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Assessing the Reliability of a Tactile Spatial Ability Instrument for Non-Visual Use in Blind and Low Vision Populations

Daniel Kane, Utah State University

Daniel Kane is a graduate student at Utah State University pursuing a PhD in Engineering Education with a concurrent master's degree in Civil Engineering. His research interests focus around the study of spatial ability with an emphasis on identifying patterns of spatial strategies and measuring spatial ability in blind and low vision populations.

Jace Russell Harris, Utah State University
Rosemary Yahne, Utah State University

Rosemary Yahne is an undergraduate student at Utah State University. She is pursuing a bachelor's degree in Civil Engineering with a minor in geology. Her research interests include determining spatial ability patterns in engineering students and testing spatial ability in underrepresented populations.

Dr. Wade H. Goodridge, Utah State University

Wade Goodridge is a tenured Associate Professor in the Department of Engineering Education at Utah State University. His research lies in spatial thinking and ability, curriculum development, and professional development in K-16 engineering teaching.

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Abstract

Spatial ability has been identified as a highly beneficial asset to student learning as well as professional performance in STEM fields. Correlational studies link it to success in STEM degrees and STEM professions. Spatial ability is a malleable skill meaning that it can be taught and learned through targeted intervention. Much research has been applied in the area of developing interventions to encourage spatial thinking in engineering students and developing proper instrumentation to measure gains in spatial ability. One such instrument that is widely accepted as a valid way to quantify individuals' spatial thinking is the Mental Cutting Test (MCT) which measures spatial constructs of mental rotation, proportion, and visualization. However, blind and low vision students (BLV) have traditionally been overlooked in the development of spatial interventions and instrumentation. This paper discusses the development of the Tactile Mental Cutting Test (TMCT) which was adapted from the existing MCT as a fully accessible spatial ability assessment for BLV populations. Previous publications have reported on the validity and reliability of the TMCT where participants utilized one of two formats intended for their level of sightedness (fully blind or low vision). This publication builds on past work by analyzing the reliability of scores specifically from participants who were fully blind or had their remaining vision blocked while taking the test. These participants were given a format of the TMCT that utilized Braille labels and tactile graphic imagery to represent two-dimensional shape outlines required in possible answers to items on the instrument. Data was acquired from students at blindness training centers, National Federation of the Blind (NFB) conventions across the United States, and NFB sponsored programs for BLV youth. Results indicate that the TMCT demonstrates good reliability among non-sighted individuals. Establishing the validity and reliability of the TMCT authenticates an instrument that has the potential to open new avenues of spatial ability research to enhance BLV learning and BLV representation in STEM education, as well as enhance existing knowledge about tactile aspects of spatial ability in sighted populations.

Introduction

Spatial ability has been defined as an intelligence related to the ability to mentally transform, retain, and generate visual images [1], [2]. Activities that require spatial ability include navigation, mental rotation, and perception of objects. In this paper we define spatial ability as a quantification of a measurement of spatial thinking.

Students who have high spatial ability have demonstrated higher levels of success in academia compared to their peers, especially in areas of science, technology, engineering, and mathematics (STEM) [3]–[5]. A longitudinal study that tracked students with high spatial performance also found that spatial ability has implications for professionals working in STEM fields [6]. Among undergraduate students, spatial skills have been shown to aid students in coursework involving geology, engineering mechanics, chemistry, physics, medicine, and computer programming. [4], [7], [8]. Additional work studying undergraduate students has shown that spatial ability positively influences degree completion [9]. Furthermore, spatial ability is malleable meaning that it can be taught through training and spatially-oriented experiences [10]. Fostering spatial thinking in students through targeted interventions has the potential to significantly boost student success in STEM fields and remove barriers for perspective students [3].

Common constructs of spatial ability include mental rotation, mental composition, mental cutting, mechanical visualization, and mental folding [11]. Numerous constructs of spatial ability have been identified but a complete list has not been established or agreed upon [12]. This paper discusses spatial ability constructs of mental rotation, proportion, and visualization of cross-sectional shapes.

Common instruments that measure spatial ability include the Mental Cutting Test (MCT) [13], the Mental Rotation Test (MRT) [14], and the Purdue Spatial Visualization Test: Rotations (PSVT:R) [15]. Each instrument is presented in a two-dimensional format and presents isometric drawings of three-dimensional objects and requires subjects to mentally transform the shapes in various ways. Each instrument measures one or more construct of spatial thinking.

One group that has largely been excluded from spatial ability research and instrument development is members of the blind and low vision (BLV) community [16]. The context in which spatial ability has historically been studied relies heavily on vision and visualization. However, similar to high-performing sighted individuals, BLV individuals are fully capable of solving spatial problems and utilizing spatial thinking in their day-to-day activities in non-visual ways. Research that has been conducted in the area of spatial ability among BLV populations includes the identification of effective spatial strategies [17], [18], the effects of the covid-19 pandemic on spatial ability in BLV populations [19], and an analysis of spatial language used by BLV individuals [20]. However, in order to effectively measure the effects of spatial training on BLV populations, there must be a valid and reliable instrument to measure spatial thinking in a non-visual way.

