With No Universal Consensus, Spatial System Perspective Affects Model Fitting and Interpretation for Mathematics

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Abstract

Although numerous studies have linked spatial ability and spatial anxiety to mathematics, there is little consensus in the research community about these constructs' exact nature and factor structure. This study demonstrates the impact of spatial ability and spatial anxiety perspective selection on predicting a geometry assessment score. The results of the spatial ability models indicated that specific factors of mental rotation and non-rotational spatial visualization, the broad factor of small-scale ability, and a unitary spatial structure were significant predictors of geometry assessment performance. For the spatial anxiety perspective models, only the specific factor of mental manipulation was a significant predictor. These findings suggest that different spatial system perspective selections may lead to different results and interpretations.

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Over the past several decades, researchers have found a strong connection between spatial abilities and mathematics performance (Young et al., 2018). Numerous studies have demonstrated that spatial ability is critical for many domains of mathematics education, including geometry (Battista et al., 2018). Difficulties in observing spatial ability in practice have spurred substantive research focused on uncovering the nature of spatial ability and its sub-components. Factor-analytic studies throughout the last 100 years have sought to determine if spatial ability exhibits a unitary structure or if it is more likely composed of various sub-factors (e.g., Buckely et al., 2018; Carroll, 1993; Kozhevnikov & Hegarty, 2001; Spearman, 1927; Thurstone, 1950). Attempts to define and classify spatial sub-components relate mainly to psychometric indices and the associations between test item performance characterizing spatial skills and are often not clearly grounded in accepted definitions, theoretical bases, or interpretations of findings in the field (Uttal et al., 2013). Like spatial ability, spatial anxiety may also consist of sub-components. However, the number and type of sub-components differ across studies (Lyons et al., 2018; Malanchini et al., 2017).

Theoretical Framework

Spatial Ability

Spatial ability can be broadly defined as the ability for an individual to imagine, retain, and manipualte visuospatial information and relations. Since the earliest conceptualization of spatial ability and its multifaceted nature (Galton, 1879), the communities of researchers studying spatial ability have yet to settle on one complete definition or a complete list of its subcomponents. Spatial ability has been investigated using factor analytical methods that sought to map the structure of the intellect (Spearman, 1927). These early studies identified spatial ability as one factor separate from general intelligence that operates on spatial or visual images mentally. Attempts to dissociate factors were often met with difficulty due to differing factor analysis techniques and spatial ability tests (D'Oliveria, 2004). The subsequent lack of cohesion in this field of study led to different camps of researchers adopting contradictory names for spatial sub-components (Cooper & Mumaw, 1985) and conflicting factorial frameworks (Yilmaz, 2009).

Proponents of broader categorical distinctions between spatial ability sub-components argue that many traditional factor structures of spatial ability relied on exploratory factor analysis rather than a clear theoretical basis of spatial ability (Uttal et al., 2013). In the last quarter of the 20^{th} century, researchers have argued for several theoretical distinctions, including those between allocentric and egocentric perspectives (Kesner et al., 1989) and categorical and coordinate representations (Kosslyn et al., 1989). Recently, other lines of thought have argued for a partial dissociation between *large-scale spatial abilities* and *small-scale spatial abilities* (Hegarty et al., 2018). These studies define large-scale spatial abilities as those requiring physical navigation through space (e.g., navigating a new environment), while small-scale spatial abilities require mental transformations of shapes or objects (e.g., mental rotation tasks). Other lines of research have drawn on linguistic, cognitive, and neuroscientific research to develop a 2x2 classification system that distinguishes between intrinsic and extrinsic information and static and dynamic tasks (Newcombe & Shipley, 2015: Uttal et al., 2013).

In contrast to the aforementioned understandings of spatial ability scholars, there is evidence for a competing view that spatial ability may be a unitary construct. A recent study by Malanchini and colleagues (2020) presents evidence supporting a unitary model of spatial ability

(SA) and the existence of a common genetic network that supports all spatial abilities. The authors administered 16 spatial tests clustered into three main sub-components: *Visualization* (V), *Navigation* (N), and *Object Manipulation* (OM) and conducted a series of confirmatory factor analyses to fit a one-factor (SA), two-factor (N & OM), and three-factor models (V, N, and OM). Results indicated that the best fitting model was the one-factor model. These results held even when accounting for general intelligence.

