An Exploratory Study of Spatial Ability and Student Achievement in Sonography

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Abstract
Spatial ability refers to an individual’s capacity to visualize and mentally manipulate 3D objects. