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Work in Progress: The Development of a Tactile Spatial Ability Instrument for Assessing Spatial Ability in Blind and Low-vision Populations

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The Development of a Tactile Spatial Ability Instrument for Assessing Spatial Ability in Blind and Low Vision Populations

Abstract

There is significant work indicating that spatial ability has correlations to student success in STEM programs. Work also shows that spatial ability correlates to professional success in respective STEM fields. Spatial ability has thus been a focus of research in engineering education for some time. Spatial interventions have been developed to improve students' spatial ability that range from physical manipulatives to the implementation of entire courses. These interventions have had positive impact upon student success and retention.

Currently, researchers rely on a variety of different spatial ability instruments to quantify participants' spatial ability. Researchers classify an individual's spatial ability as the performance indicated by their results on such an instrument. It is recognized that this measured performance is constrained by the spatial construct targeted with that spatial instrument. As such, many instruments are available for the researchers use to assess the variety of constructs of spatial ability. Examples include the Purdue Spatial Visualization Test of Rotations (PSVTR), the Mental Cutting Test (MCT), and the Minnesota Paper Foam Board Test.

However, at this time, there are no readily accessible spatial ability instruments that can be used to assess spatial ability in a blind or low vision population (BLV). Such an instrument would not only make it possible to quantify the impacts of spatially focused interventions upon BLV populations but would also provide a quantitative method to assess the effectiveness of spatial curriculum for BLV students. Additionally, it would provide a method of assessing spatial ability development from tactile perspective, a new avenue for lines of research that expand beyond the visual methods typically used.

This paper discusses the development of the Tactile Mental Cutting Test (TMCT), a nonvisually accessible spatial ability instrument, developed and used with a BLV population. Data was acquired from individuals participating in National Federation of the Blind (NFB) Conventions across the United States as well as NFB sponsored summer engineering programs. The paper reports on a National Science Foundation funded effort to garner initial research findings on the application of the TMCT. It reports on initial findings of the instrument's validity and reliability, as well as the development of the instrument over the first three years of this project.

Introduction

Spatial ability can be defined as the cognitive ability to construct, re-orient, transform, and reconstruct mental images [1]. Spatial skills are vital in a variety of fields including engineering, chemistry, biology, physics, architecture, astronomy, and many more [2]. Spatial ability is generally defined as an aptitude towards understanding spatial relations. However, there are a number of constructs that contribute to overall spatial performance. Although the number of constructs has not been formally agreed on, commonly observed constructs of spatial thinking include mental rotation, spatial orientation, and spatial visualization [3], [4]. This paper refers to spatial ability as a quantification of performance on a specific construct of spatial thinking: rotation and cutting plane.

Numerous studies have shown spatial ability to be a positive predictor of academic success in science, technology, engineering, and mathematics (STEM) fields [5], [6], [7]. Of particular interest is the correlation between measured spatial skills in undergraduate engineering students and performance in rigorous engineering courses. It has been found that students demonstrating high spatial skills are typically more successful in coursework and degree completion [8], [9]. Furthermore, spatial ability is critical in many career paths, especially those involving STEM occupations. Significant evidence of this can be found in a longitudinal study that revealed that high school students identified as high spatial performers went on to attain higher educational achievements and career proficiency [10], [11]. Also, of distinct importance, we know that spatial skills are malleable, meaning that they can be taught, learned, and maintained over time [12]. This finding is particularly promising due to the implications it indicates for positive effects that can be realized from spatial interventions. There is thus a need to create interventions to teach spatial thinking, as well as a continuing need for reliable instruments to measure spatial ability in its variety of constructs.

While spatial thinking has traditionally been measured with instruments that rely on vision, it is fundamentally a cognitive process and can also be developed and quantified through instruments that rely on other avenues of input [13]. Indeed, there is a distinct need for instruments that target other methods of spatial input, especially when we consider blind and low-vision populations.

