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PAPER

Spatial Strategies Employed by Blind and Low-Vision (BLV) Individuals on the Tactile Mental Cutting Test (TMCT)

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ABSTRACT

Spatial ability is a well-known predictor of success in science, technology, engineering, and mathematics (STEM) fields. The purpose of this study was to investigate and understand the spatial strategies that were used by blind and low-vision (BLV) individuals as they solved problems on the tactile mental cutting test (TMCT), an instrument that was designed to measure the spatial ability of BLV audiences. The TMCT is an accessible adaptation of the older, 1938 version of the mental cutting test (MCT) that has been used extensively in spatial ability research. Additionally, this paper seeks to compare these strategies with existing strategies that have been investigated with sighted populations. The BLV community is underrepresented in engineering and in spatial ability research. By understanding how BLV students understand and solve spatial problems and concepts, educators can develop and enhance educational content that is relevant to this population. By incorporating perspectives from the BLV community and making STEM curricula accessible to this population, more BLV individuals may be encouraged to pursue STEM or engineering career pathways.

KEYWORDS

spatial ability, spatial strategies, spatial cognition, blind and low-vision populations

1 INTRODUCTION

Spatial ability was defined by Lohman [1] as "the ability to generate, retain, retrieve, and transform well-structured visual images." Spatial skills aid in navigation, perception, and mental manipulation of objects or areas [2]. Constructs of spatial ability that are commonly studied are spatial visualization, mental rotation, and spatial perception [3]. Spatial reasoning skills are important for success in various science, technology, engineering, and mathematics (STEM) fields, such as chemistry, geology, and engineering [4], and can be expanded to enhance other coursework

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outside of STEM education [5] to help address the growing lack of creative-thinking skills in undergraduate education [6].

There are different types of spatial strategies that people use when solving problems or evaluating information. The choice of spatial strategy has been shown to affect scores on spatial ability tests [7], [8]. In a study, Lin [7] identified that participants used two types of spatial strategies when solving problems on spatial tests: holistic strategies and analytical strategies. Holistic strategies involve mentally moving oneself around an object or moving an object around oneself [7]. Analytic strategies involve identifying and using particular features of an object to solve a problem [8]. Lin [7] found that participants who used holistic strategies scored higher on a mental rotation test than those who used analytical strategies.

In addition, work by Uttal et al. [9] suggests that there are four different dimensions among which spatial skills can be categorized: intrinsic or extrinsic, and static or dynamic. Intrinsic information refers to identifying relationships between parts of an object and being able to identify an object based on its parts. Extrinsic information is the relationship or relative position between objects. Static information refers to objects that are stationary, while dynamic information characterizes objects that are in motion or able to be moved. The four types of spatial skills that are characterized by these dimensions are intrinsic-static, intrinsic-dynamic, extrinsic-static, and extrinsic-dynamic. Uttal et al. [9] give an example application of each of these four strategies. For example, an intrinsic-static strategy could involve being able to recognize an object, while an intrinsic-dynamic strategy would involve being able to mentally rotate the object. An extrinsic-static skill would include being able to identify the relative position between two locations on a map, while an extrinsic-dynamic skill would involve being able to identify how the relative positions of the two objects would change as the observer moved to different locations themselves. The three categories of spatial ability defined by Linn and Petersen [3]—spatial visualization, mental rotation, and spatial perception—also make use of these four types of spatial skills. Spatial visualization requires the use of both intrinsic-static and intrinsic-dynamic skills; the mental rotation construct of spatial ability involves intrinsic-dynamic skills; and spatial perception abilities involve extrinsic-static skills.

