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Quantifying Spatial Skills across STEM Disciplines: A Systematized Literature Review of Assessment Tools

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Introduction

Spatial ability has been broadly defined as an individual's ability to mentally transform, manipulate, and generate well-structured visual information [1], [2]. Numerous applications of spatial ability exist in a variety of settings. Although many constructs of spatial ability have been identified in the literature, researchers have not agreed upon a set list of defining constructs [3]. Constructs of spatial thinking that are commonly discussed in the literature include mental rotation, spatial visualization, and spatial orientation. This paper refers to spatial ability as a quantification of performance on specific constructs of spatial thinking.

Much work has been conducted to demonstrate the positive effect spatial thinking has on student performance in Science, Technology, Engineering, and Mathematics (STEM) fields [4], [5], [6], [7]. Specific areas in which studies have found significant correlations between academic success and spatial thinking include engineering [7], mathematics [8], geometric problem solving [9], geology [10], chemistry [11], and biology [12]. Spatial ability has also been linked to increased retention in undergraduate STEM programs [13]. Further work has also shown that, in addition to academic settings, spatial skills have a positive impact on professionals in STEM fields [14].

Past research has revealed a gender gap in individuals' spatial ability, with males typically demonstrating higher spatial ability, especially when measuring the spatial construct of mental rotation [15]. Gender gaps in spatial ability represent the largest gender gaps out of any cognitive ability [16]. Spatial ability may be one reason for the underrepresentation of women in STEM fields and is likely partially linked to differences in experiences between genders as they work with factors that have an impact on specific spatial constructs. Focusing on improving spatial ability in women, provides experiences that can help close spatial performance gaps and foster greater gender inclusivity in STEM fields [13]. This can help fulfil the goal of giving women and minoritized groups greater representation in STEM fields [17].

Spatial skills are malleable, meaning that they are able to be improved and maintained through targeted intervention [18]. For this reason, much effort has been put into creating coursework that increases students' spatial ability [10], [19], ultimately bringing about greater equity in STEM programs. Spatial ability research often utilizes pre/post testing to measure the effectiveness of specific interventions. This approach requires the use of proper instrumentation to measure gains in spatial ability. Throughout the history of spatial ability research, various instruments have been created to measure one or more construct of spatial thinking. Common instruments include the Mental Cutting Test (MCT) which measures constructs of mental rotation and spatial visualization, and the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R) which measures mental rotation.

Throughout recent years, a large number of new or adapted spatial ability instruments have been developed to reflect more diverse populations involved in spatial ability research. This systematized literature review provides a synthesis of how valid and reliable spatial ability instruments measure specific constructs of spatial thinking. This work is guided by the following research questions.

1. How do existing spatial ability tests measure spatial thinking?

2. How do spatial ability instruments available in the literature demonstrate validity and reliability?

Positionality Statement

The first author is a graduate student in civil engineering and engineering education who has over five years of research experience in the field of spatial ability. Although the first author is sighted, much of the work the author has done has focused on helping members of the blind and low vision community develop spatial skills, engineering knowledge, and improve their spatial ability. Throughout the course of his work studying spatial ability in BLV populations, the author has developed an interest in making engineering education more accessible for all populations, and particularly for those with physical disabilities that negatively impact their ability to participate in engineering education. The author is also interested in improving engineering curriculum for first and second year undergraduate engineering students to include more activities that involve spatial thinking which will prepare them for higher level courses that involve more spatial material.

The second author is an Associate Professor with training in fluid mechanics and hydraulics. He has extensively researched spatial ability and spatial thinking in students interested in or currently engaged in engineering training programs. Of particular interest is the author's desire to work with blind and low vision students looking to develop engineering knowledge or pursue an engineering degree. While also sighted, the author has engaged in work with the National Federation of the Blind and has had the privilege of learning from and the benefit of working with many blind and low vision professionals to try to develop engineering centered and spatial ability enhancing curriculum. The author is a passionate "teacher" who loves to open learning opportunities for anyone who is interested in the engineering disciplines.

The third author is a military veteran and licensed mechanical engineer who currently serves as an associate professor of engineering education. Her experiences instructing evening undergraduate engineering courses for rural, adult, and working students ultimately compelled her to earn a doctoral degree and conduct research in the field of engineering education. The third author centers issues of access, equity, and identity in her research for the purpose of advancing an inclusive engineering education ecosystem. While sighted, she seeks to understand the ways in which intersectional, underserved identities affect the formation of engineers, and to develop and implement new strategies for realizing a diverse engineering workforce.