In response to the lack of fully accessible tactile spatial ability instruments, the Tactile Mental Cutting Test (TMCT) was developed as an accessible adaptation of the traditional MCT test as part of a National Science Foundation grant in partnership with the national Federation of the Blind (NFB) [21]. After preliminary testing among BLV participants, the TMCT has demonstrated high reliability [22], [23] and validity [24]. Participants who participated in preliminary testing consisted both of people who identified as fully blind and people who identified as having low vision. Many of the participants with limited vision capabilities in the first phase of testing were allowed to use a large print format of the test. The purpose of this paper is to assess the reliability of the TMCT when it is administered to BLV individuals in a fully tactile format with no visual components.

Methods

The Tactile Mental Cutting Test (TMCT) was developed as an adaptation of the original Mental Cutting Test (MCT). This Mental Cutting Test was created originally as a college entrance exam in 1939, and measures spatial ability constructs of mental rotation, proportion, and mental cutting [13]. It has since been used as a method of measuring spatial thinking in multiple studies [25], [26].

The MCT consists of 25 questions, each containing a 2D isometric drawing of a 3D object with a plane intersecting it. The participant chooses the best option from 5 choices, each choice depicting a possible cross-sectional shape that is revealed by the cutting of the 3D shape at the plane intersection.

The TMCT test questions are 3D tactile versions of the same MCT questions and were designed using CAD software and printed on a 3D printer. In this regard the TMCT measures similar constructs of spatial ability to the MCT including mental rotation, proportion, and mental cutting, and derives construct validity from its roots in the MCT. The TMCT has been shown to be reliable and valid [22]–[24], and has also been effectively used in qualitative studies [17], [18].

The TMCT also differs from the original in that it is divided into two sub-tests of equal difficulty to reduce the time needed to complete the test. Each of these tests consists of 12 questions. One question was removed due to the excessive difficulty. These subtests are labeled A and B, and currently have a difficulty index of 54% and 53% respectively among the entire sample of BLV participants who have contributed to the project.

The TMCT is administered in a controlled environment with proctors available to answer participants' questions individually before beginning the test. The test was administered to anywhere from 1 to 6 people at a time. Participants are brought to a table that contains a turntable, binder, and post-it note dispenser. The turntable contains 12 slots that hold each of the TMCT items. Participants can rotate the table and pick up each question to hold and tactilely interpret them as they desire. Each test item rests on an individual stand and consists of two halves glued together with a laminated paper in between representing the planar cut. The binder consists of the potential answers for each question. Each page of the binder has 5 answer choices, which are identical to answers on the MCT. The possible answers are presented using tactile graphics with Braille labels, such that the participant can feel the shapes of the different answers on the page. The participant may then use the post-it note dispenser to mark which answer they believe is the correct one. During the preliminary stages of administering the TMCT, a large-print answer sheet was provided for participants with residual vision. Calculations of reliability in previous publications included participant scores resulting from both formats of the answer sheet. However, after preliminary testing, significant differences became apparent in the mean scores of each group ($p<.001$). This paper therefore only focuses on data from the participants who used the tactile graphics format of the answer sheet to obtain a more specific assessment of the TMCT's reliability in a fully tactile format.

Table 1. Descriptive statistics of TMCT subtests A and B.

Subtest	**Mean and Standard Deviation**		**Normality**			**Equivalence**		
	Mean (%)	*Standard Deviation (%)*	*W*	*P*	*Interpretation*	*U*	*P*	*Significant Difference*
A	49.86	29.51	0.895	<.001	Non-parametric	1813	0.331	None
B	44.32	25.79	0.926	<.001				

A standard instructional protocol was communicated to each participant before beginning the test, and they were given two example problems to help them understand the nature of the test. The example problems are also derived from the example problems on the MCT; however, they are different than the standard test questions in that they are magnetically held together, such that the participant can pull the two haves apart and feel the cross-sectional area revealed by the planar cut. A softer felt surface is also placed on the inside of the revealed area so the participant can feel the area they are looking for. (In the actual test, the questions cannot be pulled apart.)

Participants were then allowed to start the actual test. Due to the difficulty and time needed to analyze each item, the traditional 20-minute time limit established by the MCT is eliminated.

Population

TMCT raw score data was collected from participants at blindness training centers, NFB programs for BLV youth, and NFB conventions at the national and state level. All participants were required to sign an IRB-approved informed consent document before participating. None of the participants were offered or given any compensation for their participation. There was a total of 203 participants and, while not specifically asked for, the ages ranged from 14 to 65+. All participants identified as blind, low vision, or visually impaired. As the focus of the study was to establish the reliability of the TMCT, no further demographic information was solicited.

Data Analysis

Data used in this study consists of raw scores for each participant taking each subtest of the TMCT using the tactile graphics format. Of the 203 participants who participated in the study, 166 took a version of the test utilizing the tactile graphics format. Of the 166 participants who used tactile graphics answer sheets, 127 took one of the TMCT subtests and were included in the data analysis. Analysis of the data included calculating difficulty and discrimination indexes for each subtest to ensure equal difficulty [27], descriptive statistics including mean and standard deviation of scores, and a Shapiro-Wilk test for scores in each subtest to determine normality. Equivalence of means between each subtest was calculated using a Mann-Whitney U test assuming a confidence interval of 95%.

