2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #36862

Parallel Form Reliability Analysis of a Tactile Mental Cutting Test for Assessing Spatial Ability in Blind and Low-vision Populations

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Reliability Analysis of Two Parallel Tactile Mental Cutting Tests for Assessing Spatial Ability in Blind and Low-vision Populations

Abstract

There is ever-growing research indicating that high spatial ability correlates with student and professional success in science, technology, engineering, and mathematics (STEM) courses and career fields. A few valid and reliable testing instruments have been developed to measure specific constructs of spatial thinking in sighted populations. However, due to a lack of accessibility, most of these testing instruments are unable to be utilized by blind or low-vision (BLV) populations.

As part of the Spatial Aptitude Test developed by the College Entrance Examination Board (CEEB) in 1939, the Mental Cutting Test (MCT) measures both spatial visualization and spatial relational reasoning. In 2018, the MCT was converted into a tactile test, called the Tactile Mental Cutting Test (TMCT), designed to allow for tactile interpretation, instead of visual interpretation, of 3-D objects and their planar cuts. The TMCT allows all persons, including BLV populations, access to a tool that can quantify spatial ability. To increase the TMCT's utility, the original format of the 25-question TMCT was split into two subtests (A & B), each containing 12 questions. In 2021, the TMCT's reliability in measuring spatial constructs of rotation, cutting plane, and proportion in BLV populations was found to be good [1]. However, to increase the precision of the results found in our pilot analysis, the research team desired a larger sample size.

This paper presents a continued reliability analysis of the parallel TMCT subtests A & B with the BLV population. Data was collected from BLV participants attending National Federation of the Blind (NFB) conventions, learning centers for the blind, and STEM-oriented NFB summer camps for high school students. For our continued reliability analysis, we calculated the Cronbach's alpha coefficient for each parallel TMCT subtest with a larger sample size. The parallel TMCT subtests continued to show a high reliability as was previously calculated during the pilot analysis in 2021 [1]. These results indicate that the parallel version of the TMCT is a reliable instrument to measure spatial visualization and spatial relational reasoning in the BLV population.

Introduction

Spatial Ability is defined by Lohman (1994a, p. 1000) as "the ability to generate, retain, retrieve, and transform well-structured visual images," [2] although this research team would argue that images can be developed in non-visual ways as well. Spatial ability has been characterized as an individual attribute and psychological characteristic that strongly attributes to success and advancement in education and occupational credentials in science, technology, engineering, and mathematics (STEM) fields [3]. Spatial skills are also malleable, meaning they can be taught, learned, and maintained over time [4]. With the growing need for STEM professionals [5], but declining STEM major declarations and retention rates [6], [7], it is imperative that we better understand and learn how to train students' spatial abilities.

There have been valid and reliable visual tests developed to measure a student's spatial ability, but there are little-to-no available instruments or tools to measure spatial thinking in the blind and low vision (BLV) population. Currently, the BLV population is significantly underrepresented in STEM fields and in spatial ability research [8]. With the development of a valid and reliable instrument that can measure and inform us about spatial ability levels found before and after spatial interventions, a new gateway of knowledge is opened to help researchers and practitioners understand other pathways, beside visual, for spatial ability to develop from and be improved with.

The Tactile Mental Cutting Test (TMCT) was developed in 2018 at Utah State University as a part of a National Science Foundation funded project in partnership with the National Federation of the Blind (NFB) [9]. The TMCT is a tactile testing instrument that is intended to measure and quantify both spatial visualization and spatial relational capabilities of the BLV population. After analyzing pilot TMCT participant score data, our research team decided to increase the utility of the TMCT by splitting the original format of the 25-questions into two parallel subtests (A & B), each containing 12 questions. With this significant change to the format of the instrument, we needed to determine if the reliability of the TMCT was retained in its split form.

A pilot analysis confirmed that the split version of the TMCT instrument showed good reliability in both subtests [1]. However, it was desired that we have a larger sample size to increase the precision of these results. In this paper, we present a continued reliability analysis of the split version of the TMCT to answer the question: Do the parallel TMCT subtest instruments retain strong reliability when delivered to a larger sample population? Establishing confidence of the parallel TMCT subtest instruments' reliability opens new avenues into understanding spatial ability across both non-sighted and sighted populations.

