Adaptation of the Mental Cutting Test for the Blind and Low Vision

Abstract

This paper seeks to illustrate the first steps in a process of adapting an existing, valid, and reliable spatial ability instrument – the Mental Cutting Test (MCT) – to assess spatial ability among blind and low vision (BLV) populations. To adapt the instrument, the team is developing three-dimensional (3-D) models of existing MCT questions such that a BLV population may perceive the test tactilely with their hands. This paper focuses on the development of the Tactile MCT (TMCT) instrument and does not report on the use of or results from the new instrument. Future work will investigate the validity and reliability of the adapted instrument.

Each TMCT question is created by modeling and 3-D printing the objects represented by two-dimensional pictorial drawings on the MCT. The 3-D models of 25 items of the MCT are created using a solid modeling process followed by an additive 3-D printing process. The correct answer to each MCT question is the section view defined by a plane-of-interest (POI) intersecting the figure in question. A thin plane extending from the figure identifies the POI of each problem. The possible answers were originally presented in multiple representations including 3-D printed extrusions on top of a thin plate, and two forms of tactile graphics. The 3-D printed answers are developed by a combination of acquiring accurate dimensions of the 3-D figure's cross-section and scaling up the printed paper test.

To improve this adaptation of the MCT instrument, the TMCT models and their respective multiple-choice answers will be inspected by a spatial cognition expert as well as several BLV individuals. Feedback from these individuals will provide insight into necessary revisions before the test is implemented.

Introduction

Spatial ability is a measure of a cognitive capacity dealing with mental modeling of objects in visualized three-dimensional (3-D) space. Spatial ability includes many constructs such as mentally altering the configuration of a given object by rotating or folding, or mentally altering the perspective of the viewer[1]; however, it is often simplified to a single construct for which an assessment has been designed.

Spatial constructs and their respective instruments can be classified in various ways. One classification system, presented by David Uttal, labels spatial constructs as intrinsic or extrinsic and static or dynamic[2]. Intrinsic information refers to how one considers a particular object and all of the object's respective parts. Extrinsic information expands the environment to a group of objects and refers to the relative location of the objects among each other. Static constructs are those which the object and the viewer remain fixed. Dynamic constructs include movement of the objects or the viewer to provide a new perspective or relative position of the environment[4].

Although spatial ability is generally associated with visible objects or environments, its cognitive nature implies that individuals with low or no vision also have measurable spatial ability.

Though sighted individuals may mentally construct spatial models through visual cues, blind and low vision (BLV) individuals construct these models through other sensory input in order to navigate and engage with the inherent spatial nature of the world around them. This difference in spatial interpretation may create differences in methods of spatial ability development or may affect spatial ability levels; however, the potential differences have never been studied.

No spatial ability study has compared spatial ability between a BLV population and a sighted population using an instrument that can be delivered to both, and no literature looks to directly investigate how spatial ability can be improved in a BLV population. Adapting an existing spatial ability instrument provides a trajectory to investigate spatial thinking from a new and informative avenue.

Spatial ability has been shown to be an indicator of success in STEM related fields[3]. In his recent meta-analysis, Uttal stated, "Having good spatial skills strongly predicts achievement … in [STEM] fields. Improving spatial skills is therefore of both theoretical and practical importance[2]." While BLV people can be successful in STEM related careers, they are significantly underrepresented in the field. Thus, it is valuable to improve the spatial skills of these individuals to support them in future STEM related aspirations. To assess and improve spatial ability, it is important to determine how to measure spatial ability in the BLV population, and how an instrument can aid in the development of curricular interventions that enhance the existing spatial ability skills of BLV students.

Spatial ability has also been shown to be a malleable characteristic, and can improve through direct intervention. In much of her work, Sheryl Sorby has demonstrated that spatial ability can be developed through targeted activities[4]. Her work centered on basic technical drawing curriculum delivered to students including instruction on developing multi-view drawings, pictorial drawings, and patterns.

The Mental Cutting Test (MCT) was initially developed in 1939 as a portion of a college entrance exam[5]. More recently, the MCT has been used as an instrument for spatial ability research. The MCT consists of 25 problems to be answered in 20 minutes. As shown in Figure 1, each problem has a dimetric view of an object with a plane of interest (POI) intersecting the object. There are five possible solutions showing cross-sections of the object, or a similar object, and the test taker must select the cross-section that would be revealed by a cut made at the at the point of the intersecting plane shown in the original figure.