Stieff et al. [10] also investigated the types of spatial strategies used by chemistry students in an organic chemistry course. The authors identified four types of strategies, including spatial-imagistic, spatial-diagrammatic, spatial-analytic, and algorithmic. Spatial-imagistic strategies involved students developing a mental image of a structure and drawing conclusions based on the mental image. Spatial-diagrammatic strategies were used when students drew diagrams to help them understand and solve a problem. Spatial-analytic strategies were used as a heuristic approach to evaluate spatial information. Algorithmic strategies included using equations and non–spatially-related heuristics to solve a problem. Stieff et al.'s study [10] found that at the beginning of the chemistry course, students primarily used spatial-imagistic strategies, and that their strategy choice changed over time. By the end of the course, students relied more on strategies that used heuristics, particularly students who had lower spatial ability. In another study involving chemistry students, Dwiningsih et al. [11] found that the use of interactive multimedia to showcase molecular structures significantly increased students' spatial ability.

In her work, Hegarty [12] describes several types of strategies that were used by students on spatial ability tests. These strategies included mental imagery, spatial analytic, pure analytic, and test-taking strategies. She also argues how one component of spatial intelligence is the ability to flexibly choose between different spatial strategies to solve problems. She defines spatial visualization as the construction of mental images for objects shown on a test that require an "analog imagery transformation processes to mentally simulate these processes and reveal the answers" (p. 271). Hegarty [12] explains that recent research in her laboratory also suggests augmentation of analog imagery processes by more analytic thinking processes, such as task decomposition and rule-based reasoning, both of which are strategies she categorizes for complex spatial tasks. Her definition of *flexible strategy* comprises the use of both analytic forms and analog forms in the formation and of a mental model and selection of an answer. Analytical thinking was also fostered in a study by Levin and Verner [13] that required students to design and 3D-print mechanical items with geometric constraints, which requires the use of spatial ability. Amin et al. [14] also found that implementing problem-based learning in a geography class significantly increased students' spatial ability.

While the majority of research exploring spatial ability and spatial strategies has been conducted using instruments or measures that require the use of sight, spatial ability has been shown to be a cognitive process that does not require vision [3]. Therefore, people who access information nonvisually, such as individuals in the blind and low-vision (BLV) community, also make use of spatial reasoning skills. Spatial ability is important for BLV individuals as they navigate different environments, interpret the world around them, and for orientation and mobility [15]. Addressing the need for spatial ability in BLV populations fosters inclusivity and diversity in STEM education [16], [17]. Additionally, spatial ability has been correlated with success in STEM knowledge development and STEM professions [18]. STEM is an area of education that has low representation for BLV individuals [19]–[22]. Despite its importance in STEM and for BLV populations, little research has been conducted about the spatial ability of BLV individuals and the types of spatial strategies that are used by people in the BLV community as they solve spatially focused problems. This study builds off of the conceptualizations of spatial ability and types of spatial strategies that have been identified in the literature and discussed in this paper [7], [9], [10], [12] by contributing perspectives about the types of spatial strategies that are used in the BLV community.

1.1 Measuring spatial ability in BLV populations

There are several instruments that are commonly used in the research community to measure spatial ability, including the Mental Cutting Test (MCT) [23], the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R) [24], and the Mental Rotation Test (MRT) [25]. Each of these tests measures different underlying constructs of spatial ability, such as mental rotation, spatial visualization, and spatial relations.

This study employed the tactile mental cutting test (TMCT) [22], [26], a test that was adapted from the MCT to be able to be used with people who access information nonvisually, such as those in the BLV community. A full description of the development of the TMCT is presented in a paper by Ashby and colleagues [26] and Goodridge and colleagues [22]. The original MCT was developed as a college entrance examination in 1938 [23]. The test is limited to 20 minutes and consists of 25 items, each with five possible answer choices. For the TMCT, the items on the MCT were developed tactilely as 3D-printed shapes with a plastic card passing through them, representing a cutting plane. Figure 1 presents an example problem from the TMCT and the problem from the MCT from which it was based upon.

