Do All Science Disciplines Rely on Spatial Abilities? Preliminary Evidence from Self-Report Questionnaires

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Abstract. Spatial abilities are correlated with success in science. However, research on this topic has not focused on possible differences in the spatial demands of different scientific fields. Furthermore, there is a partial dissociation between spatial abilities involved in dealing with the space of environments (large-scale spatial abilities) and those involved in dealing with the space of objects (small-scale spatial abilities). We used on-line self-report measures to collect preliminary data on the spatial abilities of scientists in different fields, as well as humanists and individuals in professional fields. Geoscientists had the highest self-report ratings of both environmental and small-scale spatial abilities, whereas geographers had relatively high self ratings of environmental spatial abilities and engineers had relatively high self ratings of small-scale spatial abilities. Other scientific disciplines did not differ from the mean in self reported spatial abilities. Self ratings of verbal ability were uncorrelated with self ratings of spatial abilities and, as expected, were highest for humanities specialists.

Keywords: spatial ability, visualization, scale, science disciplines, STEM fields

1 Introduction

Spatial thinking appears to be central to many scientific domains. For example, geologists reason about the physical processes that lead to the formation of structures such as mountains and canyons, chemists develop models of the structure of molecules, and zoologists map the tracks of animals to gain insights into their foraging behavior. Thus it is not surprising that measures of spatial ability are correlated with success in various scientific domains, such as physics [1, 2], chemistry [3], geology [4], mathematics [5], engineering [6], and medicine [7, 8]. A recent longitudinal study of gifted high school graduates indicated that spatial ability was an important predictor of their participation in science and engineering disciplines 15 years later, after controlling for SAT mathematics and verbal scores [9].

The measures of spatial ability that have been found to be predictive of success in science have been standardized paper-and-pencil tests measuring the ability to imagine transformations (mental rotation and paper folding). Recent research has found a partial dissociation between performance on these object-based (small-scale) spatial ability measures and individual differences in environmental spatial cognition tasks, such as learning the layout of a new environment, retracing a route, or pointing to unseen locations in a known environment [10]. For example, a review of 12 studies examining individual differences in a variety of tasks at the object and environmental scales of space found that the median correlation between these two types of spatial tasks was less than .3 and was not statistically significant in most of these studies [11]. Using structural equation modeling to control for task-specific and error variance, Hegarty, et al. [10] concluded that small-scale spatial abilities and the ability to learn the layout of an environment are partially dissociated; that is, they share some variance but are also dissociated. In their study the path coefficient linking large- and small-scale spatial abilities was .5, suggesting that they share 25 percent of variance.

The partial dissociation between small-scale and environmental spatial ability measures raises questions about whether scientists excel on both types of measures or only on small-scale spatial ability measures, as has been shown in previous research [1, 3, 4, 5, 8]. There are reasons to expect that there might be a dissociation between large-scale and small-scale spatial abilities across different scientific disciplines. Scientists in different disciplines study phenomena that occur at different scales of space [12]. For example, astronomers study large distances on the order of light years, often unobservable directly. Geologists study relations that span a range of scales: planet-wide tectonic plates, mountains, and even the microscopic spatial organization of mineral grains. In contrast, physiologists study phenomena at the scale of human and other organisms. Chemists examine reactions that occur at the miniscule scale of molecules, much too small to see, although they often use molecular models (manipulable objects) to represent these molecules. Might these sciences be differentially dependant on large- and small-scale spatial abilities?

The goals of this research project were to gather preliminary data with respect to the following research questions:

- Does scientific thinking depend equally on large- and small-scale spatial abilities?
- Do different scientific disciplines differ in their dependence on large- and small-scale spatial abilities?