Spatial ability has considerable correlation to success in STEM educational programs as well as STEM fields. However, little work has been done to foster the development of spatial skills or the measurement of spatial ability in blind and low vision people. Blind and low vision (BLV) populations are significantly underrepresented in STEM fields and in spatial ability research [14]. It is possible that much of the reason for the latter could be because of a lack of tactile spatial ability instruments that may be used to quantify spatial ability in BLV populations. Further research of spatial ability in these populations has the potential to encourage more BLV youth to pursue careers in STEM areas. Additionally, it stands to also inform solid practices for spatial ability development that can enhance existing mechanisms used in increasing spatial ability in sighted populations. For this reason, we focus this research and this paper on a significant need to develop an accessible instrument to measure spatial thinking in BLV populations.

The purpose of this paper is to present the development of a tactile spatial ability test: The Tactile Mental Cutting Test (TMCT) developed at Utah State University as part of a National Science Foundation funded project in partnership with the National Federation of the Blind (NSF). The paper specifically focuses on the instrument's development and initial reliability calculations from preliminary testing. Work continues on increasing participant numbers as the project moves towards its conclusion. This instrument will be used to measure spatial ability gains in BLV students who are engaged with engineering focused interventions. It allows the assessment of a tactile construct of spatial ability. The instrument also provides another avenue of research in the development of spatial ability in all populations.

Methods

In order to measure spatial ability gains in BLV populations, the Tactile Mental Cutting Test (TMCT) was adapted and redeveloped as a tactile version of the commonly used Mental Cutting Test (MCT) [15]. The MCT test was used by the college entrance examination board in 1938 and measures spatial constructs of mental visualization, rotation, and proportion [9] and has been used in numerous studies to measure spatial ability [9], [16], [17]. The MCT requires a participant to look at a two-dimensional isometric drawing of a 3D object with an illustrated cutting plane intersecting the object. The participant is then required to select, from 5 drawn illustrations, the correct illustration that would accurately represent the shape and proportion of the surface revealed by the cutting plane's contact with the 3D object. The TMCT was created using computer aided drafting (CAD) software to 3D model and then print tactile models of the two-dimensional figures depicted on the original MCT test. More information about the adaptation of the TMCT can be found in a previous publication [18]. Construct validity of the TMCT is derived from its roots in the MCT as well as methods evident in a previous publication on a preliminary validation of the TMCT test [19]. While certain constructs of spatial thinking may be measured slightly differently in the TMCT due to the tactile nature of the test, measurement of spatial constructs such as proportion, scale, and mental cutting remain the same. Before pilot testing, the TMCT was reviewed by experts in the field of spatial ability as well as members of the BLV community. More information on validation of the TMCT test can be found in a previous publication [19]. After implementing the TMCT at various venues, the instrument has initially demonstrated significant reliability.

TMCT pilot data was collected at National Federation of the Blind (NFB) national and state conventions as well as training centers for the blind. Additional testing aimed to measure gains in spatial ability was performed at a week-long engineering program for blind and low vision youth offered at NFB headquarters in Baltimore during the summers of 2018 and 2019. A discussion of results from interventions and gains in TMCT scores will be given in future publications. This paper primarily focuses on measured reliability in the development of the TMCT instrument.

TMCT tests were administered in a controlled environment with up to six participants being tested at a time. Tactile test problems were presented to each participant on a rotating turntable similar to the common kitchen aid called a "lazy Susan." The fixture allows for easier access to all test problems and offers an easy mechanism to access all tactile objects without requiring the participant to stand and move. A photograph of the turntable is given in Figure 1. A binder was placed next to each turntable containing large print or tactile graphic answer choices representing the 2D cross sectional shape that would be revealed by the cutting plane indicated on the tactile object. Students were given a visual or tactile answer sheet in accordance with what they indicated as their preferred literacy format. These answer sheets contained 5 representations of what the sectioned surface of the object would look like if it were cut at the intersecting plane. A photograph of the answer sheet binders is given in Figure 2. Prior to beginning the test, a standard instruction protocol was read to each participant and proctors answered participants' questions individually. The standard time limit traditionally imposed on the MCT was eliminated on the TMCT to allow for adequate time to tactilely interpret each model.