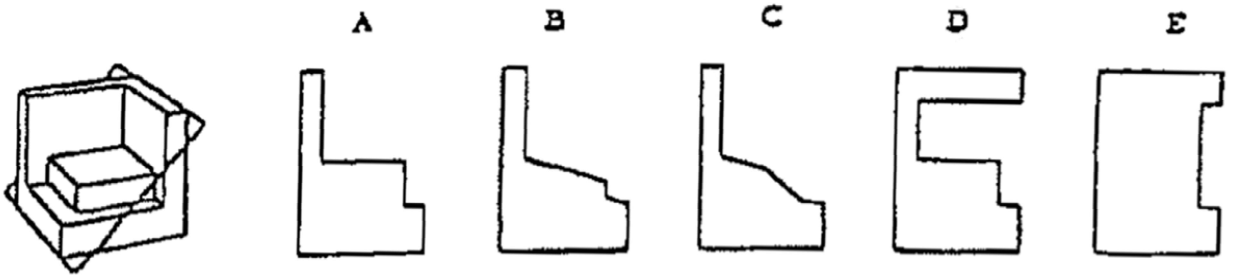


Figure 1. MCT example problem[5]

The MCT has been used as an instrument to measure the development of spatial ability in several studies, including research among college students at Michigan Technical University[1, 6], Utah State University[7], Cracow University of Technology[1], and the University of Kaiserslautern[8]. The consistency of these studies' results indicates the MCT is a valid and reliable instrument to assess a person's spatial ability.

Since the MCT has only been available through visual media, BLV individuals have not been able to participate in the MCT and use it as a measure of spatial ability. Indeed, there are no known spatial ability assessments available to the blind and low vision population at this time. Just as the availability of spatial ability tests and interventions can positively impact sighted individuals, making a spatial ability test available to the BLV population has the potential to open a door to understanding spatial ability in this population on its own and compared to sighted populations. The use of a spatial ability instrument for the BLV population can begin to inform targeted curricular interventions to help BLV students develop their spatial ability, and consequentially increase their preparedness for an engineering-related degree and career.

This work also has possibilities to study spatial ability beyond solely BLV populations. Wood et al, have shown that spatial ability is improved in a typical engineering Statics course but implied that some sighted students struggle in converting 2D represented problems found in typical Statics textbooks to a 3D mental image[7]. Other work has indicated how tactile models can improve sighted student conceptualization of Statics topics[9]. Based on this research, the development of a tactile spatial ability instrument opens a new window towards developing tactile reinforcing engineering interventions that may impact all aspects of engineering education.

Tactile Test Development

The work summarized in this paper is centered on developing a tactile spatial ability test for the BLV population by adapting the MCT to a tactile 3-D representation. A spatial ability expert, a psychometric expert, and experts in the field of blindness, who are blind themselves, are being consulted to provide feedback on the test during the development process. The National Federation of the Blind, a co-PI on the project has contributed to the work significantly by contributing to the conceptualization of the tactile test and facilitating the research team's recruitment of participants.

Initial MCT Adaption

As the MCT is originally available as a 2-D test printed on paper, or presented on a screen, the first step in making a spatial ability test accessible is to add a tactile element. Though the printed lines and sketches could be raised to create a tactile graphic, as is done with some figures such as line graphs in braille textbooks, this was considered a poor conversion due to the complexity of the images that comprise the MCT and the known limitations of raised line tactile graphics. It was determined that a tactile version of the test would be more effective if the objects drawn in 2-D were fully constructed in 3-D to allow individuals to tactually discern the various features of each object.

The MCT figures do not indicate the dimensions of the objects shown, so the object of each problem is measured approximately as printed on standard paper, and scaled up. The MCT figures were generally scaled to fit within a 3-cubic in. space. This size seemed to the authors to be large enough to allow ready perception of all significant details of the object without being so large as to make manufacturing, administration, or perception of the test a cumbersome task. A smaller version of the models was also developed for comparison.

The TMCT objects are modeled in 3-D computer aided design (CAD) software using the approximate scaled dimensions. If the final 3-D modeled object is visibly different from the original, appropriate adjustments are made to correct the object's appearance. The research team used Solid Edge™ to model the problems, but other CAD software can be used for the modeling. The POI was added as a thin rectangular plane extending through the object and one-quarter inch beyond the object edges. Figure 2 shows one TMCT question. For comparison, Figure 1 displays the original MCT drawing of the same question.