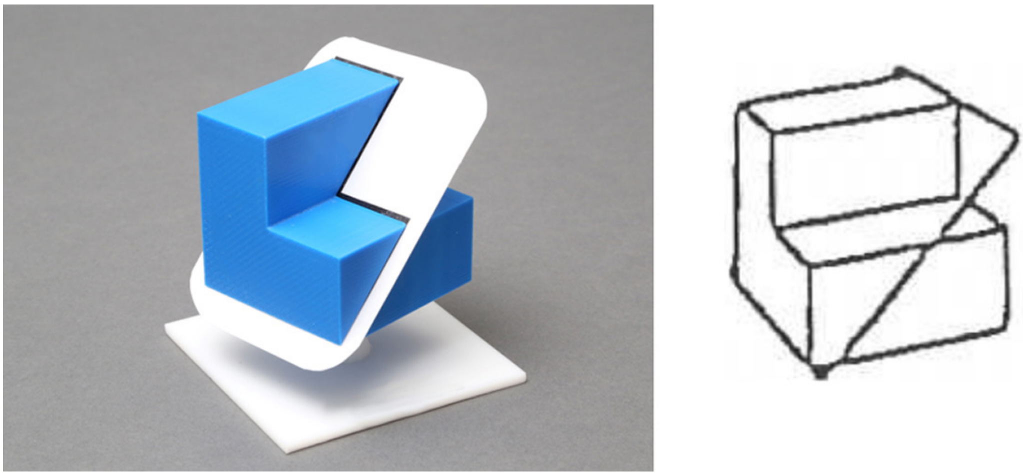

Fig. 1. Sample problem from the tactile mental cutting test (TMCT) and the problem that it was based upon from the original Mental Cutting Test (MCT)

The TMCT is comprised of two subtests: subtest A and subtest B. Each of these subtests is comprised of 12 different questions that were all adapted from the original MCT. While taking the TMCT, participants are provided with a binder containing the five answer choices for each question. Answer choices are presented either as outlines of shapes in Braille or in large print, depending on the test taker's preference or level of sight. In both formats, the answer choices represent potential cross-sections of the 3D objects where the cutting plane intersects them. Linework in the answers represents the edges of the object where the cutting plane contacts it.

The purpose of this study was to identify the types of strategies that BLV participants used as they solved problems on the TMCT. By understanding how BLV individuals conceptualize spatial problems, the research community can learn more about how people from the BLV community use spatial thinking. In addition, this study provides insights into a novel method for measuring the spatial ability of BLV individuals, a population that has traditionally been underrepresented in spatial-thinking research and in engineering fields more broadly.

2 METHODS

2.1 Participants

There were a total of 173 participants in this study. Data was collected at two different centers for blind individuals, both located in the western United States, and at a summer program administered by the National Federation of the Blind (NFB). The summer program was developed to expose BLV high school students to engineering concepts and encourage them to develop spatial skills through different program activities and workshops. Engineering concepts included force flow in a structure, truss analysis, vectors, and tactile drafting including section and multiview drawings.

Prior to conducting the research activities, an Institutional Review Board (IRB) protocol was developed by the research team at their university. Individuals were recruited at the centers for blind through the collection of signed consent forms in person. Participants were recruited from the NFB summer program through administering consent forms during the program registration online. For participants who were under 18 years of age, individual assent from parents and participants was obtained in the informed-consent letter delivered online for summer programs and in person at centers for the blind.

2.2 Data collection

This study used the TMCT to measure BLV participants' spatial ability [26]. Participants completed either the original 25-question version of the TMCT, an even and odd number split of the test items, or one of the two subtests (i.e., subtest A and subtest B), depending on the time of their participation (see Ashby et al. [26] for more detailed descriptions on the evolution of the different versions of the TMCT). A total of 25 participants took the original 25-question version of the TMCT, 7 participants took the even/odd-item split version, 64 participants completed subtest A, and 62 participants completed subtest B. After completing the TMCT, participants were asked to partake in a semi-structured interview and think-aloud session. During this session, participants were asked to think out loud about their thought process as they solved a TMCT problem from the subtest that they had not completed. The interview/think-aloud sessions were video and audio recorded to be able to observe the participants as they solved the tactile problems and later transcribe the audio recording. The research team asked follow-up questions during the think-aloud session, such as "Did you use any strategies to eliminate any possible answers as you solved this problem?" and "Did you focus on specific details of this problem, or did you look at this problem more as a whole?"

