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A Qualitative Study of Spatial Strategies in Blind and Low Vision Individuals

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Introduction

Spatial ability is a cognitive intelligence related to the capacity to generate, retain, retrieve, and transform well-structured visual images [1]. The number of various constructs of spatial ability has not been agreed upon, nor has a complete list been assembled of the factors that contribute to overall spatial ability [2]. Some commonly studied constructs of spatial ability include mental rotation, spatial orientation, and spatial visualization [3]. Due to the complexity of many spatial tasks requiring the use of multiple components of spatial thinking, many different strategies can be utilized depending on the specific situation. This paper focuses on the constructs of mental rotation and cross-sectional visualization. In the context of this work, spatial ability is referred to as the quantification of performance upon an instrument assessing a specific construct of spatial thinking. Herein, that instrument will be the Tactile Mental Cutting Test.

Significant work has been done in the field of spatial ability to show that spatial thinking has a positive effect on student success in a variety of academic settings and is especially beneficial to students in science, technology, engineering, and mathematics (STEM) fields [4]-[5]. One study in the field of engineering has shown that participation in a rigorous engineering course led to a significant increase in spatial ability [6]. One of the long-lasting benefits of enhancing spatial ability, as a student, is the positive correlation it is seen to have on success as a professional in STEM fields. Research has shown that a majority of students who demonstrated high levels of spatial thinking in high school and college went on to lead successful careers in various STEM disciplines [7]. Furthermore, studies have identified spatial skills as malleable and able to be taught to students through targeted interventions [8]-[9]. Substantial evidence exists to argue the efficacy of implementing more spatial oriented curriculum in secondary and higher education [10]. As spatial interventions are developed, it is imperative that curriculum designers understand how students interact with spatial material.

Considerable research has been conducted to inform academia of strategies students employ in solving problems. Distinctly important to STEM curriculum is how students use various strategies to solve spatial problems. Multiple studies have shown that students' specific strategies involving spatial tasks vary from individual to individual and most often vary within each student as well [11]-[12]. Multiple strategies are often utilized by an individual student to ensure accuracy if initial attempts yield excessive uncertainty [13]. In addition, there are a number of factors that are associated with high spatial performance. One factor that has shown significant correlation to solving spatial tasks is the ability to adopt various strategies to the specific task at hand [13]-[14]. Further studies have shown that in most cases, students use more visual and holistic methods to solve easier spatial tasks. As tasks become more difficult, they are seen to use increasingly more analytic strategies [15]-[16]. Use of holistic strategies has also been correlated in another study with spatial problems that can be solved quickly, and analytic strategies with slower, more complicated problems [16]. High spatial performance has been correlated more frequently with the use of holistic processing methods compared to analytical methods used alone [17]-[19]. However, it is noted that holistic and analytic strategies should be viewed as poles on a continuum of strategies allowing plenty of room for crossover rather than just existing as distinct methods [14].

Despite what is known about the types of spatial strategies employed by students and the importance that spatial ability has for individuals in STEM fields, very little work has been done to explore how blind or low vision (BLV) individuals interact with spatial problems or the types of spatial strategies they use to solve spatial problems. Although spatial ability is often defined in terms of visualization, it is fundamentally a cognitive intelligence that does not require vision [20]. There are other mechanisms that can help it develop.