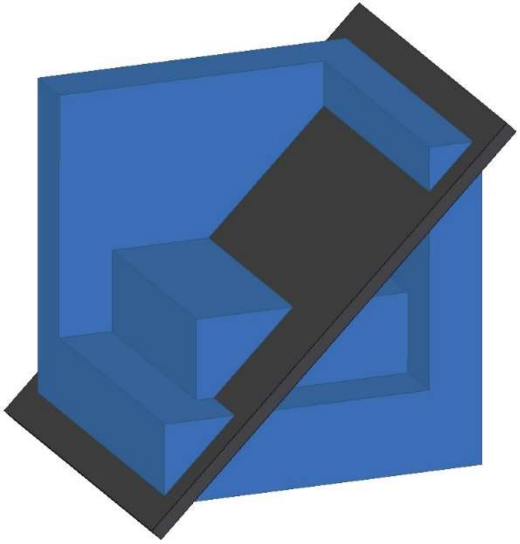
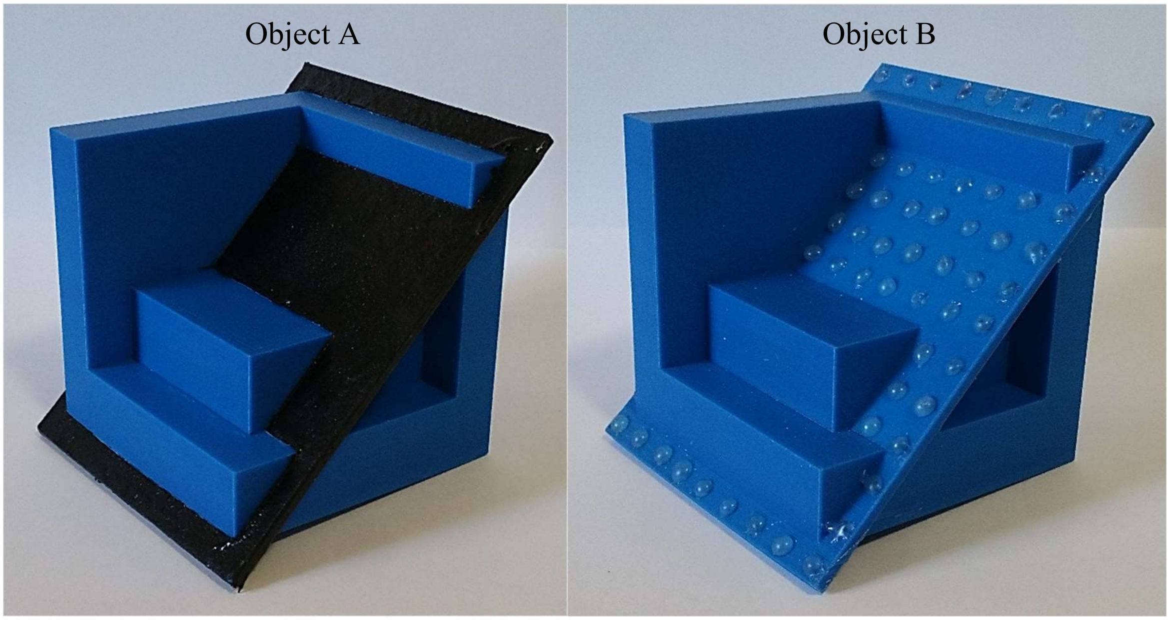


Figure 2. Solid model rendering of TMCT object

To help test-takers identify the POI of the 3-D objects, it was determined that the POI should differ in texture from the body of the object. Although 3-D printers with the capability to print different components with different materials or textures are available, the cost to print this object using separate materials for the body and POI was deemed prohibitive. Therefore, four alternative methods were considered: applying a spray-on rubber to the POI, placing a pattern of small dots of glue on the POI, placing a pattern of small holes on the POI, and printing the object in three parts. The final alternative was implemented to enable printing the POI in a different material or texture.