Literature Review

Benefits of Spatial Ability

Spatial skills have been identified as factors that contribute to retention rates and improved grade and course performance in STEM fields [10]–[13]. Wai et al. discussed the consistency of heightened spatial skills in those who excelled in STEM domains but recognized that spatial ability is often overshadowed by mathematical or verbal skills when predicting success in STEM fields [3]. A 2019 study by Veurink & Sorby found that students identified as "low visualizers" who took a course specifically designed to improve spatial skills ultimately performed at the same or higher levels on a spatial ability assessment when compared to students who had initially higher spatial skills but did not take the course. Also, students who took the spatial ability course were more successful in their first attempt at introductory engineering courses than those who did not take the course [10].

There is evidence from previous work that vision is not required to learn certain STEM concepts, and BLV individuals were able to perform at similar or higher levels than sighted populations [14], [15]. Giudice emphasizes the importance of developing spatial skills, and that the development and use of these skills can be equally as beneficial as the use of visual skills. Crollen et al. [14] found that BLV youths were able to perform numerical tests assessing working memory at the same level of, or better than, their sighted peers. Additionally, there was no difference in the tactile spatial span of BLV youths compared to the visual spatial span of sighted youths.

Research supports the use of tactile aids, as opposed to physical presence, as a way for non-sighted populations to familiarize themselves with a new environment [12], [16]. Experiencing an environment for the first time using a tactile/audio aid, such as a scaled-down 3-D map of the environment or a map that verbally describes an environment's layout, can be considerably beneficial for BLV individuals when developing an accurate mental model of the new environment [12]. In a study by Lahav & Mioduser [16], participants were successful in completing orientation tasks when they were physically present in an environment that they had only previously experienced through virtual exploration. It has been suggested that one's level of visual impairment does not influence the amount of improvement seen as a result of spatial skills training, and that training in one specific area of spatial ability, such as distance discrimination, can transfer over into other areas of spatial skills [13].

Interventions to Improve Spatial Ability

There have been multiple findings that spatial skills are not fixed and can be improved through intervention [10]–[13], [16], [17]. Intervention does not have to be a complex process, it can consist of short spatial exercises conducted once or twice a week, and still be effective in boosting students' spatial skills [11]. In a study by Sorby & Baartmans [18], a group of freshmen engineering students who initially failed a spatial abilities test were enrolled in a course focused on 3-D spatial visualization. Students who participated in the course achieved higher grades and higher retention rates in future courses requiring the use of spatial visualization skills [18].

In BLV populations, a study by Leo et al. [13] showed that individuals who received tactile stimulation training were able to improve distance discrimination skills and succeed at a higher difficulty level. Instruments such as tactile maps or virtual environments, which provide haptic and audio stimulation, help BLV individuals develop an accurate interpretation of a space [12], [16]. In one study, participants had more success in accurately recalling routes they had interpreted using tactile and audio aids than participants who had physically walked the routes, which supports the idea that spatial intervention can be beneficial in BLV populations [12].

Strategies & Errors in Tactile Interpretation

Lahav & Mioduser [16] found that the strategies used by BLV individuals were similar when tactilely interpreting an environment compared to physically experiencing an environment. However, for those exploring the space virtually, a greater number commonly explored the interior first, then moved towards the perimeter of the model. Those exploring the space in-person commonly examined the perimeter of the area first, then moved towards the interior. In line with this, Hill et al. [19] found that BLV individuals who utilized spatial skills, such as object-to-object relationships or perimeter/gridline patterns, were able to effectively explore a new space and locate objects. One error seen in tactile interpretation, which was identified in a study by Leo et al. [13], was the overestimation of short lengths and the underestimation of long lengths.

Developing the TMCT

In 1939, the College Entrance Examination Board developed the Mental Cutting Test (MCT) as a part of the Spatial Aptitude Test to measure both spatial visualization and spatial relational reasoning of incoming potential students [20]. The MCT consisted of 25-questions, each illustrating a plane cutting through a 3-D object and five possible answer choices. The objective was to select the correct illustration of the planar slice that would match the illustrated planar cut in the 3-D object.

In 2018, the MCT was converted into a tactile test, called the Tactile Mental Cutting Test (TMCT), designed to allow for tactile interpretation instead of visual interpretation of 3-D objects and their planar cuts. The development of the TMCT is detailed in a previous publication [9]. This conversion allowed the MCT to accommodate BLV students in an accessible manner, as well as open other possible research avenues into understanding spatial ability in both BLV and sighted populations.