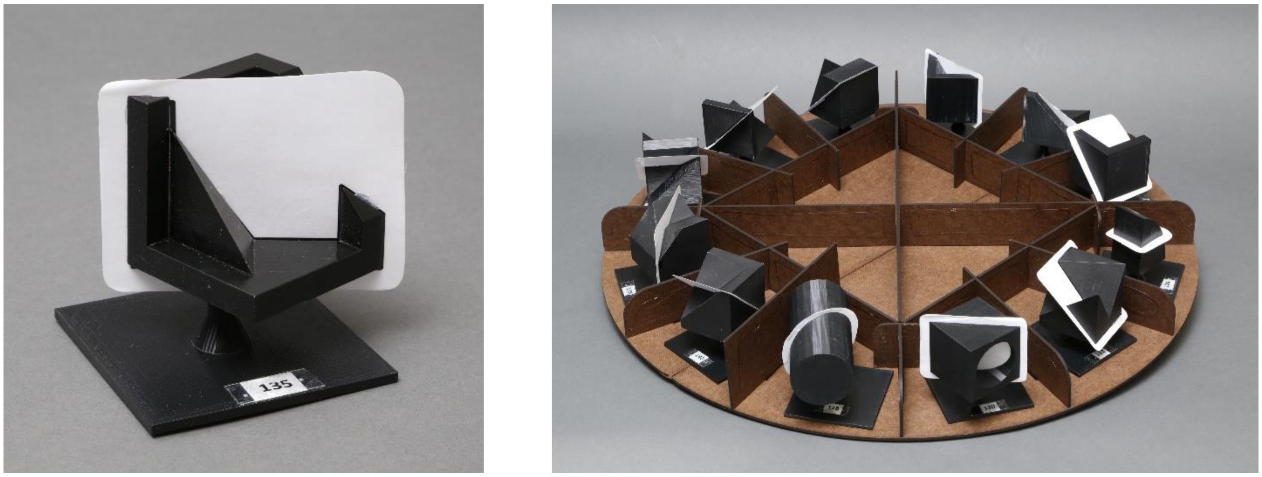
There is great potential to attract a larger number of BLV students to STEM fields if educators are able to encourage spatial development in BLV populations [21]. A significant opportunity exists, therefore, to develop accessible spatial ability learning experiences that cater to the needs and abilities of BLV students. One of the key components of developing such interventions is understanding how BLV students interact with spatial tasks and the strategies they use to solve spatial problems successfully. This paper explores the spatial strategies that were most effective for four BLV students engaged in solving a tactile spatial task which is found on a recently developed Tactile spatial ability instrument [22]-[23]. Findings from this study can be used to inform the development of improved spatial interventions for BLV individuals.

Data Collection Methods

In order to more accurately measure spatial thinking in BLV populations, the Tactile Mental Cutting Test (TMCT) was developed as a fully accessible adaptation of the Mental Cutting Test (MCT) [24], an instrument that is commonly used by researchers in the field of spatial ability [25]-[26]. The TMCT requires subjects to tactilely interpret a small three-dimensional plastic object with a laminated paper plane running through the middle of it indicating an imaginary cutting plane that passes through the object. The objective for the test-taker is to determine the two-dimensional cross-sectional outline created at the interface of the paper plane with the edges of the plastic object. This outline represents a cut surface. Answer sheets are provided to the participants in a tactile graphic or large print format, based on that participant's reading medium, showing five possible shapes that could represent the correct cross-sectional shape. More information on the adaptation of the TMCT can be found in a previous publication [22]. For the purposes of this research, the test was split into two versions (subtest A and subtest B) of equal length and difficulty. Each version of the test consists of 12 questions. Construct validity of the TMCT is inherited from its roots in the MCT, and is manifest in evidence presented in a previous publication [27]. The TMCT has also demonstrated significant reliability based on preliminary pilot testing detailed in an additional publication [23]. Figure 1 includes photographs of several problems on the TMCT for reference.

Figure 1: Photographs of selected problems from the TMCT, including (a) one of the two TMCT problems that was used during think-aloud interview sessions with participants and (b) the entire set of TMCT problems included on the subtest B version of the test.

(a) (b)



In the present study, the TMCT was administered to students participating in a summer program designed specifically for BLV youth interested in STEM subjects. Throughout the week-long program, students engaged in hands-on engineering activities designed to encourage spatial development. Upon arrival at the beginning of the week, participants were asked to take one version (subtest A or B) of the TMCT. At the end of the week, students were given the version of the TMCT that had not been previously administered to them. Immediately following their first test, students were asked to participate in a think-aloud interview process to describe the strategies they employed while solving problems from the TMCT. Interviews were conducted individually with each participant and video or audio recorded for further analysis. In each interview, the participant was given a preselected TMCT problem (e.g., Figure 1a) to solve while verbally explaining the cognitive processes they were employing. Interviewers followed a standard protocol which asked specific questions to prompt open discussion related to the student's spatial strategies. In certain cases, the interviewer asked follow up questions or more specific questions to encourage discussion. The live "think-aloud" protocol was utilized in order to maximize reported information with the most possible detail [28]. All participants were also interviewed at the beginning of the week in order to identify initial spatial strategies, but only those with statistically high or low TMCT scores were chosen to be interviewed a second time at the end of the week to see if their initial strategies had evolved. TMCT scores were considered high if the participant correctly answered 9 or more of the 12 problems. Scores of 3 or lower were considered low scores.

