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An Analysis of Low-Scoring Blind and Low-Vision Individuals' Selected Answers on a Tactile Spatial Ability Instrument

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Introduction

Spatial ability has been generally defined as an intelligence related to generating, representing, transforming, and recalling well-structured symbolic or visual images [1] - [2]. Activities such as navigation, mental rotation, and perception of objects require the use of spatial thinking to accomplish, as well as topics and procedures in many Science, Technology, Engineering, and Mathematics (STEM) fields [3] - [4]. There is uniform agreement on the multidimensionality of spatial ability; however, the exact number of constructs has not been formally agreed upon [5]. A few of the more prevalent constructs of spatial ability include mental rotation, spatial orientation, and spatial perception [1], [6]. This paper refers to spatial ability as the quantification of performance on a specific construct of spatial thinking.

Past research has shown the extent to which spatial thinking aids students in academia [4], [7], [8], and specifically in rigorous engineering courses [9]. Spatial ability has proved to be a significant predictor of success and boosts student retention in undergraduate coursework [10]. Another longitudinal study has shown that spatial ability is beneficial beyond the classroom in professional settings as well [11]. Uttal et al. has demonstrated that spatial ability is a malleable skill and that it can be taught and learned through targeted interventions [12] which highlights the need to develop spatial training material as well as instrumentation to reliably measure spatial thinking.

Despite the value developing spatial ability brings to students and professionals, little has been done to address spatial development in blind and low vision (BLV) individuals who have historically been underrepresented in STEM fields [13]. However, it should be recognized that spatial thinking is fundamentally a cognitive process that does not just require sightedness. While literature has a tendency to describe spatial ability and spatial thinking in terms that represent it as a visual input and manipulation process, it can also be a tactile input process that forms the foundation that mental modeling is then conducted upon. While members of the BLV community have led successful careers in STEM fields, there is great potential to attract many more when tactile spatial interventions can be leveraged to help teach spatial content. Limited research has been done to study spatial vocabulary [14] and spatial strategies [15] in BLV populations, but in order to effectively measure the effects of spatial training in BLV populations there must be a valid and reliable spatial ability instrument that is tactilely accessible.

In order to address the need to measure spatial thinking in BLV populations, the Tactile Mental Cutting Test (TMCT) was created at Utah State University in cooperation with the National Federation of the Blind (NFB) as part of a National Science Foundation (NSF) grant [16]. The purpose of this paper is to analyze patterns in the selected answer choices of high and low scoring blind and low vision individuals to further understand how BLV individuals perceive

TMCT items and to evaluate the effectiveness of these items. Previous work has investigated and reported on the validity and reliability of this instrument [17].

Methods

The TMCT test was adapted and redeveloped from the commonly used Mental Cutting Test (MCT) [18]. The MCT was developed in 1938 by the college entrance examination board and has been used in a variety of settings to study spatial thinking [19] - [21] . The MCT requires takers to observe a two-dimensional isometric illustration of a three-dimensional object with an imaginary plane intersecting the object. The participant then picks from five 2D illustrations, the shape that best fits the cross-sectional area that would be revealed by cutting the 3D object at the interface of the cutting plane. The TMCT was adapted using Computer Aided Design (CAD) to draft 3D versions of the MCT items. The files were then materialized using 3D printing. More information about the development of the TMCT can be found in a previous publication [16]. Similar to the MCT, the TMCT measures constructs of spatial ability including mental rotation, proportions, scale, and mental cutting. Construct validity in the TMCT is derived from its roots in the MCT. The TMCT has demonstrated significant reliability in past studies [17], [22], and has been used as a tool in qualitative studies [15], and to measure gains and losses of spatial ability over time [23].

The original TMCT contained all 25 items from the MCT, however after preliminary testing, in order to reduce the amount of time it took to complete the test, it was split into two subtests of equal difficulty based on each item's difficulty index calculated during pilot testing, with each new subtest containing 12 items. One original TMCT item was removed due to its excessive difficulty.

The TMCT was administered in a controlled environment with multiple proctors readily available to assist participants and answer questions. At each data collection site, up to six participants were tested at one time. Participants were asked not to discuss the test as they were taking it in the presence of other participants.

The TMCT consists of two parts – a rotating turntable partitioned into 12 segments, each holding one TMCT item to allow participants greater autonomy in item selection, and a binder containing five answer choices for each item. TMCT items were presented to the participants in the same orientation on the turntable as MCT items appear on the paper test. However, participants were free to pick up the objects and reorient them as they pleased. Answer choices were presented on paper containing tactile graphic outlines replicating the two-dimensional shapes contained in the MCT answer choices. Item numbers were provided in a Braille format. Participants with low vision capabilities were given the option to utilize answer choices presented in a large print format. However, in this study, only participants who used tactile graphic answer choices were included in the analysis due to differences in how each format of answer choice is perceived. The traditional 20-minute time limit from the MCT was eliminated to allow for adequate time to tactilely interpret each TMCT item.