Internal consistency of each subtest was calculated using Cronbach's Alpha and McDonald's Omega. Cronbach's alpha has been widely used in social science research as a quantification of instrument reliability despite its known limitations [28]. One of the alternative measures of reliability that researchers have argued is more robust than Cronbach's Alpha in areas of human research is McDonald's Omega [29], [30]. In this paper we utilize McDonald's Omega in an effort to provide a more accurate measure of the test's reliability. We also present the reliability using Cronbach's alpha to be consistent with calculations in previous publications [22], [23]. All calculations for this study were performed in Microsoft Excel or Jamovi version 2.3 [31].

Results and Discussion

Difficulty indexes for subtest A and B were calculated as 52% and 51% respectively, showing that the two subtests are of approximately equal difficulty. The discrimination indexes of 63% and 60% for tests A and B respectively also demonstrate that the two subtests discriminate at approximately equal levels.

Table 2. Difficulty and discrimination index for each subtest.

Subtest	**Difficulty**	**Discrimination**
A	52%	63%
B	51%	60%

Results of the Shapiro-Wilk normality test yield that participant scores from each subtest are not normally distributed. We therefore use non-parametric statistical tests for analysis. A comparison of the mean scores for each subtest yield that there is a difference of 5.54% in the mean scores of subtests A and B. However, results of the Mann-Whitney U test indicate that there is no statistically significant difference in the means of the two groups which further confirms that the two subtests can be used in parallel among BLV individuals using the tactile graphics format of answer sheet.

Coefficients for Cronbach's Alpha and McDonald's Omega in subtest A were found to be 0.846 and 0.853 respectively indicating high internal consistency among participants using the tactile graphics format. Cronbach's Alpha and McDonald's Omega were calculated as 0.767 and 0.777 respectively for subtest B indicating acceptable internal consistency [32]. Results of the reliability analysis are summarized in table III.

Table 3. Reliability coefficients for subtests A and B.

Subtest	**Sample Size**	**Cronbach's α**	**McDonald's ω**
A	61	0.846	0.853
B	66	0.767	0.777

It is notable that Cronbach's Alpha coefficients for this study are lower than in previous studies that examined scores of all participants [22], [23]. One reason for this behavior may be due to the diversity of the population that participated in the study. Much of the data collection occurred at training centers for the blind where many of the students had different levels of education, the presence of different comorbidities may have affected their performance, or they may have recently lost their vision. One of the limitations to this study is the lack of demographical information about the participants which could provide insights to unique factors that may contribute to spatial ability in BLV populations such as level of sight and the duration of their sightedness before visual impairment. Participants with vision capabilities who used the large-print format of the test during preliminary testing were significantly more likely to answer TMCT items correctly.

Although the primary purpose of this paper is to asses the reliability of the TMCT, there is construct-related evidence to argue for its validity. To establish the validity of the TMCT, the validity of it's parent test, the MCT, was evaluated (the original test statistics are not readily available). Performance on the MCT was correlated to another spatial ability test, specifically the PSVT:R. Test results on the MCT and PSVT:R were obtained from an introductory level engineering statics course. The MCT was strongly correlated to the PSVT:R with a Spearman-Rho coefficient of 0.532 (n=209). [33] The strong correlation between the tests indicates validity of both tests. Since the TMCT is an altered version of the MCT, the TMCT inherits the MCT's validity.

Future Work

Given that the reliability of the TMCT has been verified among all BLV participants as well as the group who only used the tactile graphics answer sheets, future projects could focus on verifying the reliability of the TMCT among participants with residual vision who use the large print version of the test. It may be possible to adapt the TMCT for use with individuals with low vision while maintaining a comparable level of difficulty. Furthermore, future research could collect demographical information about participants to quantify possible relationships between factors such as duration of blindness or level of sight with spatial ability.

Further research could also include studying the reliability of the TMCT among sighted populations who have their vision temporarily blocked. Results of this study could lead to a better understanding of the non-visual components of spatial ability that are present in sighted populations.

Additional analysis in future publications will include results from exploratory and confirmatory factor analysis to further establish the validity of the TMCT.

Conclusion

Internal consistency coefficients for both Cronbach's Alpha and McDonald's Omega were calculated for two subtests of the TMCT and indicated that both subtests are sufficiently reliable to be used among BLV populations with no visual elements of the test while utilizing the tactile graphics format of answer sheet. Furthermore, among this population, the difficulty and discrimination indexes indicate that the two subtests represent equal levels of difficulty and are suitable to be used as parallel tests for application in pre-post testing experiments. These results have the potential to help educators effectively assess the spatial ability of BLV students and help researchers verify the effectiveness of targeted interventions for teaching spatial thinking in BLV populations. Results of this study have the potential to impact BLV populations by increasing representation of BLV students in STEM fields and aiding in retention efforts.

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