To begin to answer this question, this paper presents preliminary evidence from an on-line questionnaire study in which scientists in different disciplines and specialists in other disciplines and professions completed self-report questionnaires regarding spatial abilities at different scales, and self-report measures of verbal ability. Although self-report measures are indirect measures of ability, they have been shown to have predictive validity. These measures range from those that simply ask people "how good is your sense of direction" to multi-item scales, such as the Santa Barbara Sense of Direction Scale, in which people report how much they agree with statements such as "I am very good at judging distances" or "I very easily get lost in a new city." Measures of self-reported sense of direction prove to be reliable and predict performance in such objective tasks such as ability to update one's position and orientation while walking blindfolded or in visually impoverished environments, to learn the layout of a new environments, and to judge the direction (in environment-based coordinates) from which a photograph of a familiar landmark had been taken [13, 14, 15]. Self-report measures are typically better predictors of performance in large-scale spatial cognition tasks than paper-and-pencil tests of spatial ability [10, 13].

We developed new self-report measures of small-scale spatial ability (the Philadelphia Spatial Abilities Scale) and verbal ability (the Philadelphia Verbal Abilities Scale) in the context of this research. These questionnaires, along with the Santa Barbara Sense of Direction Scale, were administered to scientists and individuals from other disciplines and professions in an on-line questionnaire. We predicted that scientists should rate themselves as higher on small-scale spatial abilities than individuals in non-scientific disciplines (humanities and other professions) reflecting previous evidence that performance in scientific disciplines is correlated with performance on small-scale (object-based) spatial abilities tests. We examined whether they also rated themselves higher on large-scale spatial abilities. Finally it was important to rule out the possibility that high self ratings on spatial abilities merely reflect general self esteem or high ratings of general ability. Thus we predicted that scientists would not rate themselves higher than average on verbal abilities and that self ratings of verbal ability would be dissociated from self ratings of spatial abilities

2 Method

Participants. The participants were 850 individuals (485 female, 365 male) who responded to an email request to take an on-line survey. Four participants were currently in high school, 50 reported their level of education as high school, 237 had a bachelor's degree, 285 had a master's degree, and 274 had a doctorate. Given our interest in disciplinary specialization, the data from participants without a college degree (N = 54) were not analyzed further. The final sample that was analyzed had 796 participants (457 female, 339 male) with a mean age of 36.0 years (SD = 13.0).

Materials. The participants completed three questionnaires.

(1) *Santa Barbara Sense of Direction Scale (SBSOD).* Participants were administered the Santa Barbara Sense of Direction Scale, which consists of 15 Likert-type items adapted from previous self-report scales of environmental spatial abilities [13]. Each item was a self-referential statement about some aspect of environmental spatial cognition; participants responded by clicking on a number from 1 ("strongly agree") to 7 ("strongly disagree") to indicate their level of agreement with each statement. The items are phrased such that approximately half of the items are stated positively, half negatively. An example of a positively stated item is "I am very good at judging distances"; an example of a negatively stated item is "I very easily get lost in a new city". In scoring, positively stated items were reversed so that a higher score indicates a better sense of direction. Sums of the 15 items were used for the analyses. The internal reliability (Cronbach's alpha) for this administration of the scale is .89.

(2) *The Philadelphia Spatial Abilities Scale*. The PSAS is a 25 item, Likert-style questionnaire that assesses reasoning in four categories of common spatial tasks [16]: static relations within objects (e.g., what the inside of an apple looks like), relations

among objects (e.g., does a car fit into a parking spot), relations within deforming object (e.g., what a crushed can will look like) and relations among moving objects (e.g., putting together furniture) [17]. For this study, the PSAS was shortened to 16 questions. Each of the items asked the participants to assess their ability to complete a spatial task (e.g., "I am good at determining if my car fits into an available parallel parking spot") by selecting a number from 1 (strongly agree) to 7 (strongly disagree). The PSAS contains both negative statements (I have trouble with…) and positive statements (I am confident I can…), to avoid participants answering all items with "1". Questions spanned different types of spatial changes including rotation, crushing, and construction. While addressing various small-scale spatial skills, the instrument maintains a strong internal consistency, Cronbach's alpha = .87 for this administration of the 16-item scale.