After preliminary testing, the TMCT was split into two subtests, A and B, of equal difficulty to allow for faster completion of the test and to measure gains in scores over a weeklong period of interventions. In order to create two equal forms, a difficulty index was calculated for each test problem based on pilot data. After an analysis of the results, subtest A had an average difficulty index of 0.627 and a standard deviation of 0.163, and form B had a difficulty index of 0.654 and standard deviation of 0.112.

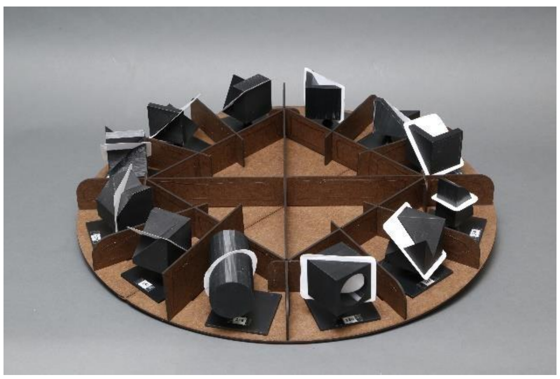

Figure 1. Rotating turntable holding subtest B, one of two T-MCT subtests of equal difficulty.

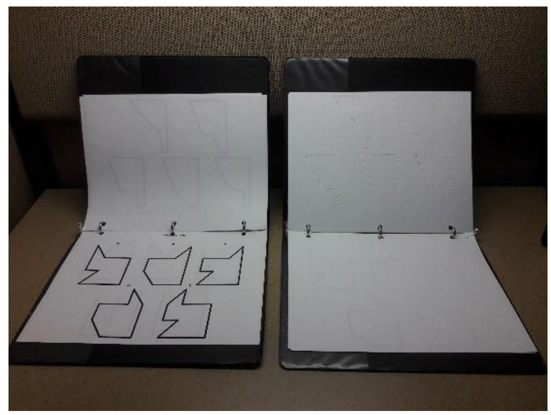

Figure 2. Participants were given a binder containing five multiple-choice answer options for each T-MCT problem. Answer sheets were available in large print or tactile graphic format.

Population

Participants in the TMCT research were recruited by the research team at conventions, by training center administrators at their respective institutions, and by the NFB engineering programs for youth held at NFB headquarters. Participants who sought to volunteer were informed of the nature of the test and study and of the IRB process that was developed for this work. Signatures on consent forms were acquired. All participants identified as blind, low vision, or visually impaired. There was a total of 119 participants, with 104 participants choosing a Braille tactile graphic answer sheet, and 15 choosing large print. Ages ranged from 14 to 65+, however participants' age was not specifically requested. At the NFB EQ 2019 program for youth, students were asked in a survey for their high school grade level. Gender was only recorded at the Colorado Center for The Blind and the NFB EQ 2019 program. Of the 79 participants with recorded gender, 39 were female and 40 were male.

The national NFB convention is a week-long event held annually and serves as the governing body for the NFB. Throughout the week members participate in seminars and activities relating to blind and low vision culture, accessible technology, and research. The NFB national convention attracts thousands of BLV people of all ages and backgrounds. Of the pilot data, nine participants were recruited at the national convention. State NFB conventions operate in a similar manner at a more local level. Seven participants were recruited from the NFB Utah convention. NFB training centers provide a nine-month training program for blind or low vision individuals. Many of these students have recently become blind. In total, 50 participants were recruited from training centers, all of whom had their vision occluded during the test. As such, all of the training center participants used tactile graphic answer recording sheets. The remaining 53 participants were high school aged youth at the NFB EQ program, a week-long program that teaches students engineering skills using nonvisually accessible methods. EQ 2018 students were all given tactile graphic answer sheets. In 2019, students were given a choice between tactile graphic and large print answer sheets in order to better understand differences between blind and low vision students. EQ 2019 students were given subtests A and B separately, with the intent of measuring gain in spatial ability over a week of interventions.