Prior to beginning the test, a standard instructional protocol was communicated to the participants, and each participant was given two example items to familiarize them with the nature of the test. Each example problem was adapted from the two MCT example problems and contained a three-dimensional item as well as five answer choices per item in a tactile graphic format similar to the following TMCT items. However, each example problem was held together magnetically across the cut, allowing participants to split the object and directly feel the cut surface. One side of the cross-sectional shape was textured with a felt surface to allow for better interpretation of the cross-sectional shape. The following test items were not able to be split around the cutting plane.

Population

Data was collected quantitatively by administering the TMCT at blindness training centers, an NFB program for BLV youth – the Engineering Quotient (EQ) program - and NFB national and state conventions. No compensation was given and each participant was required to sign a consent form prior to beginning the test informing them of the IRB process that was developed for this work. In total, 196 participants participated in this study. Demographical information was not specifically solicited, however ages ranged from 14 to 65+ and all participants identified as blind, low vision, or visually impaired.

Recruitment from blindness training centers occurred at the Colorado Center for the Blind (CCB) in Denver, Colorado, the Division of Services for the Blind and Visually Impaired (DSBVI) in Salt Lake City, Utah, and the Idaho Commission for the Blind and Visually Impaired (ICBVI) in Boise, Idaho. The CCB is operated by the NFB, and DSBVI and ICBVI are operated by their respective state governments. Each training center assists BLV individuals in achieving independence through coursework and exercises in cane travel, woodshop, Braille, and a variety of home management areas. Students typically complete the training program in six to nine months. Many of the students at these centers have recently lost their vision, however no preference was given in recruitment for level of sight or how long students had been without vision. The EQ program for BLV youth was held during the summers of 2018 and 2019 at the NFB national headquarters in Baltimore, Maryland. The program lasted for one week in each of the years it was offered and consisted of STEM-based activities that were designed to increase students' spatial ability. Week-long national NFB conventions provide members with information about blindness culture, technology, and research, and attract thousands of BLV people from around the country. State NFB conventions operate in a similar manner at a less-populated state-level.

Data Analysis

TMCT items were analyzed by examining answer choices picked from those who took the test – focusing on both low scoring and high scoring participants. These participants where those in the group who utilized the tactile graphic answer choice format. Low scoring participants were defined as those who achieved a raw score of 25% or lower on the TMCT. High scoring participants were defined as those who scored 75% or higher. After removing responses from low vision participants who choose to use the large print answer format, a total of 94 participants were included in this study. Of the 94 participants included, 52 were considered low scoring and 42 were high scorers. Due to the tendency for high scoring participants to select the correct answer, this paper will primarily focus on the other distractor solutions or answers that the low scoring group picked. For each TMCT item, in both the low and high scoring groups, the number of instances of a participant selecting each answer choice was summed and converted to a percentage, indicating the relative frequency that each answer choice was selected. All analysis was conducted using Microsoft Excel. TMCT items with particularly large numbers of participants selecting any of the incorrect answers were evaluated to determine specific characteristics of those items or their respective answer choices that could have distracted participants from selecting the correct answer.

Results

Among participants in the low scoring group, four TMCT items had the correct answer picked the most frequently. All other items had an incorrect answer picked more frequently. Only two TMCT items from the high scoring group had a non-correct answer selected the most frequently. Four TMCT items had particularly high percentages of wrong answers picked and were selected for further analysis. These items are problems 118, 124, 131, and 140. Images of each selected item with its corresponding answer choice page are given in appendix A. Of the 35 participants who answered item 118, 17 (49%) participants picked answer choice B. Only two out of 24 high scoring participants picked answer B. The correct answer to problem 118 is answer choice C. For problem 124, 19 of the 27 (70%) participants who answered this item picked answer choice B. None of the low scoring participants chose the correct answer, D, while all 30 of the high scoring participants who answered the question successfully chose the correct answer. For problem 131, 16 of 30 (53%) picked answer choice A while only one out of 24 high scoring participants picked A. However, 6 low scorers did pick answer D, the correct answer. For problem 140, 13 out of 28 (46%) picked B. 2 out of 22 (9%) of high scorers picked B. Among low scorers, the correct answer, A, was the least popular choice. Results are summarized in table 1.

Table 1. Percentage of low-scoring participants who selected each answer choice on each of the selected TMCT items.