Spatial Anxiety

Though some scholars may argue that low levels of general anxiety are essential for neurocognitive performance, high anxiety levels may reduce neurocognitive performance (Derakshan & Eysenck, 2010; Meyers et al., 2013). Domain-specific trait anxiety refers to the individual differences in tendencies to experience anxiety in response to the anticipation of a threat, while state anxiety refers to a temporary response to a perceived threat (Spielberger, 1966). High levels of trait anxiety are associated with reduced efficiency on tasks with both high and low working memory load (MacLeod & Donnellan, 1993). For example, mathematics anxiety predicts low mathematics performance even when controlling for other anxiety factors such as test anxiety (Lukowski et al., 2019). Thus, it is possible that the effect of spatial anxiety when faced with spatial tasks could affect spatial performance similarly.

Lyons and colleagues recently defined spatial anxiety as the "fear and apprehension towards spatial processing" (pg. 527, 2018). Spatial anxiety and spatial ability are negatively correlated (Malanchini et al., 2017), with studies showing higher scores on spatial anxiety assessments were related to lower performance on spatial puzzle tasks (Ramirez et al., 2012) and a reduced sense of direction (Hund & Minarik, 2006; Kremmyda et al., 2016; Lawton, 1994). Additionally, children showed reduced spatial skill gains when their teachers reported higher spatial anxiety (Gunderson et al., 2013). Thus, spatial anxiety may hinder opportunities for developing spatial skills.

Spatial anxiety, like spatial ability, appears to be composed of sub-components. One study of nineteen 21-year-old twin pairs identified two spatial anxiety components: *navigation anxiety* and *rotation/visualization anxiety* (Malanchini et al., 2017). However, Lyons and colleagues identified three sub-components of spatial anxiety (*mental-manipulation*, *navigation,* and *imagery*; Lyon et al., 2018). Like with spatial ability, there may be a lack of cohesion in the field of spatial anxiety.

Thus, our two main research questions are: (RQ1) What is the impact of spatial ability perspective selection?; and (RQ2) what is the impact of spatial anxiety perspective selection?

Methods

As part of a larger study, undergraduates (N=131) from a large Mid-Western institution completed a collection of surveys and assessments on geometry, anxiety, and spatial ability. It should be noted that this year of data collection coincided with the 2020 Covid-19 pandemic,and consequently, all participants completed surveys virtually through Qualtrics . Inclusion criteria for this study were fluent English production and comprehension and completion of all covariate measures of interest.

Measurements

The measurements applied in this study are as follows. See Table 1 for descriptive statistics and Table 2 for psychometric properties.

Demographic Information. A range of demographic information included are age, gender, linguistic background, and ethnicity.

Geometry Assessment. A Shortened Version of the *Diagnostic Geometry Assessment* (DGA, Masters, 2010) is a reliable (κ_{Total}=0.65) and validated 11-item instrument that assesses learners' domain knowledge of three major concepts in geometric thinking: (1) Properties of Shapes, (2) Measurement, and (3) Geometric Transformations. Correct and answers were scored 1 point, and partially correct answers 0.5 (e.g., selecting choice A, when A and D were both correct).

Spatial Ability Measure. A Truncated version of the *Spatial Reasoning Instrument* (SRI, Ramful et al., 2017). This 15-item assessments includes 3 sub-scales: (1) Spatial orientation (SO, i.e., extrinsic/allocentric/large scale), (2 & 3) non-rotational spatial visualization (SV) and mental rotation (MR) intrinsic/egocentric/small scale). Scoring is summative (1 point per question) and pilot reliability (N=101) was κ_{Total}=0.75, κ_{SO}=0.71, κ_{SV}=0.79, and κ_{MR}=0.78.

Novel Spatial Anxiety Scale. This 24-item 5-point Likert scale assessment measures participants' anxieties across three sub-scales: (1) mental manipulation (MM), (2) navigation (N), (3) imagery (I) (Lyons et al., 2018). Moderate positive correlations between the sub-scales allow each to be considered separate constructs. External reliability was established with significant unique negative relationships between each anxiety subscale and established measures of ability/attitudes in the respective subdomain of spatial processing and internal reliabilities are κ_{MM}=0.88, κ_{N}=0.86, κ_{I}=0.81, κ_{Total}=0.92.