The PSAS has good predictive validity for scores on paper-and-pencil tests of object transformation (Vandenberg and Kuse MRT) and disembedding (ETS hidden figures test). Overall score on the PSAS correlates .38 and .32 with the MRT and the hidden figures test, respectively [17].

(3) *The Philadelphia Verbal Abilities Scale*. The PVAS is a 10 item, Likert-style questionnaire that assessed verbal abilities, which was developed in the context of this research project. Each of these items asked the participants to assess a common verbal ability (e.g. "I am good at crossword puzzles" and "I would rather read a text explanation than look at a drawing or figure.") by selecting a number from 1 (strongly agree) to 7 (strongly disagree). The PVAS contains both negative statements, (I often have trouble…) and positive statements (I am good at…). Questions included examples of receptive (e.g., I would rather read), generative (e.g., I am good at expressing what I mean in words), and problem solving (e.g., I am good at Scrabble) skills. The instrument has a strong internal consistency reliability, Cronbach's alpha = .80 for this administration of the test.

Procedure. Participants were recruited by email, through mailing lists associated with the Spatial Intelligence and Learning Sciences (SILC) and Spatial@UCSB, by postings on the Web sites of the authors and their colleagues, and through personal contacts of the authors in different disciplines. People contacted by these methods were encouraged to forward the email request to their colleges, especially those in the physical sciences.

Invited participants visited a publicly available Web site, which presented each with brief instructions and the three-part survey form. First, participants were asked to provide their sex, age (optional), country, highest level of education completed, field of study, and subfield of study. The list of fields and subfields was a slightly restructured version of the list used by the National Opinion Research Center at the University of Chicago to conduct its annual Survey of Earned Doctorates.[1] In the next section, the 15 SBSOD items and the 16 PSAS items were combined together and randomly ordered for each administration of the survey. And in the final section, the 10 PVAS items were also randomly ordered.

After completing the survey, participants were presented with three dials plotting their mean sense of direction, small-scale spatial, and verbal skill ratings (on a scale of 1 to 7).

[1] http://www.norc.org/projects/Survey+of+Earned+Doctorates.htm

Coding. Scripts on the Web server recorded each administration of the survey to a database. Ratings were stored in their original form, but when calculating totals and means, ratings were reverse coded for negatively worded items. That is, on a question like “I am very good at giving directions,” a rating of 1 (“strongly agree”) was reverse scored to be 7. Thus in all cases, larger values on the totals, means, and resulting analyses indicate a self report of higher of ability.

3 Results

Descriptive Statistics. Means and standard deviations for the three scales are given in Table 1. The correlation between the two spatial ability scales was in the moderate to high range (r = .61, p <.001). Neither the Santa Barbara Sense of Direction Scale (r = .04, p = .30) nor the Philadelphia Spatial Abilities Scale (r = .00, p = .97) was correlated with the verbal abilities scale.

Table 1: Descriptive statistics for the three self-report scales.

Scale	**Possible Range**	**Mean**	**SD**
Santa Barbara Sense of Direction (SBSOD)	15-105	74.36	16.66
Philadelphia Spatial Abilities (PSAS)	16-112	79.18	15.57
Philadelphia Verbal Abilities (PVAS)	10-70	48.99	9.47

Table 2 shows the number of respondents by field for respondents with a bachelor’s, master’s, and doctoral degree. Participants listing their field as physics, chemistry or astronomy were categorized as physical scientists. Biological sciences included those listing biomedical fields as their major area of specialty. The category of geoscientists included specialists in geology, oceanography, and meteorology. Finally, the category of professional fields included education, business, law, and health sciences.