Case Descriptions

This case study [29] is part of a larger research project aiming to measure the spatial ability and identify the spatial strategies used by BLV populations. Annually, thirty participants were recruited from all areas around the United States for this larger study. The study spanned 5 years but had interruption due to the Covid-19 pandemic. All participants were high school students ranging in academic grade level from 9th grade to 12th grade. This paper presents a case study of four of the 30 total participants from one year. These four participants were selected because they represented one of two cases: having a *high* spatial ability score or a *low* spatial ability score based on their score when taking the TMCT. Participants who achieved a TMCT score of 9 or higher were considered to have a high spatial ability score. Likewise, participants scoring 3 or lower were considered to have a low spatial ability score. Of these four participants, two exhibited high spatial ability and two exhibited low spatial ability. In the high spatial ability case, one participant identified as male and one participant identified as female. In the low spatial ability case, both participants identified as female. In addition, three of the participants identified as being fully blind and one participant identified as being visually impaired. Table 1 summarizes the information about these four participants.

Table 1: Summary of participants in this case study.

Participant ID	Grade level	Gender	Level of sight	TMCT score (out of 12)	High/low designation
207	10	Male	Blind	11	High
208	11	Female	Blind	3	Low
209	11	Female	Blind	3	Low
225	10	Female	Visually impaired	10	High

Data Analysis

Data sources for this study included transcripts from the think-aloud interview sessions with the participants and participants' numerical scores on the TMCT. Interview transcripts from the four participants in this case study were analyzed in MAXQDA [30] using first and second cycle coding methods [31] to identify codes and categories related to strategies the participants used to solve the TMCT problems. During the first cycle of coding, two members of the research team independently coded the think-aloud transcripts for strategies that were used by the participants as they completed the think aloud. The two team members then held meetings together to discuss the generated codes, their definitions, and to resolve discrepancies between their code applications. Codes and their applications were revised until an intercoder agreement of 90% was reached. During the second cycle of coding, the same two research team members independently analyzed the transcripts to group the first cycle codes into broader categories or themes that characterized the participants' strategies.

Quantitative data in this study consisted of frequency counts of the first and second cycle codes (strategies and strategy categories) and participants' scores on the TMCT. Frequency counts of codes were used to determine the most commonly used strategies and categories of strategies. Participants' scores on the TMCT were used to determine test score averages and to categorize participants as high or low performers. Frequency counts of codes and test scores were also compared to identify potential relationships between strategy usage, frequency of strategy usage, and resulting scores on the TMCT.

Findings

Results of first cycle coding were grouped into three main categories of codes: geometric strategies (e.g., identifying basic shapes), analytical strategies (e.g., using process of elimination), and mixed strategies (e.g., picking a reference point). The individual codes that comprise these main categories are presented in Table 3 in Appendix A. Of the four participants, those who were in the high-scoring case were the most likely to use geometric strategies while solving TMCT items. The participants in the low-scoring case were most likely to use analytical strategies a majority of the time. Table 2 shows the relationships between the three categories of strategies used by the four participants and the average TMCT score earned by these students as they used these strategies.

Table 2: Relationships between strategy categories with student performance on the TMCT.

Strategy	**Number of codes**	**Average TMCT score**
Geometric	28	70.5%
Mixed	22	61.8%
Analytic	23	59.3%