A significant reason that the MCT was chosen as the foundation for developing a tactile spatial ability test was due to the MCT's already established reliability and validity in measuring two spatial constructs in its visual form [21]. Additionally, the original MCT presented illustrations of 3-D objects that could readily be developed into tactile 3-D models. Pilot analysis of the TMCT's reliability in measuring spatial constructs of rotation, cutting plane, and proportion in the BLV population was completed by Goodridge et al in 2021 and is detailed in a prior publication [1].

Current Research Contributions

Although significant research has been done examining spatial abilities in STEM fields within sighted populations, there is very little work focused on identifying spatial abilities in BLV populations, and how improvement in this area could impact representation of BLV populations in STEM fields. Since spatial skills are an indicator of success in STEM fields, the opportunity for BLV individuals to receive spatial training will increase the success in their pursuit of a STEM degree or in attaining occupation in a STEM career.

Methods & Experimental Setup

MCT Adaptation & Development of TMCT

The TMCT was adapted from the MCT, taking the 25 items from the MCT, and using computer aided drafting (CAD) software to develop three-dimensional physical models for each item that could be tactilely interpreted by BLV participants [1], [9]. Items from the MCT were measured as printed on paper in the original test and scaled up to fit within a 2.25 in^3 space, then were 3-D modeled using CAD software Solid Edge^{TM} [9]. Adjustments were made to 3-D models if there were any obvious differences from the original. Each item was 3-D printed in two parts, which were divided by the plane of interest (POI). The POI is a thin sheet of plastic material that intersects the object and provides a point of reference for a section view of the outline that students are aiming to interpret. Each item could then be assembled into its final form using these three components (see Figure 1). For a more detailed description of the adaptation and development of the TMCT, see previous work [1], [9].

To increase its utility, the TMCT was split into two parallel subtests (A & B) of equal difficulty, each with 12 distinct items from the original TMCT. To balance the number of items between subtests, we reviewed our pilot data and chose to exclude the one item that showed a much higher level of difficulty compared to the other 24 items of the original TMCT. Having two TMCT subtest increased utility by making pre- and post-testing possible without risking participants remembering items or experiencing practice effects. Also, many participants found the original version of the TMCT to be too long and too mentally taxing, leading to many participants ending their participation early. By shortening the length and time requirements, the utility of the split version of the TMCT was further increased.

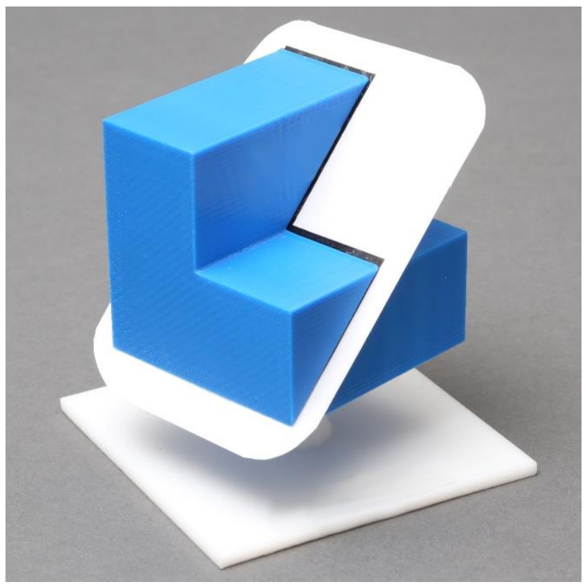

Figure 1. Example 3-D TMCT item

Administering the TMCT

The population sample were participants from BLV training centers, NFB conventions, NFB Engineering Quotient (EQ) STEM-focused programs for BLV youth. All participants were at least 14 years old. No further demographic information was collected for this study of reliability. Additionally, separation of BLV participants into levels of sightedness, for those of low vision, or into groups based on duration of sightedness before visual impairment creates sample size issues in determining statistical significance. At this time, analysis of data categorized by demographic information beyond BLV designation and typical age attending BLV training centers, NFB conventions, NFB Engineering Quotient (EQ) STEM-focused programs is beyond the scope of this work. Convenience sampling was used over random sampling due to the difficulty in finding enough members of the BLV population to participate in this study outside of the chosen locations.

As participants entered the testing room, they were assigned, in alternating order, either subtest A or B to ensure random selection. Prior to taking the test, a consent form was read to and signed by all participants. During the pilot data collection, participants were given one of two answer recording sheets determined by their level of sight. Participants with very little or no remaining vision were given a tactile graphics representation of the answer choices with Braille labels. Individuals who identified as having low vision or a visual impairment were given a large print format of the answer choices. For the more recent data collection, low vision or visually impaired participants were asked to wear blindfolds or sleep shades and given the tactile graphic answer sheets to ensure a tactile-only testing experience for all participants.