Descriptive Statistics

Of the 119 participants who took the TMCT, 97 (82%) participants completed all questions given them. The full TMCT test contains 25 problems, all of which were administered together at the NFB EQ 2018 program, the Colorado Center for the Blind in 2019, and the Division of Services for the Blind and Visually Impaired in Salt Lake City, Utah. Tests at these sites containing all 25 problems were given to 62 subjects. However, only 18 (29%) of the tests administered were fully completed. The remaining 57 participants were administered a split test (subtest A or B) at different sites. A total of 48 participants had complete data for all subtest A problems while 44 participants completed all of the subtest B problems. The mean score for all tests is 58.2% with a standard deviation of 27.1%.

Reliability Analysis

The reliability analyses performed included both internal consistency testing, using Cronbach alpha, and parallel forms reliability of the A and B components, using correlation and means and variance comparison.

In order to determine overall test reliability, the 62 tests containing all 25 TMCT questions were analyzed using Cronbach's alpha. Of the 62 tests, only 18 of the participants completed all 25 questions. A Cronbach's alpha of 0.88 was calculated for the group of tests where all 25 questions were answered, signifying a very good internal consistency. For subtest A, Cronbach's alpha was calculated to be 0.81 with 48 participants having complete data, signifying very good internal consistency, while Cronbach's alpha for subtest B was 0.77, with 44 participants having complete data, which suggests good internal consistency. A summary of internal consistency is given in Table 1.

Table 1. Internal consistency of TMCT subtests A and B.

	Cronbach's Alpha	N
All Questions	0.88	62
Subtest A	0.81	48
Subtest B	0.77	44

To determine equivalence between subtests A and B, parallel forms reliability was tested using data from the 62 tests where all problems were answered at the same time. A strong correlation ($r = .78$, $p < .0001$) was measured between the average scores of each subtest. Furthermore, mean scores contained in Table 2 confirm equivalence in difficulty between subtests.

Table 2. TMCT mean scores for subtests A and B ($r=.78$, $p<.0001$)

Subtest	Mean	Standard Deviation
A	54%	29%
B	52%	27%

The results of a preliminary reliability analysis of the TMCT show overall very good reliability as shown in Tables 1 and 2. However, results should be viewed with caution due to the relatively small sample size. The small sample size is a result of eliminating data from participants who did not complete all questions on the instrument. Participants who did not answer all of the questions on the test were thus not included in the internal consistency analysis. This is because in many cases, the reason for incomplete test results was due to inadequate time to take the test. A larger sample size would likely increase Cronbach's alpha. As the project continues, data from a greater number of participants will help improve the strength of these statistics.

Conclusion

Calculations performed on preliminary data from the TMCT initially show that the instrument is significantly reliable in measuring spatial constructs of rotation, cutting plane, and proportion in blind and low vision populations. These results indicate that the instrument is showing reliability that argues for its continued use and development in spatial ability research. The instrument not only provides a reliable step forward in assessing spatial ability in blind and low vision populations, but also stands to open a new avenue of spatial ability research in sighted populations as well.

Future Work

Future work will involve the collection of more data on blind and low vision participants to allow for a more robust analysis of reliability on the entire instrument and its split forms. It is desired to extend participant numbers well beyond 150 but the process has slowed significantly due to the recent Covid-19 pandemic and its impacts on human subject research. Additionally, the researchers would like to extend the instrument's use into sighted populations to begin to quantify a tactile component of spatial ability in this group. There are likely many uninvestigated areas of spatial thinking and its development that access to a tactile instrument such as the TMCT can shed light upon.

As part of a larger work, this instrument will also be used to continue existing work involving a mixed method study where high and low spatial performers will be identified through their spatial ability results on the TMCT. Their spatial strategies will then be investigated to determine methods that can help teach spatial ability skills to future students.

Finally, this research group is also in the process of adapting other spatial ability instruments into tactile forms. There are many instruments that can be made available to blind and low vision populations if we "engineer" them to help research critical areas to help BLV students in the STEM areas.

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