Results and Discussion

For our analyses, we used Ordinary Least Squares (OLS) regression to predict geometry assessment scores with participant gender and age as fixed effects (following Lawton,1994; Maeda & Yoon, 2013, Voyer et al., 1995).

RQ1: Spatial Ability Perspectives

We calculated three separate multiple linear regression models to predict geometry knowledge scores based on the types of spatial ability perspectives (specific, broad, and unitary) controlling for age and gender (Table 3). While no significant age or gender effects were found in any model, at least one spatial ability factor was significantly predictive of geometry knowledge scores overall. Slight model differences demonstrated how different interpretations of significant associations depend on the choice of initial perspectives.

The specific factor structure model (Model 1, Table 3) breaks spatial ability into three categories: *spatial orientation (SO)*, *non-rotational spatial visualization (SV)*, and *mental rotation (MR)*, based on the definitions and question types presented by Ramful and colleagues (2017). SV and MR were both significantly associated with geometry knowledge scores (p = .014 and p = .008, respectively; cf. Model 2 in Schenck & Nathan, 2020). However, there is no consensus on the definition of spatial ability or its sub-components (e.g., Carroll, 1993; Lohman, 1988; McGee, 1979; Yilmaz, 2009). Critics of specific factor structures have posited that spatial tasks cannot be mapped to one factor as they require combinations of spatial skills and problem-solving techniques (Okamoto et al., 2015); thus, interpretation of these findings is limited.

For the broad factor structure model (Model 2; Table 1), spatial ability was broken into two categories: *small-scale* (SS) and *large-scale* (LS) abilities (see Hegarty et al., 2018) that also aligns closely with intrinsic/extrinsic distinctions (Newcombe & Shipley, 2015) and egocentric/allocentric perspectives (Kesner et al., 1989). In this model, SS was significantly associated with geometry knowledge scores while LS was not (p < .001 and p = .698, respectively). Corroborated by previous studies (e.g., Mix et al., 2018; Schenck & Nathan, 2020), the results may provide researchers with more specificity about the relationships between spatial ability and mathematics. However, some proponents of the small-scale and large-scale distinctions recommend that LS are more reliably measured through navigation activities than through pen-and-paper assessments like those used in this study (Hegarty et al., 2018). It may be that the large-scale spatial ability factor was not measured with validity, which impacts the results of the model. Researchers selecting a broad factor analytic structure should consider these validity concerns in their study designs and analyses.

In the unitary factor structure model (Model 3; Table 1), spatial ability scores were significantly predictive of geometry assessment scores ($p < .001$), aligning with prior studies on the association between spatial ability and mathematics (e.g., Davis, 2015; Newcombe, 2013). However, it does not suggest any specific association, and the assessment used combined several specific spatial factors. Thus, the spatial-math association could be different or insignificant if a different set of questions or standardized measures for a specific spatial ability skill were used.

RQ2: Spatial Anxiety Perspectives

We fit two separate multiple linear regression models to predict geometry knowledge scores based on spatial anxiety perspectives (unitary and specific) while controlling for age and gender. As with spatial ability, no significant age or gender effects were found in either model (Table 4).

Model 1 used a unitary factor structure of spatial anxiety that was not significantly associated with geometry knowledge scores ($p = .299$). However, when spatial anxiety was broken into three subscales (mental manipulation (MM), navigation (V), and imagery (I)), MM was a significant predictor of geometry knowledge ($p = .028$). Every one-point increase in the MM was associated with a 0.06 point decrease in geometry knowledge scores. Spatial anxiety is still an emerging construct. Thus, guidance for best usage of this measure as a single composite score or a series of subscores is still in flux.