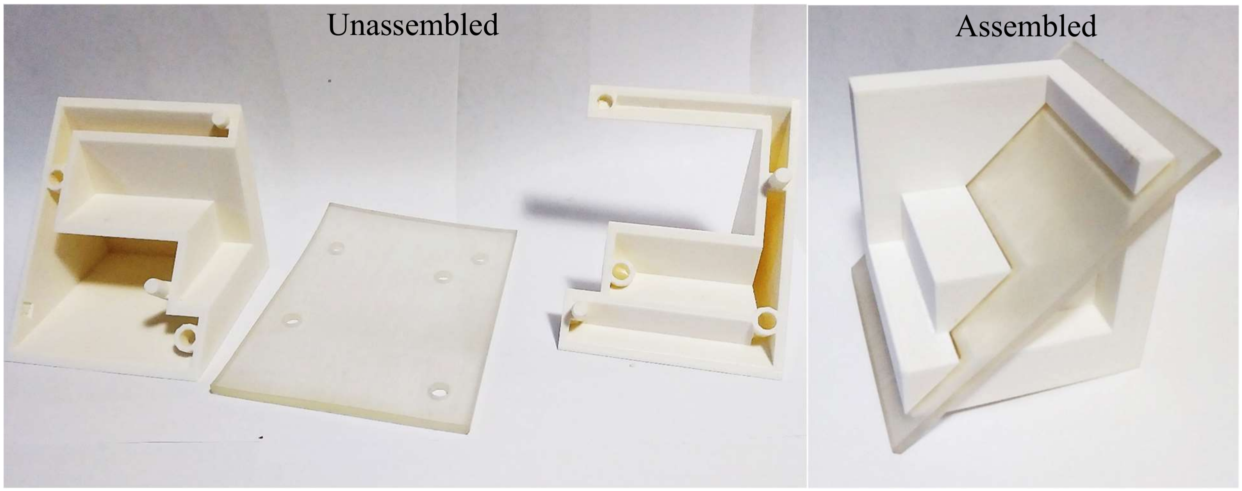
Applying the rubber and the glue methods is simple. The spray-on rubber is applied to the POI after masking the body of the object. At least four coats are sprayed on the entire POI. After the rubber cures, the tape is removed from the body, leaving rubber only on the POI. The glue is applied in a square pattern of dots using a hot glue gun. Figure 3 shows two copies of the same object, one with the POI textured with rubber and the other with the POI textured with glue.

The alternative including three separate parts is modeled such that two parts are on either side of the cutting plane of the POI. These two parts have a series of pegs holes such that they can be placed together. The third part is the POI itself, which can be printed in a rubber material. The three parts are assembled, and the object appears the same as the other alternatives (see Figure 4). Ultimately, the texture type that receives the most positive feedback from the consultants will be selected and incorporated into each of the 25 problems for the final instrument.


Object A

Object B

Figure 3. Photographs of 3-D printed TMCT Objects. Object A has a rubber-textured POI, Object B has a glue-textured POI


Unassembled

Assembled

Figure 4. Photographs of three part 3-D printed TMCT Object before and after assembly.

The possible TMCT answers for each problem are adapted using the section view of the POI intersecting the 3-D model as well as approximate scaled dimensions from the original instrument. The correct answer is identical to the cross-section of the cut determined from the

POI and body of the object within the software model. Scaling is only used to adapt incorrect answers if there is no other method to approximate the dimensions from the software model.

The 3-D answer choices were initially modeled as a one-quarter inch extrusion of the cross-section; however, two of the twenty-five problems have answer choices with more than one detached piece, which would be unstable. To solve this problem, and to keep all answer choices consistent, the team added a one-eighth inch thick base under all answers. This alteration also simplifies the presentation of the answers by creating a uniform footprint for all answer choices.

Tactile graphics answer choices were developed by scaling up the original paper answer choices to a size that matched the 3-D model and 3-D answer choices and printing them using two different tactile graphics technologies. One set of graphics was printed using a braille embosser with graphical capability and another set of graphics was printed using swell paper, which are both commonly used in the BLV community to represent graphical information by creating raised features on a sheet of paper. All three versions of the answer choices were presented to the consultants, and a single answer style will be chosen for the final test based on their feedback.

Test Presentation

To preserve the validity of the MCT, and help the reliability of the TMCT, it was deemed important to administer the test problems in a fixed, consistent layout that matches the MCT as closely as possible. To do this, the research team is developing a testing stand that will secure the 3-D object in a fixed location and orientation and elevate it so that the participant may feel the entire object.

It is expected that a proctor will assist the test taker by arranging the object, its stand, and the answer choices for each problem. The proctor will ensure the test taker has possible answers that correspond with the object the test taker is observing, provide the next test question when the test taker answers the older one, and by keeping track of the running time during the test.

Initially, the original 20-minute time constraint of the MCT will be maintained during pilot testing; however, as is common with other standardized tests, the appropriate time limit for the TMCT is expected to increase because feeling the object and all possible answers may take longer than viewing the original paper test. Initially allowing twenty minutes establishes a comparative starting point for continued adaptation.

Target Population Sampling and Feedback

The research team is currently consulting with the spatial cognition expert and blind or low-vision professionals to find appropriate alterations to the test. These experts have expressed support for the concept of the adapted TMCT, but further feedback on the implementation of the instrument is still sought as the development of the TMCT evolves during the project. Feedback from these consultants will continue to inform iterative improvements on the instrument until it is finalized.