Once the consent form had been signed and the test fully prepared, participants were given two example items, adapted from the example problems on the MCT, to practice tactilely interpreting the cut section of the object. The participant did so by taking the two sides of the 3-D item apart, which were held together magnetically, feeling the cut plane, and then selecting their answer from a sheet of five tactile graphic answer choices. Following the completion of the example TMCT items, the participants began their selected TMCT subtest, in which the items could not be separated. Thus, the participants had to tactilely explore the plane that intersects the outside of the item to determine the correct outline of the planar slice. For each testing item, the participant marked their selected answer out of the five possible answer choices using sticky tabs. Start and end times were recorded but there was no time limit for participants taking the test. Following the completion of the TMCT, participants were asked a series of semi-structured interview questions to assess strategies used. Participants received their scores after interviews were conducted.

Data Analysis Tests

Descriptive statistics such as mean, standard deviation, frequency distribution, and percentiles of parallel TMCT subtest scores were calculated. Difficulty and discrimination indexes were calculated to identify items that were significantly harder or easier than others to ensure that each subtest was of equal difficulty. The difficulty and discrimination index test results are detailed in a prior publication [1].

To confirm that the two TMCT subtest remained parallel, we desired to determine if the two TMCT subtests remained equivalent in difficulty with a larger sample size. Since the two parallel versions of the TMCT have distinct items and participants attempt either subtest A or B, but not both, then the results of the two parallel versions of the TMCT are independent of one another. Analysis of the data shows the scores of each participant are approximately normally distributed and the variance of the scores are approximately equal. Since we can assume independence, normality, and homogeneity of variance between the parallel versions of the TMCT, we performed an independent samples t-test to compare the mean scores of the two subtests. A summary of this comparison is provided in Table 1.

In the pilot analysis completed in 2021, we used the Cronbach's alpha coefficient to determine the parallel TMCT subtests' internal consistency, a type of reliability [1]. In the pilot data, there were three sets of parallel TMCT subtest score data that were incomplete due to the participants ending their participation before completing their test, so the incomplete data sets were not included in the analysis. The pilot analysis calculated the Cronbach's alpha coefficient of subtest A's data to be 0.81 with 48 participants having complete data and the Cronbach's alpha coefficient of subtest B's data to be 0.77 with 44 participants having complete data, signifying high internal consistency. A summary of these results is given in the second and third columns of Table 2.

To determine the reliability of the parallel version of the TMCT, we calculated Cronbach's alpha using the participant's TMCT subtest A & B score data. Cronbach's alpha is a coefficient that measures reliability (or internal consistency). We utilized recent and pilot data from participant performance on the parallel versions of the TMCT. The prior existing data included results from participants who had taken either subtest A or B prior to 2021 (Table 2). All data analysis tests were done in either Microsoft Excel or SPSS software.

Results & Discussion

We have had 73 BLV participants take the TMCT subtest A and 75 BLV participants take the TMCT subtest B. However, only the data for participants who completed all 12 questions given to them was utilized in the analysis. A total of 72 participants had complete data for all subtest A problems while 73 participants completed all the subtest B problems. For subtest A, the mean score is 58.5% with a standard deviation of 29.6%. For subtest B, the mean score is 52.1% with a standard deviation of 27.9%. The summary of mean scores is given in Table 1. An independent samples t-test was performed to determine if the difficulty of the two parallel versions of the TMCT are approximately equivalent. With a two-tailed t-score of 1.312 and 147 degrees of freedom at a .05 significance level, we found a p-value of 0.177. Since our p-value is greater than our significance level, we cannot conclude that there is a difference between the mean scores of TMCT subtest A and B. This result means that we can continue to assume that the two parallel versions of the TMCT are approximately equivalent in difficulty, even with the increased sample size.

Table 1. Mean Scores for TMCT Subtest A & B ($p - \text{value} = 0.18 > 0.05 = \alpha$)

	Mean	Standard Deviation
Subtest A	58.5%	29.6%
Subtest B	52.1%	27.9%

Cronbach's alpha coefficients were calculated for each of the parallel TMCT subtests with their larger sample populations that include the combined pilot and recent participant TMCT subtest A & B score data. For subtest A, the Cronbach's alpha coefficient was calculated to be 0.86 with 72 participants having complete data, signifying high internal consistency. For Subtest B, the Cronbach's alpha coefficient was calculated to be 0.81 with 73 participants having complete data, signifying a high internal consistency. A summary of these results is given in the fourth and fifth columns of Table 2.