A review of the first cycle codes revealed that the two participants in the high-scoring case tended to utilize multiple strategies simultaneously, while the two participants in the low-scoring case typically only paid attention to certain aspects or details of the problem. For example, participant 207, a high TMCT scorer, focused primarily on features of the object that were directly adjacent to the cut through the middle of the object while also specifically paying attention to direction and spacing between features. Participant 208, who scored low on the TMCT, reported viewing the TMCT object more holistically, not necessarily paying attention to the details surrounding the cross-sectional shape. This participant also noted picking a certain reference point on the object to start at and then moving around the object while identifying simple geometric shapes which they then compared to the answer options. Participant 209, another low scorer, approached the problem somewhat similar to participant 208 in that she focused on simple geometric shapes, but rather than establishing a certain reference point to work around, she simply tried to remember which side of the object certain shapes were on. This participant also mentioned that she utilized her short-term memory by feeling the object and answer sheet separately. Participant 225, a high scorer, used a variety of methods, most of which fell under the geometric category of strategies. This participant's main strategy was to trace certain segments of the cross-sectional plane that appeared the most distinguishable and then search for the same shape on the answer recording sheet. In reporting how she identified a correct answer, she discussed symmetric properties and spatial relations between features. In addition, participant 225 used terms related to familiar objects such as "boot" and "butterfly wings" to describe various shapes.

Some of the most common codes that emerged after the first cycle of coding were: *identifying basic shapes, how shapes fit together*, *picking the most defining feature*, and *tracing perimeter*. The code *identifying basic shapes* was applied when the participant identified geometric shapes such as rectangles, circles, trapezoids, etc. The code was applied whether the participant was referring to shapes on the face of the TMCT object or on the 2D cross-sectional shape. For example, participant 209 described using simple shapes as a defining feature:

> "So basically, what I do is I just feel it and try to remember what shapes are on which side. 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."

Often used in conjunction with *identifying basic shapes*, the code *how shapes fit together* was applied when the participant described features in relation to one another and the interactions between various geometric shapes. For example, participant 225 described the possible resultant cross-sectional shapes associated with a previously encountered TMCT problem:

> "There was one that was like a square that had a circle in it and it was going sideways, I know that one of the answers was A... They were squares with the same oval in the middle, but even if it's going sideways or forward, it's probably not going to be an oval even though it was going through the square sideways."

Identifying shapes and their relations to one another was often executed as a means to establish reference points. The code *picking the most defining feature* was applied when the participant reported choosing a certain feature on the TMCT object to compare with the 2D shapes on the answer sheet. Participant 207 described picking a particular angle to compare with the answer choices:

> "I'll look back at a detail that seems odd in the problem. 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."

Participant 225 provided some insight on how she determined which of the apparent features to select as a comparison tool between the 3D object and the answers provided on the answer sheet:

> "I'll know that this isn't it because this is not a circle, it's a square. But typically, I look for something that has more definition like as to what the shape would be that could separate it from the other shapes."

Many of the participants paired picking a defining feature with tracing the perimeter of the cross section of the TMCT problem. The code *tracing perimeter* was applied when the participant demonstrated that they used their finger to tactilely interpret the interface of the paper plane with the plastic object starting at a certain point, and tracing all the way around the object. Participant 207 provided an example of how solely focusing on the perimeter of the cut section was valuable:

> “What I'm seeing here is I'm tracing the outline of the shape as before and I'm just getting the basic features. I don't want to get distracted by the three-dimensional shape because that's not important.”

Participants in the low-scoring case reported in their interviews that they did not have a specific strategy that they employed throughout the test. In contrast, the two participants in the high-scoring case both employed a wide variety of strategies, typically centered around geometric strategies, but augmented with analytical methods.

Discussion

Consistent with research of spatial strategies among sighted populations, findings from this study support the claim that analytical strategies, when used alone, tend to be less effective when solving spatial tasks [13]. Furthermore, this work also suggests that analytical strategies in BLV populations are best utilized in tandem with more spatially-oriented strategies. In light of the revealed relationship between high spatial ability and use of geometric strategies, these findings suggest that in the development of STEM curriculum for BLV youth, greater focus should be given to helping students develop geometric skills such as an understanding of symmetry, proportion, and how shapes of various dimensions interact with each other. This is a particularly important finding given geometry is customarily taught using visual, as opposed to tactile, figures thereby rendering most geometry instruction inaccessible to BLV youth. The inaccessible instructional approaches used to teach geometry necessitate substantial remediation (e.g., producing all figures in a tactile form) to ensure BLV youth have access to the learning opportunities afforded their sighted peers by default. Even when geometry courses are made nonvisually accessible and employ tactile figures, BLV youth often still do not get an equitable geometry learning experience because they are forced to learn geometry at the same time as they are learning how to read tactile pictures. Unlike sighted youth, BLV youth do not have the privilege of growing up in environments rich with imagery (e.g., photos, pictures, STEM figures) that is accessible to them; the majority of BLV youth grow up in environments almost completely devoid of tactile imagery. There aren’t tactile pictures on cereal boxes, in picture books at the library, in family photo albums, at science museums, or in the vast majority of classrooms. Consequently, BLV youth don’t get to learn to read images tactually until someone intentionally provides them with the opportunity to do so; it is common for geometry instruction to be one of the first times this occurs.