Methods

Literature pertaining to spatial ability instruments was identified on the Scopus database as well as ERIC via EBSCOHost and reviewed using guidelines presented by Borrego, Foster, and Froyd in their introduction of systematic literature reviews to the field of engineering education

[20]. Search terms included three components. The first component included a variety of terms to describe spatial ability. The second component required results to focus on instrumentation, and the third component required search results to include discussion of validity and reliability. An initial search of each database using these search terms yielded 57 papers on Scopus and 34 on ERIC. To further narrow the scope of the review the following inclusion criteria were applied to the search process:

1. The paper was peer reviewed
2. The paper was published between 2013 and 2023
3. The publication appeared in an academic journal or conference proceedings
4. The paper was published in English
5. Instruments discussed in the paper had some reported measure of validity and reliability

Criterion 1-3 were applied to the search process to ensure results reflect current research that has been conducted within the past ten years and that the studies are academically sound. Papers were required to be published in the English language such that the reviewer could interpret results in their native language. Instruments were required to be validated and have demonstrated sufficient reliability and both were reported in literature on the instrument. It is vital to the study of spatial ability that instrumentation truly measures one or more specific constructs of spatial ability rather than an unrelated cognitive ability.

Abstracts for the 91 initial results were examined against the five inclusion criteria to identify papers that were applicable to the research questions. After a review of the abstracts, 12 full papers were selected for inclusion in the review. All full papers that were selected for the review were organized in a literature coding table which included columns for the article title, reference, name of instrument, spatial ability constructs measured, population type, sample size, validity measures, reliability measures, and a short summary of the article. Synthesized results regarding spatial ability constructs, validity, and reliability are contained in the findings section. Populations studied in the selected articles ranged from children to adults and were comprised of individuals of multiple nationalities. One study had a sample size of only 67 individuals, however, the majority of studies had well over 100 participants.

Limitations

One limitation to this review is the lack of standard measures of validity and reliability across all of the instruments reviewed. Although each publication reported that their associated spatial ability instrument was valid and reliable, it is difficult to compare instruments against each other without a standard statistical measure of reliability such as Cronbach’s alpha or McDonald’s omega. Furthermore, due to the variety of spatial ability instruments that have been developed for a wide range of applications, it is impossible for this review to give a comprehensive overview of the existing instrumentation or associated constructs of spatial ability. This review of articles in the Scopus and ERIC databases reflects only a fraction of the available articles regarding spatial ability instruments.

Findings

Spatial ability instruments from the literature were grouped based on the constructs of spatial ability they measure. Six major spatial ability constructs that were prevalent in the papers include perspective taking, cross-sectional visualization, mental rotation, visuospatial memory, and orientation and navigation. Seven of the thirteen instruments reportedly measure multiple constructs of spatial ability.

Table 1. Reviewed instruments with constructs of spatial ability that they measure.

	Perspective Taking	**Cross-Sectional Visualization**	**Mental Rotation**	**Visuospatial Memory**	**Orientation and Navigation**
Ghost Rotating PC			X		
Perspective PC	X				
MCQ		X	X		
VSAT	X		X		
AISAT			X		
VSAD				X	X
TMCT		X	X		
SASRS				X	X
Spatial Ability Test - University	X		X		
SBST		X			
Spatial Ability Test – Middle School	X		X		X
Revised MRT			X		
3D-MR			X		

Perspective Taking

Perspective taking is related to mental rotation but is distinct in that rather than the object being rotated, the viewpoint of the observer is moved to a new location. In the case of the Perspective PC test designed for children [21] and the spatial ability test designed for middle school students [22], three-dimensional objects representing simple shapes such as cubes, cones, and cylinders are shown with a model camera pointed towards the objects. Four images of the 3D objects are then given which could represent the perspective of the camera. The object of each question is to determine which of the four perspectives matches the view from the camera. In a similar way, the VSAT test [23] gives an isometric view of similar 3D objects of differing colors and textures with five potential options for overhead views of the given isometric view. The spatial ability test for university students [24] presents an isometric view of a 3D object and asks for the 2D view from the rear perspective of the 3D object. These tests are similar in that they each measure perspective taking and the Perspective PC and VSAT tests allow for color recognition between views. However, the VSAT may be less difficult due to the answer choices all representing one overhead view whereas the other tests include perspective drawings from a variety of angles.