	Bachelor’s	**Master’s**	**Doctorate**	**Total**
Physical Sciences	16	18	44	78
Biological/Biomedical	30	22	31	83
Geosciences	19	25	32	76
Geography	5	14	10	29
Engineering	22	23	14	59
Computer/Information Science	12	26	31	69
Psychology	35	45	51	131
Social Science	18	18	13	49
Humanities	26	41	16	83
Professional Fields	51	47	26	124

Differences between Specialties in Self-Reported Sense of Direction. To compare self-reported abilities across the different specialties, the scores on the three self-report scales were converted to standardized scores (z scores). Figure 1 shows the mean standardized scores by specialty for the Santa Barbara Sense of Direction Scale. The scores differed significantly by specialty, F (9, 771) = 3.12, p = .001. Geoscientists clearly had the highest self-ratings on this ability. Post-hoc (Tukey) tests indicated that geoscientists rated their sense of direction significantly higher than did biological scientists ($p < .001$), computer/information scientists ($p < .05$), humanists ($p < .01$), and those in professional fields ($p < .01$). No other differences between the professional groups were statistically significant and the pattern of results was very similar when only those with an advanced degree (master's or doctorate) were included in the analyses.

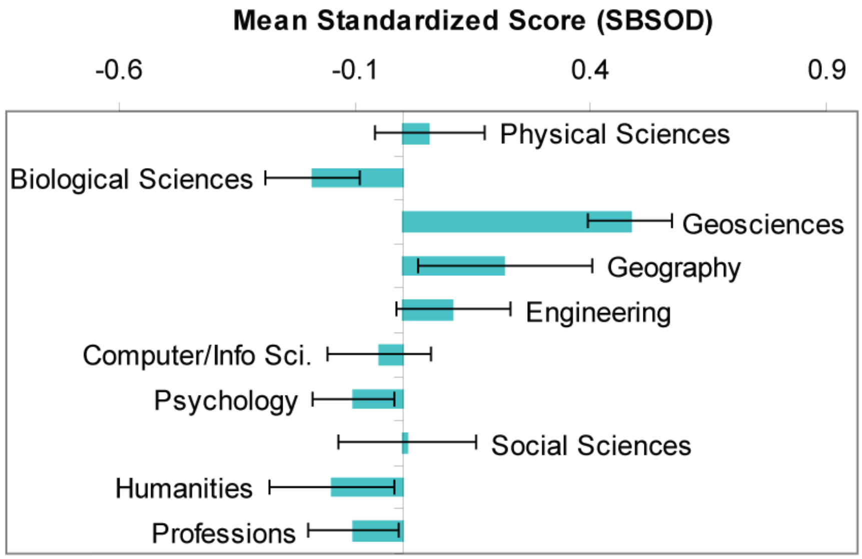

Figure 1. Mean standardized score by specialty on the Santa Barbara Sense of Direction Scale by discipline for all participants with a college degree.

Differences between Specialties in Self-Reported Small-Scale Spatial Ability. Figure 2 shows the mean standardized scores by specialty for the Philadelphia Spatial Abilities Scale. The scores differed significantly by specialty, F (9, 771) = 4.95, $p < .001$. Again geoscientists had the highest self-ratings on this ability. Compared to sense of direction, engineers rated their object-based spatial abilities as somewhat higher, while geographers rated their object-based spatial abilities as somewhat lower. Post-hoc (Tukey) tests indicated that geoscientists rated their object-based abilities as significantly higher than did biological scientists (p < .01), computer/information scientists (p < .05), psychologists (p < .001), social scientists (p < .01), humanists (p < .01) and those in professional fields (p < .001). Engineers also rated their object-based spatial abilities as significantly higher than those of psychologists (p < .05) and those in professional fields (p < .05). No other differences were statistically significant and the pattern of data was very similar when we considered only those participants with an advanced degree (master's or doctorate)