Similarly, of distinct interest to the development of spatially-oriented curriculum is how students utilize and choose between possible strategies. Similar to findings in sighted populations, findings from this study demonstrated that BLV students who had one or more distinct methods of solving each problem performed at a much higher level on the TMCT than their peers. Students who specifically stated that they did not have a strategy scored low on the TMCT. In consideration of BLV secondary education, students should be encouraged to think of and/or adopt specific strategies for solving spatially-related problems. In addition, BLV students should be mentored on the value of thinking critically about the nature of various spatial tasks and determining which of their learned strategies is best suited for the specific application.

In some cases, students engaged in the think-aloud process overcomplicated the problem-solving process to the point that they became confused about the overarching goal of the problem. This suggests that targeted spatial interventions should be developed with succinct and direct instructions that clearly communicate to the student what task is to be solved. This is consistent with findings from another study by the authors [32].

Conclusion

Results of this case study have demonstrated the value of BLV students using a clear strategy or multiple strategies as they solve spatially-related problems. An analysis of the student interviews and corresponding TMCT scores has shown that BLV students who utilize geometric methods of solving spatial problems tend to score higher on the TMCT, especially when their selected geometric strategies are augmented with analytic strategies. These findings can inform development of spatially-oriented curricula for BLV students in secondary and higher education. Results of this study are also a valuable step in more fully understanding the non-visual aspects of spatial ability which has the potential to impact not only BLV populations, but sighted populations as well.

Limitations

One limitation of this study is that some strategies, such as subconscious strategies, may have not been reported by participants. While it is likely that certain strategies were used without being verbalized, the interview protocol was designed to solicit what each participant's main strategies were. Utilizing the live think-aloud protocol enabled the research team to obtain the closest possible record of what strategies were being used. Results of this study should be viewed with caution due to the limited amount of data obtained.

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Appendix A

Table 3: Codebook containing code names, number of coded instances, and code descriptions for codes within the three main categories of strategies (i.e., geometric, mixed, and analytical) used by participants as they solved the TMCT.

Code name	Number of coded instances	Description
Geometric Strategies		
Identifies basic shapes	12	Identifies rectangles, circles, triangles, trapezoids, etc. Either on the face of the object or the 2D cross sectional shape.
How shapes fit together	9	When participant describes features in relationship to one another and the interactions between various geometric shapes.
Looks at both sides of cut	2	Feels both sides of cut.
Symmetry	3	Describing shapes as inverted, reflected, backwards, etc.
Proportion	2	Anything to do with comparing sizes of features.
Mixed Strategies		
Sense of direction	6	Whenever the 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	9	Picking one certain feature to compare with answer sheet – could be used just as a starting point before looking at more details.

Reference points	3	Picking a certain point to start at or refer to as other answer choices are evaluated.
Traces perimeter	2	Traces perimeter of cut section.
	Analytical Strategies	
Educated guess	3	Participant makes an assumption. Could be due to inability to logically reason any further – or just out of laziness.
Looks at object as a whole	3	Feels entire object rather than just area next to cut.
Comparative terms	2	Describes the object in terms of something else (a house, a tower, a butterfly etc.)
Creates mental image of model	2	Reports storing information in short term memory.
Process of elimination	2	Process of elimination.
Analyzes each line sequentially	4	When the participant breaks down shapes into a series of lines.
Feels shape and answer simultaneously	3	One hand traces object while the other hand traces the answer choices.
Ignores material away from cut	4	Participant only feels the part of the object around the cut and tries not to be distracted by the rest of it.