2.3 Data analysis

The data for this study was analyzed using qualitative coding procedures [27]. Transcripts from the think-aloud sessions were analyzed by two members of the research team using MAXQDA, a qualitative data-analysis software [28]. The team members initially used first-cycle coding methods to generate preliminary descriptions of the strategies that the participants used [27]. The two research team members then held meetings to discuss the applications of these codes and to refine their definitions. These meetings were held as often as necessary until an intercoder agreement of 90% was reached. Next, the team members used second-cycle coding methods (i.e., axial coding) to identify broader categories to represent constructs underlying the initial codes [27].

3 RESULTS

3.1 Three categories of spatial strategies

The initial codes generated during the first cycle of coding consisted of different types of specific strategies that the BLV participants used as they solved problems on the TMCT. Several of these strategies included *identifying basic shapes*, *analyzing each line sequentially*, *using comparative terms*, *counting features*, and *feeling the shape and answer simultaneously*. A complete list of the strategies found during the initial coding process is presented in Table A1 in the Appendix.

During the second cycle of coding, the researchers developed a set of axial codes that represented the broader constructs that related the different initial codes. These constructs represented the categories of strategies that were used by the BLV participants as they solved the TMCT problems. These three categories included using *analytical strategies, holistic strategies,* and *mixed strategies*. The following sections describe each of these three strategies along with specific instances in which they were used by the participants.

Analytical Strategies. The first category of spatial strategies that was used by the BLV participants was *analytical strategies*. These strategies included using the *process of elimination*, *counting features*, *identifying basic shapes*, *feeling the object and the answer choices simultaneously*, and *using comparative terminology*. Analytical strategies were evident when participants considered individual features of the objects rather than mentally manipulating the object as a whole [3]. For example, one participant said during their think-aloud session,

> "This first one does have two flat sides, it does have a little part that goes down and then over, but this one doesn't have a pointy part, so it's not this one. It's also not this one for similar reasons. Could be this one? Let me see, so there's two flat sides, then this flat side goes down, but this one doesn't go over, so it's not this one. I think it's this one because it feels kind of like the outline of this one."

This participant was using the *process of elimination* in order to narrow down the potential correct answer choices. They compared each answer choice to the object in their hand by sequentially analyzing different features, such as the orientation of a side or the location of a point, and determining whether the answer choice reflected the object. Another participant *counted features* and compared the number of a certain feature on the object to the number of that feature on the answer choices:

> "I guess comparing both the sides and counting, seeing how many sides there are and then count on here how many there are and then, like, I have one hand on the model and one hand on the paper and trace it to see where the differences are, if there are any."

This process allowed the participant to also use the *process of elimination* when evaluating the different answer choices. They were able to count the number of sides on the object and eliminate answers that did not have the same number of sides. This example also introduces a unique tactic to tactile interpretation, where both hands are used simultaneously, one tracing solution linework while the other traces sides, so that quick comparisons can be made. In another instance, as they were solving a TMCT problem, one participant described different geometric features of the potential answer choices as they were making their selection:

> "Well, there's just a triangle on the left side. A and E pretty much just looked exactly like each other, so I just picked E. Because they both have the triangle on the left and they have the same shape on the other side."

This participant *identified basic shapes* as they evaluated the objects and each of the five answer choices and sought out those shapes when evaluating the correctness of an answer.

Holistic Strategies. Next, participants used *holistic strategies* when solving problems on the TMCT. These types of strategies required participants to mentally manipulate the objects in some way, such as through mental rotation or visualization.