TMCT Item	Correct Answer	Percent of Participants Answering				
		A	B	C	D	E
118	C	17%	49%	11%	17%	6%
124	D	7%	70%	7%	0%	15%
131	D	53%	13%	7%	20%	7%
140	A	7%	46%	18%	18%	11%

Discussion

In the case of problems 118 and 124, the most frequently selected answer choice among low-scoring participants exactly matched the shape of the TMCT object as seen from the side. The 3D object for problem 118 is a cylinder with the cutting plane intersecting it at an angle. The most commonly picked answer was a circle, which matches the shape of the end of the cylinder or the cross-sectional shape of the object anywhere along its body if it were cut perpendicular to the length of the object. Answer choice B of problem 124 was selected at the highest frequency of any answer choices on the entire test among the BLV population analyzed. Similar to the answering trends of problem 118, answer choice B of item 124 depicts a quarter-circle shape that represents the side of the object above the cutting plane. These trends suggest that TMCT participants may not have a solid understanding of what a cross-sectional shape is – either due to misunderstanding the instructional protocol communicated to them at the beginning of the test (see appendix B) or, in the case of problem 118, the angle of the cutting plane in relation to the length of the cylinder may be difficult for BLV participants to perceive. Furthermore, problem 118 is the first non-example problem on subtest B of the TMCT which could contribute to students' confusion about how to interpret cross-sectional area.

Problem 131 is unique with its cross-sectional area consisting of two parts, which may distract some students. Unlike problems 118 and 124, the most commonly picked answer does not match one face of the object. If the object were held with the cutting plane orthogonal to a sighted viewer's line of vision, the head-on view would resemble answer choice A which is the most picked answer. However, BLV people do not tactilely interpret TMCT items the same way sighted people do visually. BLV participants may be trying to find the head-on view that sighted people see and not understand that the object of this exercise is to find the cross-section rather than a snapshot from a certain angle. Problem 140 provides an example of where most participants chose an answer that was similar to the correct answer, but varied slightly from the true answer. The most selected answer, answer B, is identical to the correct answer with the exception of a short line segment rotated approximately 30 degrees. While the differences between answer choices A and B is obvious to a sighted individual using vision, subtle differences in the tactile graphics format of the answer sheet can be much harder to discern, especially if the participant, such as many of the training center students, has recently lost their vision and is in the process of adjusting to Braille and a more tactile environment.

Conclusion

Results of this study have shown that there are a variety of reasons low-scoring BLV individuals may be distracted from selecting the correct answer on several TMCT items discussed herein. Factors such as participants misunderstanding the nature of a cross-sectional shape, participants not fully understanding the instructional protocol, or subtle differences between shapes in the tactile graphic answer format may cause confusion and lead to participants selecting incorrect answer choices. Results from this study will help direct future projects relating to the development of tactile spatial ability assessments for BLV populations to eliminate challenges that are more prevalent in non-visual applications.

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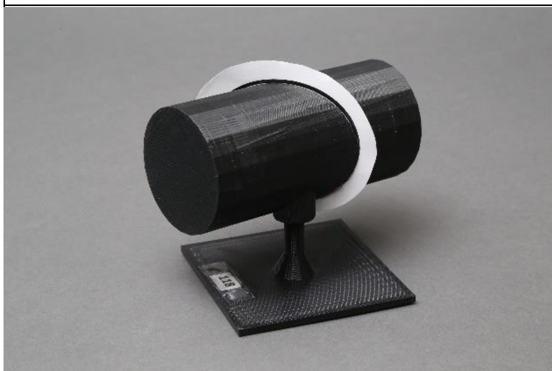
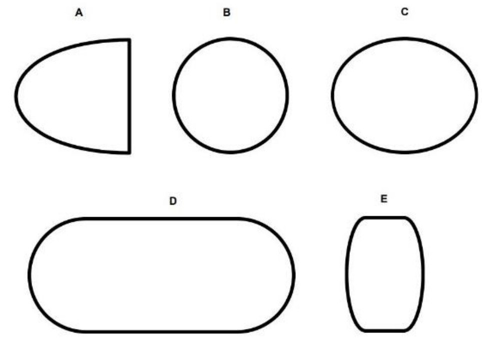
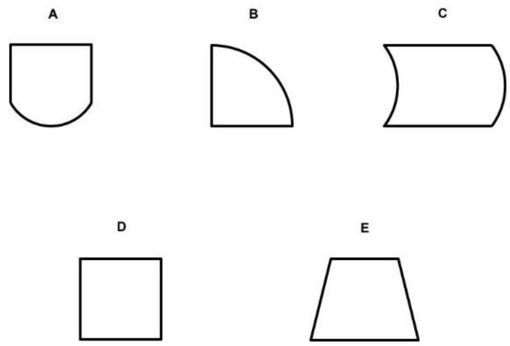
Appendix A