Table 2. Internal Consistency of Parallel TMCT Subtest A & B

	Cronbach's Alpha (pilot analysis)*	Sample Size*	Cronbach's Alpha (current analysis)	Sample Size
Subtest A	0.81	48	0.86	72
Subtest B	0.77	44	0.81	73

*All data in columns 2 & 3 are from pilot analysis [1]

Our analysis found high internal consistency of both TMCT subtests, which means that TMCT subtests have high reliability. Since completing the pilot reliability analysis of the TMCT subtests in 2021 [1], the sample size of the TMCT subset A has increased by 50% and the sample size of the TMCT subset B has increased by 65.9%. The Cronbach's alpha coefficient becomes more precise with larger sample sizes. Since the Cronbach's alpha coefficient of each TMCT subtest has increased with the higher participant numbers, we can conclude the reliability of the parallel versions of the TMCT will remain high with further utilization of the instruments.

A limitation to this study is that limited demographic information was collected for participants. The lack of demographic information means that we cannot compute any calculations that would require direct comparisons between, or grouping of, the TMCT score data by participants' age, gender, level of visual impairment, or duration of sightedness before visual impairment.

Conclusion

Cronbach's alpha coefficients, which measure a type of reliability called internal consistency, were calculated for each TMCT subtest using all collected, and complete, participant TMCT subtest score data. Both parallel TMCT subtests showed higher Cronbach's alpha coefficients compared to the pilot reliability analysis completed in 2021, which include 50 - 65.9% less samples. The parallel TMCT subtest instruments retained strong reliability when delivered to a larger sample population. Thus, the two parallel TMCTs are reliable instruments to measure spatial visualization and spatial relational reasoning in BLV populations. Considering these results, the two parallel TMCT subtests can be used as a pre- and post-test system to assess spatial capabilities prior to, or following, any interventions aimed at increasing spatial capabilities in BLV populations. Another significant finding is that the two reliable tactile spatial ability instruments, TMCT subtests A & B, are equitable in difficulty and can be used in pre- and post-test experimental design research by engineering education educators.

Future work

Given the verification of the reliability of the parallel TMCT instruments, future work can be done looking at the long-term effectiveness of spatial intervention in BLV populations. A suggested method for testing the effectiveness of spatial interventions is to have participants take one subtest before receiving an intervention and taking the opposite subtest following the intervention. This could help determine if, and to what extent, different interventions are effective for long-term improvements in spatial capabilities for the BLV population.

We will complete a qualitative analysis of responses to the semi-structured interview questions. The focus will be on participants' strategies and developed mental models formulated while taking the TMCT. This qualitative analysis will also provide an opportunity to revise the semi-structured interview procedures and questions before implementation during further data collection.

Finally, we are looking at beginning collecting TMCT data from blind-folded sighted populations. The TMCT could be administered to sighted students in STEM-related fields as a way of measuring spatial skills that is different from tests commonly administered (such as the MCT).

References

[1] W. H. Goodridge, N. L. Shaheen, A. T. Hunt, and D. Kane, "Work in Progress: The Development of a Tactile Spatial Ability Instrument for Assessing Spatial Ability in Blind and Low-vision Populations," presented at the 2021 ASEE Virtual Annual Conference Available: https://peer.asee.org/work-in-progress-the-development-of-a-tactile-spatial-ability-instrument-for-assessing-spatial-ability-in-blind-and-low-vision-populations

[2] D. F. Lohman, in *Spatial Ability*, in Encyclopedia of intelligence, vol. 2. New York: Macmillan, pp. 1000–1007.

[3] J. Wai, D. Lubinski, and C. P. Benbow, "Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance," *J. Educ. Psychol.*, vol. 101, no. 4, pp. 817–835, Nov. 2009, doi: http://dx.doi.org/10.1037/a0016127.

[4] D. H. Uttal *et al.*, "The malleability of spatial skills: A meta-analysis of training studies," *Psychol. Bull.*, vol. 139, no. 2, pp. 352–402, 2013, doi: 10.1037/a0028446.