Specific holistic strategies identified in this study included *creating a mental image of the model*, *analyzing the basic shape before details*, and *considering the object as a whole.* One participant described their holistic strategy:

> "Keeping that image in mind I say okay, so we have all the specific details: the pointed edges, the square edges, this triangle shape here. And then turning this 3D image into a 2D view. Like, what would this look like if we just flatten it down, and then using that to gauge my answer."

This participant described how they *created a mental image* of the 3D object they were holding and imagining how it would look represented in two dimensions on their answer sheet. Another participant described how it was important to look at each problem from all angles so that they could develop a mental model that accounted for all of the details within the problem:

> "What I think about these problems is that you have to search in every angle, because if you look at it straight, if you look at it from an angle especially, for example, if you look at it from a downside angle, you're not going to see that top triangle; you will just see a square with just a dent on it. If you look at it from the top part, you may not see the other bottom part, the other bottom dent, and you will just see maybe, like, a rectangle with two triangles on each side, which one triangle is larger than the other. If you look at it from the side view, you will just get like a triangle, a double triangle, so you have to see all the angles, how they contribute to the cut."

Both these examples show how some participants employed a holistic approach to solving problems on the TMCT. They factored in different views of the problems and ensured that they had an overall sense of the shape of each object before focusing on the specific details that would differentiate among the five possible answer choices.

Mixed Strategies. Last, participants used *mixed strategies* that involved a combination of holistic and analytical techniques, such as *tracing the perimeter of the object*, *picking the most defining feature on the object*, *using reference points*, and *employing a sense of direction*. These types of strategies involved using analytical approaches, such as identifying a specific detail or number of a feature, in conjunction with a more holistic approach, such as referencing the direction in which a feature was facing compared to another feature.

For example, many participants indicated that they used *reference points* as a starting strategy to refer back to as they solved the problem. Participants said, "[I] started at one point," "I always start at one spot," or "the top seems to be a good place for me to start." Similarly, participants *picked a defining feature* from which they evaluated different answer choices. One participant described the defining feature they focused on: "Specifically this angular piece right here—on the right side for me, this piece is something that I focused on when looking at this one to ensure that the answer matched the original." Another participant described how they looked for certain shapes that would match the answer choices: "So, like, how there's two triangles that come out, and there's a straight edge; that's kind of what I pay attention to, and then I just come over and look at this."

Mixed strategies also involved both intrinsic/extrinsic and static/dynamic processes. For example, participants compared the *proportion* of different features on the 3D objects to those same features on the answer choices. When describing how they evaluated the different answer choices, one participant said,

> "Then I go to the next one (C), and there's, like, a valley in there, but it's not that one, because it's too long."

This solution process involves comparing the relative size and relationship between two "valley" features (extrinsic) without needing to mentally or physically rotate the object (static). This extrinsic-static example is also analytical in nature. The participant was directly comparing the size of one feature on the 3D object in their hands while assessing whether the feature on the answer sheet was the same size. In addition, intrinsic-dynamic approaches were also used as a mixed strategy. As they were solving a TMCT problem, one participant said,

> "if I have something on the paper that might resemble something on the object, I would spin the object around to see if that would possibly be the answer."

This participant described how they would feel a feature on the object (intrinsic) and would then rotate it (dynamic) to determine whether or not it resembled a particular answer choice from a different direction. This is also a holistic approach, where the participant was able to identify the overall shape of the 3D object and, in their mind, recognize that it needed to be rotated in order to match the orientation of the cross-section on the answer sheet.

4 DISCUSSION

The BLV participants in this study were found to use different types of spatial strategies to solve problems on the TMCT, each of which can be classified into three different strategy categories: analytical, holistic, and mixed. These three strategy categories are similar to the types of spatial strategies that have been identified previously by other researchers in the area of spatial ability. Table 1 presents an overview of different spatial strategies that have been discussed in the literature and how these strategies map onto the three strategy categories that were identified in the present work. In addition, the following sections describe each of these three strategy categories based on our results with BLV participants, as well as how the strategies identified by other authors in the literature relate to our findings.

