only accessible but vulnerable to perceptual interference from a representation.

The similarity to Treisman's concept regards the two representations as broadly equivalent, with emphasizing as a thinking process, and other with the memory representation created to a visual stimulus. The attention is a sub-region of its representational ability. An analogy to Cowan (2011) & Oberauer & Hein (2012), the abilities of thinking or working in the visual representations hold a chunk. In another respect, the theoretical description is different from both models that regard the memory as the activated region of long-term memory. The researcher notes that the visual memory as a combination of propositions represented as a function of representation level and account for the different types of thinking and implied by the representations.

The procedure of prioritizing visual representation conducted through instruction before presented differs from the retro-cue that provides information about the probabilities of the problems solved by the students. The difference is of evidence that appears to visual representation from the algebraic interference. The answer of the visual representation configures in different ways to respond. The retro-cue attention only begins after encoding - the re-thinking of visual representation coupled with form of solution.

We found evidence for a visual representation that serves the purpose of understanding the geometry concepts. There are: (1) to provide any other geometry object that revealed on the image of the perceptual solution; (2) to interference from the observable in visual thinking; (3) as a distractor for the problem solution; and (4) concerns whether the distractor would do to the image; (5) the visual distractor assumed to hold any manipulation in the representation; (6) the visual representation of the problem needs attention in geometry concepts that reflects on the knowledge for an integration of the two kinds of thinking and the re-representation to solve it; and (7) the visual materials would be needed to solve mathematics problems.

The findings from the study indicate that a significant portion of students struggle with utilizing visual representations effectively in mathematical problem-solving, often opting for familiar geometric representations despite challenges with more complex concepts. This highlights a gap in students' visual abilities and a preference for algebraic approaches over visual representations, limiting the full potential of conceptual understanding (Hegarty & Kozhevnikov, 1999). Moreover, Hawes & Ansari (2020) aimed to provide a mechanistic account of spatial-numerical relations to enhance mathematics learning and curriculum design. Understanding the underlying mechanisms of spatial and mathematical skills can inform the development of interventions to bridge the gap in students' visual abilities and improve mathematical understanding.

CONCLUSIONS

The results indicate that students often struggle to effectively utilize visual representations, favoring algebraic approaches that do not fully exploit the potential of conceptual representation. These findings underscore the importance of developing teaching strategies that enrich students' visual capabilities, as an integral part of mathematics education.

This emphasizes the need for a deeper integration of visual education within the mathematics curriculum to enhance students' understanding of mathematical concepts through conceptual representation. It indicates that educators should place greater emphasis on teaching that utilizes visual representations and develop effective strategies for interpreting these representations. Therefore, future research is crucial for designing, implementing, and evaluating innovative teaching strategies specifically aimed at strengthening students' visual abilities in mathematics education.

AUTHOR CONTRIBUTIONS STATEMENT

In this study, MR was responsible for conceptualization and methodology, S handled data collection and formal analysis, and KI focused on data analysis and drafting the initial manuscript as well as revisions.

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