Cross-Sectional Visualization

Cross-sectional visualization relates to the ability to visualize the two-dimensional shape that would be revealed by cutting a three-dimensional object along a certain plane or the ability to identify a 3D object based off a 2D cross section. The MCQ assessment was created to assess the spatial ability of anatomy students who often deal with cross-sections [25]. The MCQ provides subjects a photograph of a 2D surface of a canine limb and asks questions about where on the limb the cut was made. Successful completion of the assessment requires both spatial ability and an understanding of anatomy. The TMCT test [26] was developed as an adaptation of the commonly used Mental Cutting Test. The TMCT is designed for members of the blind and low vision community. Test takers are given a three-dimensional object with a paper plane bisecting the object. The purpose of the test is to determine the 2D cross sectional shape of the 3D object at the interface of the paper plane. Five shapes are provided in a tactile format in a binder that could represent the cross-sectional shape. In a similar manner, the Santa Barbara Solids Test (SBST) [27] provides an illustration of one or more 3D objects joined together with a plane intersecting it. Like the TMCT, there are multiple 2D shapes that could represent the cut surface. These instruments represent the two major types of cross-sectional visualization assessments. The MCQ gives a 2D prompt while the TMCT and SBST provide a 3D shape and expect the test taker to identify the 2D shape.

Mental Rotation

Mental rotation refers to the ability to imagine how a particular shape would appear if it were rotated in a certain direction. Of all the identified constructs of spatial ability, mental rotation is one of the most commonly used measures of spatial ability in published instruments. Nine of the instruments reviewed in this paper measure mental rotation.

Eight of the instruments that measure mental rotation provided test takers with an image and multiple illustrations that could represent a rotated depiction of the original image. The AISAT test [28] was developed for use with architect students and provides a sample drawing typical of what may be used in architecture and asks test takers to determine which of the given representations is a rotated version of the original drawing. Similarly, the VSAD test [29] was developed for children with vestibular impairment and requires subjects to view a drawing of a shield with certain marks and determine which of the given rotated shield drawings represents a rotated version of the original. The spatial ability test for middle school students presents similar figures with unique identifying marks in 2D with four possible answers. 3D rotation tasks are also included in the same format [22]. The Ghost Rotation Task [21],VSAT [23], and Revised Mental Rotation Test [30] were developed with children as their target audience. Each test operates similar to the VSAD test but the VSAT test begins with a 3D object and requires participants to rotate it from the isometric view to a top view and in some cases more rotation is required after mentally rotating the shape to the top view. The TMCT [26] requires mental rotation to align the cutting plane with the 2D outline answer choices. However, due to the tactile nature of the test, subjects may be able to physically align the 3D model with the answer choices, reducing the need for mental rotation. The 3D-MR test [31] was also developed as a tactile test with children as a target audience. The test is similar to other mental rotation tests such as the spatial ability test for university students [24] where the taker is required to match which of several blocks is an identical rotated version of a reference block. However, the 3D-MR test uses physical blocks rather than illustrated 3D blocks. Finally, the MCQ spatial-anatomy test [25] contains items that require mental rotation in tandem with an understanding of anatomy. Mental rotation items on the MCQ provide photographs of 3D anatomical structures and requires subjects to identify both the name of the structure and the proper view such as the caudal or cranial view. Although the methods of mental rotation vary from test to test, each assessment requires test takers to internalize the structure of a certain shape and identify an identical shape in a different orientation.

Visuospatial Memory

Visuospatial memory refers to the ability to internalize and retain spatial information over time. The SASRS was developed as a self-report test to assess spatial ability [32]. Rather than giving subjects specific imagery, the SASRS asks questions such as “I immediately forget the faces of people I have met” to assess spatial memory. The visuospatial memory section of this instrument was included based on the fact that in order to have good spatial ability, subjects need to have good memory. The VSAD test was designed for children with vestibular impairments and is not a self-report scale like the SASRS test. However, it tests the ability to remember spatial information by having the children replicate a sequence of movements that is shown to them prior to completing the visuospatial memory items.