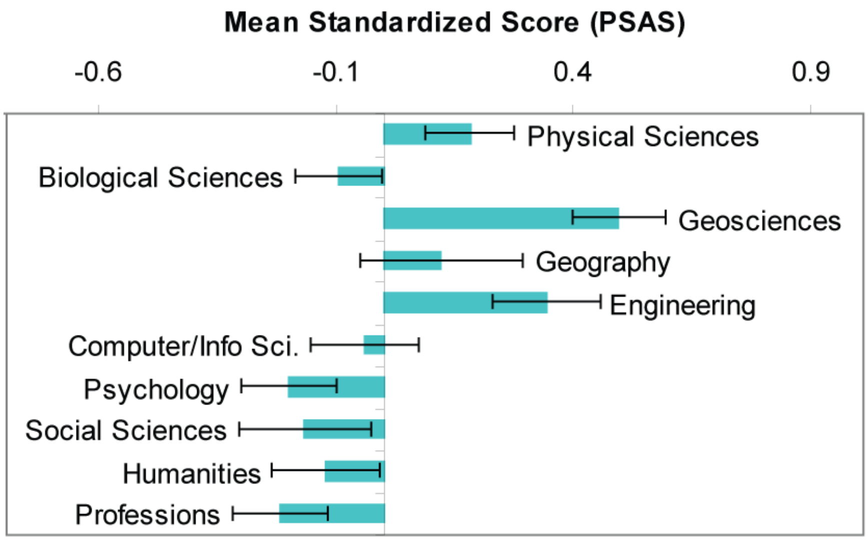

Figure 2. Mean standardized score by specialty on the Philadelphia Spatial Abilities Scale by discipline for all participants with a college degree.

Differences between Specialties in Self-Reported Verbal Ability. Finally, Figure 3 shows the mean standardized scores by specialty for the Philadelphia Verbal Abilities Scale. It can be seen that the pattern is very different from those observed for the spatial ability scales, indicating that participants discriminated between the abilities and did not merely rank themselves as high or low on all abilities. Furthermore the relative ratings were as expected, with humanities specialists rating themselves highest on verbal ability. The ratings differed significantly by specialty, F (9, 771) = 5.74, $p < .001$. Post-hoc (Tukey) tests indicated that humanists rated their verbal abilities as significantly higher than did biological scientists ($p < .01$), computer/information scientists ($p < .001$), geoscientists ($p < .001$), engineers ($p < .001$), and physical scientists ($p < .001$). Social scientists and psychologists also rated their verbal abilities higher than did physical scientists and engineers ($p < .05$). No other differences were statistically significant. When we considered only those with an advanced degree, participants in professional fields rated their verbal abilities as higher (mean standardized score = .25) but otherwise the patterns were very similar.

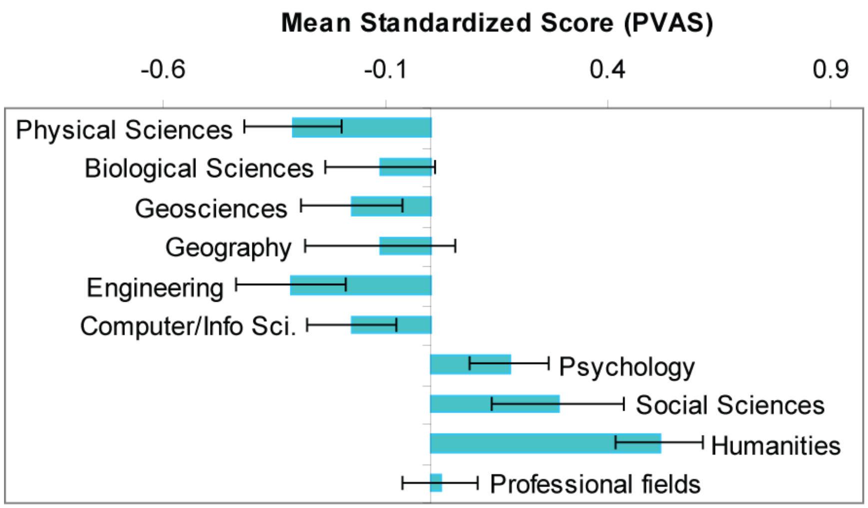

Figure 3. Mean standardized score by specialty on the Philadelphia Verbal Abilities Scale by discipline for all participants with a college degree.