Significance

Investigating spatial ability requires selecting theoretical perspectives and analytic approaches that are appropriate for one's research goals. Researchers may select specific spatial measures based on practical rather than theoretical considerations, such as study time constraints and usage in prior studies. The current post hoc analysis is limited in that it was not designed a priori to test the effects of design decisions on theoretical perspectives, experimental methods, and measurements. Still, the current analysis demonstrates ways these decisions can influence study outcomes, as when specific sub-factors of spatial ability and anxiety are more strongly associated with certain subdomains of mathematics than others (Delgado & Prieto, 2004; Schenck & Nathan, 2020). These design considerations are often tacit or neglected by researchers, even though they may dramatically impact a study's findings. Moreover, the abundance of spatial system perspectives and the lack of consensus make it difficult for researchers to select an appropriate perspective and anticipate possible limitations that may affect outcomes, interpretations, and recommendations for future educational practices and policies. Future work will strive to develop a framework to help researchers navigate design and analytical decisions for spatial system perspectives in their work.

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Tables

Table 1

Demographic Characteristics of Participants (N = 131)

Variables	Mean (SD)	N (%)
Age	20.26 (2.73)	
Sex		
Male		45 (34%)
Female		85 (65%)
Other		1 (1%)
Ethnicity		
White (Non-Hispanic)		81 (62%)
Asian		36 (27%)
Other		14 (11%)
Native Language, English		108 (82%)

Note. SD = standard deviation.

Table 2

Psychometric Properties from Cognitive Tasks (N = 131)

Variables	Mean	SD
Geometry Assessment [11]	9.75	1.50
Spatial Ability Measure [15]	12.56	2.11
Spatial Orientation [5]	4.86	0.39
Non-Rotational Spatial Visualization [5]	4.02	1.04
Mental Rotation [5]	3.69	1.32
Novel Spatial Anxiety Scale [96]	38.69	15.90
Mental Manipulation [32]	10.21	5.88
Navigation [32]	13.84	7.38
Imagery [32]	14.72	6.98

Note. SD = standard deviation. [m] reflects the maximum score. For the geometry and spatial ability assessment, higher scores indicate better performance. For the spatial anxiety measure, higher score indicates higher self-rated anxiety.

Table 3

Results of the OLS Regression Predicting Geometry Knowledge with Spatial Ability

Variables	β	SE	p-value	
Model 3: Specific Factor Structure				
(Intercept)	6.363	1.860	.000	***
Age	0.007	0.046	.871	
Male[a]	0.160	0.274	.561	
Other[a]	1.306	1.475	.378	
Spatial Orientation	0.144	0.354	.684	
Non-Rotational Spatial Visualization	0.334	0.134	.014	*
Mental Rotation	0.306	0.114	.008	**
Model 2: Broad Factor Structure				
(Intercept)	6.428	1.790	.000	***
Age	0.008	0.046	.865	
Male[a]	0.150	0.264	.570	
Other[a]	1.317	1.467	.371	
Small-Scale Spatial Ability[b]	0.319	0.067	.000	***
Large-Scale Spatial Ability[c]	0.134	0.344	.698	
Model 3: Unitary Factor Structure				
(Intercept)	5.754	1.180	.000	***
Age	0.006	0.046	.898	
Male[a]	0.152	0.263	.564	
Other[a]	1.473	1.429	.305	
Spatial Ability	0.304	0.059	.000	***

Note. SE = standard error.

[a]"Female" is the reference group.

[b]Small-Scale Spatial Ability is the combined Non-Rotational Spatial Visualization and Mental Rotation scores.

[c]Large-Scale Spatial Ability is Spatial Orientation Score.

*$p < .05$, **$p < .01$, ***$p < .001$.

Table 4

Results of the OLS Regression Predicting Geometry Knowledge with Spatial Anxiety

Variables	β	SE	p-value	
Model 1: Unitary Factor Structure				
(Intercept)	9.922	1.112	.000	***
Age	0.004	0.050	.943	
Male[a]	0.280	0.287	.331	
Other[a]	1.450	1.567	.356	
Spatial Anxiety	-0.009	0.009	.299	
Model 2: Specific Factor Structure				
(Intercept)	9.694	1.109	.000	***
Age	0.012	0.050	.807	
Male[a]	0.204	0.287	.489	
Other[a]	1.067	1.532	.497	
Mental Manipulation	-0.063	0.027	.028	*
Navigation	0.017	0.021	.436	
Imagery	0.009	0.022	.675	

Note. SE = standard error.

[a]"Female" is the reference group.

**p* < .05, ****p* < .001.