Table 1. Spatial strategies that have been identified by various authors in the spatial ability research literature and how they fit into the spatial strategy categories that were identified in the present study with BLV participants

Type of Strategy	Our Definition	Author(s)			
		Hegarty (2010)	Stieff et al. (2012)	Uttal et al. (2013)	Lin (2016)
Analytical	Strategies that are algorithmic in nature; often do not use spatial information to solve the problem	Pure analytic Spatial analytic	Spatial-analytic Algorithmic	–	Analytic
Holistic	Strategies that account for the entire object; often require the use of mental rotation and visualization abilities	Mental imagery	Spatial-imagistic	–	Holistic
Mixed	Strategies that employ the use of both analytical and holistic approaches	Flexible strategy choice	Spatial-diagrammatic	Intrinsic-static Intrinsic-dynamic Extrinsic-static Extrinsic-dynamic	–

4.1 Analytical strategies

Similar to the discussions in the studies by Hegarty [12], Stieff et al. [10], and Lin [7], BLV participants in this study used *analytical strategies* as they solved problems on the TMCT. These strategies were often used as a way for participants to methodically consider the individual parts of an object rather than the object as a whole. This type of strategy is also similar to the algorithmic strategy described by Stieff et al. [10] and the intrinsic-static strategy type described by Uttal et al. [9]. In the present study, participants often counted the number of instances of a feature on an object, such as the number of sides (e.g., "So, what I first do is, I look at the shape on the block and determine how many sides it has"), and compared that number to the number of that feature on the answer choices. The analytical strategies identified in the present study were algorithmic and intrinsic in nature because they involved the analysis of non-spatial constructs and relied on individual physical characteristics of the objects (e.g., "I had to … see line by line, like, if they fit. Like, everything. Like, compare each line.") These strategies also primarily involved static processes because they required little to no application of mental-rotation skills.

Hegarty [12] discusses pure analytic and spatial analytic strategies in her paper. Pure analytic strategies involved participants counting certain features and matching those numbers to the number of that feature on the answer choices. Spatial analytic strategies were when participants used analytical reasoning about the spatial features of objects on spatial ability tests, such as determining the direction a feature of an object was facing and comparing the direction to the directions of the feature on the answer choices.

The present study demonstrated how BLV participants used analytical strategies as they solved the TMCT problems. The most commonly used analytical strategy was *identifying basic shapes* (e.g., "this is a square, this is a circle, this is a triangle.") as shown in Table A1 in the Appendix. This finding suggests the importance that knowledge of geometry has for BLV individuals. They frequently looked for familiar geometric shapes, both to understand the structure of the 3D objects and also to serve as reference points when looking for answer choices.

4.2 Holistic strategies

Participants in this study also used *holistic strategies* that are similar to the types of holistic strategies mentioned by other authors in the literature, such as *creating a mental model* of the object and *considering the object as a whole*. These strategies are similar to the spatial-imagistic strategy described by Stieff et al. [10] and the mental imagery strategies described by Hegarty [12]. For example, BLV students in the present study described how they would *create a mental model* of the TMCT problems in their mind as they solved them. They would also have to mentally rotate their mental models of the 3D objects in order to match their mental visualization to the answer choices on paper, depending on the orientation they had analyzed the object from.

In the study by Stieff et al. [10], the spatial-imagistic strategy involved chemistry students mentally rotating 3D molecules or imagining themselves rotating around a 3D molecule. Similarly, Hegarty's mental imagery strategy involved participants imagining the rotation of a 3D object or folding/unfolding paper on a paper folding test [12]. BLV participants used a holistic strategy similar to the aforementioned strategies in which they *looked at both sides of the cut* on the 3D objects (e.g., "Depending on where the cut was, I would maybe flip it over and do the other side the same way.") They would hold the object and analyze the cut section from one perspective before rotating it around and viewing the object from the other side.