[5] Members of the 2005 "Rising Above the Gathering Storm"Committee, National Acadmeny of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5*. Washington (DC): National Academies Press (US), 2010. Available: http://www.ncbi.nlm.nih.gov/books/NBK259118/

[6] X. Chen, "STEM Attrition: College Students' Paths into and out of STEM Fields. Statistical Analysis Report. NCES 2014-001," National Center for Education Statistics, Nov. 2013. Accessed: Apr. 13, 2023. [Online]. Available: https://eric.ed.gov/?id=ED544470

[7] C. Hall, J. Dickerson, D. Batts, P. Kauffmann, and M. Bosse, "Are We Missing Opportunities to Encourage Interest in STEM Fields?," *J. Technol. Educ.*, vol. 23, no. 1, pp. 32–46, 2011.

[8] C. A. Supalo, "A Historical Perspective on the Revolution of Science Education for Students Who Are Blind or Visually Impaired in the United States," *J. Sci. Educ. Stud. Disabil.*, vol. 17, no. 1, pp. 53–56, 2013.

[9] T. J. Ashby, W. H. Goodridge, S. E. Lopez, N. L. Shaheen, and B. J. Call, "Adaptation of the Mental Cutting Test for the Blind and Low Vision," presented at the 2018 ASEE Zone IV Conference, Mar. 2018. Available: https://peer.asee.org/29599

[10] N. L. Veurink and S. A. Sorby, "Longitudinal study of the impact of requiring training for students with initially weak spatial skills," *Eur. J. Eng. Educ.*, vol. 44, no. 1–2, pp. 153–163, Mar. 2019, doi: 10.1080/03043797.2017.1390547.

[11] S. Titus and E. Horsman, "Characterizing and Improving Spatial Visualization Skills," *J. Geosci. Educ.*, vol. 57, no. 4, pp. 242–254, Sep. 2009, doi: 10.5408/1.3559671.

[12] K. Papadopoulos, M. Barouti, and E. Koustriava, “Differences in Spatial Knowledge of Individuals With Blindness When Using Audiotactile Maps, Using Tactile Maps, and Walking,” *Except. Child.*, vol. 84, no. 3, pp. 330–343, Apr. 2018, doi: 10.1177/0014402918764300.
[13] F. Leo *et al.*, “Enhancing general spatial skills of young visually impaired people with a programmable distance discrimination training: a case control study,” *J. NeuroEngineering Rehabil.*, vol. 16, no. 1, p. 108, Aug. 2019, doi: 10.1186/s12984-019-0580-2.
[14] V. Crollen, H. Warusfel, M.-P. Noël, and O. Collignon, “Early visual deprivation does not prevent the emergence of basic numerical abilities in blind children,” *Cognition*, vol. 210, p. 104586, May 2021, doi: 10.1016/j.cognition.2021.104586.
[15] N. A. Giudice, “Navigating without vision: principles of blind spatial cognition,” *Handb. Behav. Cogn. Geogr.*, pp. 260–288, Apr. 2018.
[16] O. Lahav and D. Mioduser, “Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind,” *Int. J. Hum.-Comput. Stud.*, vol. 66, no. 1, pp. 23–35, Jan. 2008, doi: 10.1016/j.ijhcs.2007.08.001.
[17] M. Stieff and D. Uttal, “How Much Can Spatial Training Improve STEM Achievement?,” *Educ. Psychol. Rev.*, vol. 27, no. 4, pp. 607–615, Dec. 2015.
[18] S. A. Sorby and B. J. Baartmans, “The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students,” *J. Eng. Educ.*, vol. 89, no. 3, pp. 301–307, 2000, doi: 10.1002/j.2168-9830.2000.tb00529.x.
[19] E. W. Hill, J. J. Rieser, M.-M. Hill, M. Hill, J. Halpin, and R. Halpin, “How Persons with Visual Impairments Explore Novel Spaces: Strategies of Good and Poor Performers,” *J. Vis. Impair. Blind.*, vol. 87, no. 8, pp. 295–301, Oct. 1993, doi: 10.1177/0145482X9308700805.
[20] “CEEB Special Aptitude Test in Spatial Relations (MCT),.” 1939.
[21] S. E. Lopez, W. Goodridge, I. Gougler, D. E. Kane, and N. Shaheen, “Preliminary Validation of a Spatial Ability Instrument for the Blind and Low Vision,” in *Roundtable Session*, San Francisco, CA, Apr. 2020. Available: http://tinyurl.com/qlemtgm