In initial consultation with seven BLV individuals, they affirmed the importance of distinguishing the texture of the cutting plane. Each individual had different preferences, but the printed rubber cutting plane that had been printed in three pieces seemed the most popular, although it was considered somewhat strange and too soft. As for the three styles of answer choices, most participants were able to interpret each of them equally, although the most common preference seemed to be the braille embossed paper.

It was also discovered that a key portion of the test had been omitted during the adaptation. The instructions that describe the process of solving the MCT problems had not been considered carefully, and simply describing the question or reading the instructions was quickly found to be insufficient. The original MCT instructions consist of words as well as multiple example figures that show a problem and the sequential process of cutting the object and rotating the cut plane to reveal the answer shape. The researchers are currently working to adapt the instructions and model the example problems in order to accurately describe how test-takers should interpret the objects and what question they are trying to answer.

Conclusion and Future Implications

The results from using the TMCT have the potential to quantify one construct of spatial ability in a population that has never been studied in this way and is underrepresented in the STEM fields. The results will inform researchers and practitioners about how spatial thinking may be similar and different between sighted and blind or low vision individuals. The capability to quantify spatial ability in a BLV population will allow researchers to understand how their spatial ability may develop.

Furthermore, the work provides a measure that can inform the development of, and assess the impact of interventions designed to improve the spatial ability of BLV populations. Spatial ability is teachable, and, “training in spatial thinking is effective, durable, and transferable[3]”. The durability of spatial ability training means that a single intervention course improves spatial ability long term without sustained training. The transferability of spatial ability training means that training for a specific and isolated task carries over to other innately spatial tasks. This work sets forth an endeavor to facilitate a new arm of research on spatial thinking and spatial ability. Future work looks to further refine the TMCT, assess it for reliability and validity, and use it to assess the impact of spatially related curricular interventions.

Acknowledgements

The author gratefully acknowledges the support of the National Science Foundation for their support of this research through the following grants: DRL-1712887. Several others have been collaborators on this research including: David Uttal, Anne Hunt, Ann Cunningham, and the National Foundation of the Blind.

Disclaimer

This material is based upon work supported by the National Science Foundation under Grant No. 1712887. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation

References

[1] Gorska, R., Sorby, S. A. (2008, June 22-25), “Testing Instruments for the Assessment of 3-D Spatial Skills”, *Proceedings of the 2008 ASEE Annual Conference Proceedings*, Pittsburg, PA.

[2] Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., Newcombe, N. S. (2013, March), “The Malleability of Spatial Skills: A Meta-Analysis of Training Studies”, *Psychological Bulletin*, Vol. 139 Issue 2, pp. 352-402.

[3] Shea, D. L., Lubinski, D., Benbow, C. P. (2001, September), “Importance of Assessing Spatial Ability in Intellectually Talented Young Adolescents: A 20-Year Longitudinal Study”, *Journal of Educational Psychology*, Vol. 93 Issue 3, pp. 604-614, September 2001.

[4] Sorby, S. A., Baartmans, B. J. (2000, July), “The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students”, *Journal of Engineering Education*, Vol. 89 Issue 3, pp. 301-307.

[5] CEEB Special Aptitude Test in Spatial Relations (MCT), (1939), Developed by the College Entrance Examination Board, USA.

[6] Wai, J., Lubinski, D., Benbow, C. P. (2009, November) “Spatial Ability for STEM Domains: Aligning Over 50 Years of Cumulative Psychological Knowledge Solidifies Its Importance”, *Journal of Education Psychology*, Vol. 101 Issue 4, pp. 817-835.

[7] Wood, S. D., Goodridge, W. H., Call, B. J., Sweeten, T. L. (2016, June), “Preliminary Analysis of Spatial Ability Improvement within an Engineering Mechanics Course: Statics”, ASEE Annual Conference & Exposition, New Orleans, Louisiana.

[8] Leopold, C. (2005, July 25-29), “Geometry Education for Developing Spatial Visualisation Abilities of Engineering Students”, *Proceedings of the International Conference on Engineering Education 2005*, Gliwice, Poland.

[9] Mejia, J.A., Goodridge, W. H., Green, C, (2013), “Enhancing Engineering Mechanics - Statics Instruction Using Manipulative Truss Models”, *43rd Annual Frontiers in Education Conference*, Oklahoma City, OK, doi:10.1109/fie2013.6684849