Lin [7] recommended that students should be trained to use holistic strategies to help them better develop mental models and 3D visualizations in order to more effectively solve spatially related problems. This recommendation may carry over to BLV populations as well. By teaching BLV students how to use holistic strategies when thinking spatially, their ability to interpret spatial information by developing mental models might be improved. In addition, their mental rotation abilities might be strengthened. For BLV populations, tactile interpretation is essential to forming a mental model. Providing BLV students with more opportunities to learn spatial concepts in STEM fields tactilely could help them make meaning of abstract concepts that are typically designed for sighted populations, such as reading and interpreting cross-sections of parts on engineering drawings.

4.3 Mixed strategies

Research exploring the problem-solving strategies of science experts reveals that there are potential interactions between how experts approach problems using holistic strategies, analytical strategies, and external representations of information, such as images or diagrams [29]. In the present study, BLV participants were found to use problem-solving strategies that employed elements of both holistic and analytical approaches and incorporated intrinsic/extrinsic and static/dynamic processes. This combination of strategies is what is termed *mixed strategies* in this paper. As shown in Table 1, Uttal et al.'s [9] intrinsic/extrinsic and static/dynamic skills were classified as a mixed strategy type. This was done because these skills involved both analytical techniques, such as being able to identify the distinctive features that characterize an object, and holistic approaches, such as being able to mentally rotate an object in space.

In addition, Stieff et al.'s [10] spatial-diagrammatic strategies were also classified as a mixed strategy in this paper (Table 1). Spatial-diagrammatic strategies involved participants drawing diagrams to help visualize certain aspects of a problem. Similar to how BLV participants were observed to be using both analytical and holistic strategies, Stieff [29] found that participants used a combination of both holistic mental reasoning, and algorithmic analytical strategies to solve complex problems. Indeed, BLV participants used both individual holistic and analytical strategies in addition to mixed strategies that made use of the techniques of both approaches.

Last, the flexible strategies mentioned by Hegarty [12] were also classified as mixed strategies in this work and have similarities to the types of strategies that the BLV participants used. Flexible strategies were when participants used both analytic and holistic approaches, such as using both mental rotation and counting when solving problems. BLV participants in the present study also employed this type of strategy when they used their *sense of direction*. Participants identified a feature of an object and used their mental-visualization skills to determine which direction it was facing relative to them (e.g., point left or right). They then used their analytical abilities to check the direction that this feature was facing on each of the answer choices and eliminate answers that did not have the feature in the same direction (e.g., "… except it's facing the wrong way, because the 90-degree angle is on the bottom right side instead of the bottom left, like in the figure.").

Hegarty [12] also noted that using a mix of strategies may encourage better performance on spatial ability tests; while mental imagery strategies (i.e., a type of holistic strategy as identified in this paper) were the dominant strategy used by participants on a paper-folding test, these strategies were also used in conjunction with analytic approaches, at least one of which was correlated with performance on the test [12]. This finding is consistent with a previous analysis conducted by the authors of the present study exploring the strategies used by high- and low-performing BLV participants on the TMCT, which found that high performers were more likely to used mixed strategies compared with analytical strategies alone [30].

These findings suggest the importance that teaching multiple types of strategies has for BLV populations. When equipped with knowledge about different approaches to take when solving problems, BLV participants can make educated choices about the types of strategies they would want to employ when solving certain problems.

5 LIMITATIONS

One limitation of this work is the lack of demographic information that was collected during the recruitment and administration of the TMCT. Participants were not required to specify their identified gender, age, or any other demographic information. Prior studies that used this data sought to establish reliability and validity information about the TMCT and therefore did not collect demographic data about the participants. Future work should seek to include a demographic survey as part of participation in taking the TMCT to have a better understanding of the participants and their scores.