4 Discussion

In summary, this study provides evidence that people's self assessments of their environmental (large-scale) spatial abilities are not completely parallel to their self assessments of smaller scale object-based spatial abilities. This pattern of partial dissociation between spatial abilities at small and large scales—found here using self-report questionnaires—is similar to that found when measuring people's objective performance [10]. Second, it shows that all sciences are not equal in terms of self-reported spatial abilities. While geoscientists have the highest ratings on both large-scale and small-scale spatial abilities, geographers have the second highest ratings on measures of large-scale spatial abilities and engineers and physical scientists rate themselves as higher than geographers on small-scale spatial abilities. While previous research has highlighted the importance of spatial ability in various scientific disciplines, this study raises the question of whether spatial ability is equally important for success in all sciences.

Our results support the validity of the self-report scales. They provide discriminant validity in that the mean self-report ratings for the two spatial abilities scales are uncorrelated with the self-report ratings for the verbal abilities scale. Thus, participants were not merely rating themselves as high or low on all abilities. The fact that the two spatial ability scales were somewhat correlated provides convergent validity, as we would expect these two scales to be more highly correlated with each than with verbal ability. At the same time, it was clear that participants differentiated small-scale from large-scale spatial abilities in that the correlation of the two spatial ability scales was in the moderate (not high) range. Finally, there was evidence for criterion validity of the scales in that the scientists who ranked themselves as high in environmental spatial ability were from disciplines that deal with larger-scale spaces, while humanities specialists rated themselves as highest on verbal abilities.

It is perhaps surprising that physical scientists (physicists, chemists and astronomers) do not rank themselves more highly in spatial abilities, given that spatial ability is often assumed to be a prerequisite for success in physical sciences. This group was made up of 54 physicists, 19 chemists and 5 astronomers, and a further breakdown into these 3 groups did not reveal any significant differences between these sciences, although this analysis is limited by low power. However, recent research suggests that the development of expertise in science is often accompanied by the acquisition of analytic heuristics for solving spatial problems. For example, Stieff [16] found that beginning organic chemistry students almost always used a mental rotation strategy when determining whether two molecules had the same structure, but expert chemists were much more likely to use an analytical strategy, especially when the molecule was symmetrical. A post-hoc analysis revealed no differences in self-rated abilities of physical scientists as a function of education level, but again this analysis is limited by low power. In examining the use of visualization versus analytical strategies in domains such as mechanics and chemistry, researchers have suggested that visual-spatial strategies are default domain-general problem solving heuristics that are used by novices or by experts in novel situations, whereas rule-based analytic strategies are learned or discovered in the course of instruction and are used by experts in routine problem solving [18, 19].

Our research suggests that geoscientists (geologists, oceanographers, and meteorologists) appear to be most dependent on spatial abilities in that geoscientists had the highest self ratings on both large-scale and small-scale spatial abilities. These disciplines may be particularly dependent on spatial abilities because they are more grounded in real-world experiences of spatial structures and processes, such as rock configurations, ocean waves, and thunderstorms. Geologists must keep track of spatial locations at the environmental scale when they go on field trips and observe outcrops to reason about the spatial processes that give rise to structures and processes at the earth's surface. They also depend more on spatial representations than do other scientists, in that their publications have a greater ratio of graphics to text area than other sciences [20]. While chemists, for example, are also highly dependent on graphical representations and have invented many different diagrammatic conventions for molecules, the structures and spatial processes that they study are less tied to real-world spatial experience, in that they do not have direct experience of the space of molecules.

While intriguing, the results of this study have several limitations. First, they are based on self reports of ability, which at best are only a reflection of objective differences in spatial intelligence. It will be important to follow up these results with studies that measure the abilities of scientists and other specialists more objectively. Second, our results are based on responses from a convenience sample rather than a truly representative sample of the populations being compared. Finally, the data are correlational, so they cannot be interpreted as evidence for a causal relationship between levels of spatial abilities and participation in sciences or vice versa. Nevertheless, our results are important in highlighting the need for studies of the role of spatial thinking in science to be mindful of both varieties of spatial intelligence and varieties in the spatial demands of different sciences.

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