Problem 118

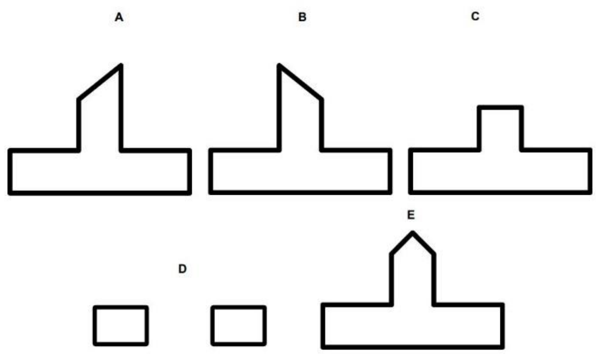




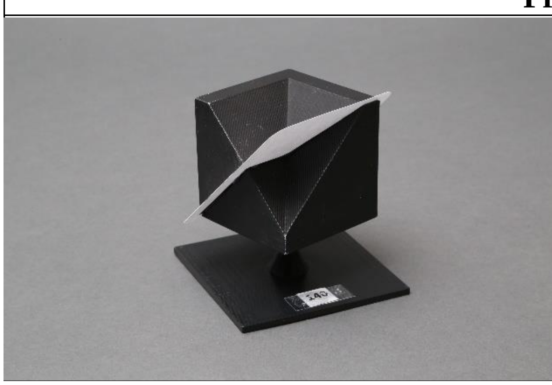
Problem 124

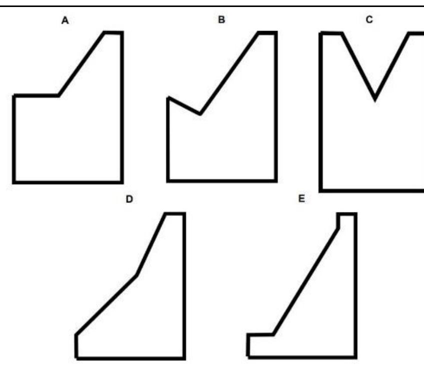


Problem 131



Problem 140





Appendix B

T-MCT administration protocol

(Actions for test administrator are given in light type, verbal instructions to be read to students are given in bold)

Have student sit in seat at desk or table. Place answer binder (with student's chosen media) in front of student, open to Example 1. Place Example 1 to the right of binder.

In this test each problem consists of a plastic block with a flat paper plane through the middle of it, showing a cut through the object. The answer to the problem is the shape of the surface which would be made by cutting along the plane.

There are two examples for you to go over, and then you will be asked to work through a set of 12 problems.

To the right of the binder in front of you, there is an example problem. Feel the solid plastic block and the paper plane cutting through it. You may pick up the block and manipulate it in order to feel the shape of it.

This example is specially made so that you can take it apart where the cut would be, so that you can directly feel the cut side. Go ahead and pull this example apart, and feel the shape of the cut surface. This surface is indicated by a softer felt texture.

(pause for interpretation of the cut side. If needed, help student identify felt surface.)

In the binder in front of you, there are 5 answer choices that may represent the shape of the cut side.

(pause for interpretation of answer choices)

Based on the surface that was revealed when you took the example apart, the correct answer choice is the shape in the bottom left with a post-it flag in the center.

(pause for interpretation of answer choices and flag)

Do you have any questions about this example?

Answer any student questions

When you feel comfortable with this example, flip to the next page in the binder.

When student flips the page, replace example 1 with example 2.

This page also has five answer choices that correspond to Example Problem two, which I have placed to the right of the binder.

Like before, you can take the example apart to feel the shape of the cut side. This is only a feature of the examples, and test problems will not come apart.

(Long-ish pause for interpretation of Example 2 and corresponding answer choices.)

Go ahead and mark the answer choice you think is right by pulling a post-it flag from the flag dispenser, and placing it in the middle of the answer choice. Be sure that it fully sticks to the paper. If during the test you change your mind about a problem, the flag may be pulled up from the paper and moved to a new answer choice.

If student struggles to use the flags, provide any needed explanation.

The binder in front of you contains the answer choices for all test questions. To your right is a lazy susan that contains all of the problems. You can rotate this in order to access each of the problems. The stand supporting each problem is labeled with the problem number, which will correspond to the number at the top of the answer sheet.

When you have completed the problems, raise your hand to let me know and I will collect your answers.

(pause for interpretation of lazy susan and binder)

Once you begin the test, I can no longer answer any questions. Do you have any questions now, before you get started?

Answer any questions…

You may now begin.

(Write the time on a sticky note, and place it in the binder (on the backside of example 2)

When student is finished, record the time on a sticky note, and place it in the binder

Thank you very much for participating in this research.

(dismiss student, record their answers, and prepare binder for new student)