6 CONCLUSIONS

The BLV participants in this study used different types of strategies to solve problems on the TMCT. They used analytical strategies to identify and conceptualize different parts of the objects; holistic strategies were used to conceptualize problems as a whole and develop mental representations; and mixed strategies were used as a combination of holistic and analytical approaches. Findings from this study provide insights for educators looking to develop instruments or interventions for BLV participants designed to target their spatial ability skills. As more is learned about how people in the BLV community interpret and evaluate content related to spatial ability, interventions that can train spatial ability in these populations can be developed more effectively and with greater relevance.

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9 APPENDIX

Table A1. Types of spatial strategies within the three identified categories—analytical, holistic, and mixed—that were used by BLV participants as they solved problems on the TMCT. Strategies are presented in descending order, starting from the most commonly used strategy in each category

Code Name	Number of Coded Instances	Description
Analytical strategies		
Identifies basic shapes	96	Participant identifies rectangles, circles, triangles, trapezoids, etc., either on the face of the object or the 2D cross-sectional shape.
Process of elimination	47	Participant methodically eliminates answer choices based on their determined criteria.
Detail focused	37	Participant focuses on small distinct differences in shape.
Analyzes each line sequentially	25	Participant breaks down shapes into a series of lines and analyzes them one by one.
Comparative terms	23	Participant describes the object in terms of something else (a house, a tower, a butterfly, etc.)
Looks at object as a whole	20	Participant feels entire object rather than just area next to cut.
Counting features	17	Participant counts angles, line, planes, etc., to identify shape or to analytically compare with answer choices.
Measures distances	15	Participant measures with an object (finger, etc.) or estimates distances between features.
Educated guess	11	Participant makes an assumption. Could be due to inability to logically reason any further—or just out of laziness.
Finger size	5	Participant mentions the size of their finger in relation to feeling details of the object.
Holistic strategies		
How shapes fit together	75	Participant describes features in relationship to one another and the interactions between various geometric shapes.
Creates mental image of model	28	Participant reports storing information in short-term memory.
Looks at object as a whole	20	Participant feels entire object rather than just area next to cut.
Analyzes basic shape before details	19	Participant obtains a general idea of the object's cross-sectional shape to compare with answer choices before feeling specific details. Often they narrow the options down to two or three possibilities and then look at details.
Looks at both sides of cut	17	Participant feels both sides of the cut in the object.
Ignores material away from cut	14	Participant feels only the part of the object around the cut and tries not to be distracted by the rest of it.
3D features get in way of 2D shape	7	Participants have difficulty feeling the shape's perimeter due to features protruding in front of or behind the cross-sectional cut.
Transforms 2D outline on paper to 3D	1	Participants imagining the shape on paper into a 3D object.

(Continued)

Table A1. Types of spatial strategies within the three identified categories—analytical, holistic, and mixed—that were used by BLV participants as they solved problems on the TMCT. Strategies are presented in descending order, starting from the most commonly used strategy in each category *(Continued)*

Code Name	Number of Coded Instances	Description
Mixed strategies		
Sense of direction	66	Participant makes mention of directions of features in relation to one another, e.g., to the left of, above, near, touching, etc.
Picking most defining feature	46	Participant chooses one certain feature to compare with answer sheet—could be used just as a starting point before looking at more details.
Angles	37	Participant specifically reports the angle between two features.
Reference points	31	Participant picks a certain point to start at or refer to as other answer choices are evaluated.
Traces perimeter	31	Participant traces perimeter of cut section.
Feels shape and answer simultaneously	30	Participant uses one had to trace the object while the other hand traces the answer choices.
Proportion	25	Participant uses language to compare sizes of features.
Comparative terms	23	Participant describes a shape using a common object. For example, shaped like a boot, L-shaped, like butterfly wings, etc.
Symmetry	20	Participant describes shapes as inverted, reflected, backwards, etc.
Curved edge	8	Participant reports a curved edge.
Intrinsic-dynamic skills	7	Participant identifies and differentiates between objects by translation and rotation.
Bisection, intersection	4	Participant mentions areas of bisection or intersection of features.

10 AUTHORS

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