Orientation and Navigation

Orientation and navigational abilities refer to a person’s ability to understand where they are in relation to reference points and move to desired locations using those reference points. The SASRS test which relies on takers’ honest assessment of their abilities asks questions such as “I can visualize the shortest route on the streets that I travel. [32]” Results from this test may be biased due to the test takers’ perceptions of their ability. The VSAD test [29] also contains a portion dedicated to spatial orientation where students are required to complete twelve different mazes and receive a score based on the how short of a line they are able to complete the maze with and how many errors they make. The orientation section of the spatial ability test for middle school students [22] requires students to mentally situate objects in a coordinate system and provide directions to other objects in reference to the original object. Each of these tests measure the ability to optimize routes and travel the shortest distance possible between features.

Validity and Reliability

Inclusion criteria 5 requires that all articles discuss the instrument’s validity and reliability in order to ensure quality of the assessment. Measures of validity in each article ranged from cross-validation with other common instruments to confirmatory factor analyses. The majority of studies used Cronbach’s alpha as a quantification of reliability. Tables 2 and 3 present a compilation of validity and reliability measures respectively for each instrument.

Table 2. Methods of validating each instrument.

	Content Validity	**Construct Validity**	**Concurrent Validity**
Ghost Rotating PC		Factor analysis	Cross-validated with classical test
Perspective PC		Factor analysis	
MCQ	Examined by experts	Factor analysis	Cross-validated with three classical spatial ability tests
VSAT	Examined by experts		
AISAT	Examined by experts		Compared with spatial design performance
VSAD			Cross-validated with four classic tests
TMCT		Inherited from MCT test	
SASRS	Examined by experts	Exploratory factor analysis	Cross-validated with MRT test
Spatial Ability Test - University	Examined by experts	Factor analysis and examination of difficulty, discrimination, and item-total correlation	
SBST			Cross-validated with classical test
Spatial Ability Test – Middle School	Examined by experts	Factor analysis	
Revised MRT	Examined by experts	Factor analysis and inherent validity from MRT	Cross-validated with SPM test
3D-MR			Cross-validated with 2D version of test

Table 3. Instrument reliability.

	Cronbach's Alpha	**Rasch Reliability**	**Separation Index**	**ICC**	**KR-20**	**Spearman-Brown**
Ghost Rotating PC	0.86					
Perspective PC	0.9					
MCQ					0.63	
VSAT		0.87	2.60			
AISAT	0.6 – 0.81					

VSAD				0.39 – 0.91		
TMCT	0.88					
SASRS	0.88					
Spatial Ability Test - University					0.775	0.798
SBST	0.82					
Spatial Ability Test – Middle School	0.802					0.561
Revised MRT					0.75	0.74
3D-MR	0.71					

Implications

While many of the instruments reviewed in this report measure multiple constructs of spatial ability, there are very few that measure singular constructs. Continued work developing instrumentation to measure singular constructs of spatial ability could help both teachers and researchers assess specific abilities that could be difficult to isolate when using instruments that measure multiple constructs. Furthermore, the majority of papers contained in this review discuss instruments that measure mental rotation. While mental rotation is an important element of spatial ability, it would be advantageous for researchers to develop instruments that measure lesser-known but significant constructs of spatial ability such as proportion, pattern development, or mechanical reasoning. For example, mechanical reasoning could be measured through the design of rotating interlocking gears. A correct assessment of multiple specific constructs of spatial ability could help teachers of engineering determine appropriate interventions to teach students based on their current spatial ability. This would, in turn, prepare students for course material that requires significant spatial skills. Tactile Spatial Ability instruments can also continue to be developed that align to the same spatial constructs thus opening more venues of investigation that focus on different senses' capabilities of inputting spatial stimuli.

Conclusion

This review of the literature indicates that spatial ability can be manifest in a wide variety of applications. Likewise, a wide variety of spatial ability instruments have been created or adapted to measure specific constructs of spatial ability for particular domains. This review indicates the variety of methods that can be used to measure a single construct of spatial ability and the need for instrumentation that goes beyond measuring common constructs of spatial ability such as mental rotation. Additionally, instruments focusing on non-sighted methods of spatial thinking could expand our understanding of how spatial information is used. This review underscores the importance of the development of a variety of spatial ability instruments to meet the needs of researchers and educators across all disciplines of STEM education.

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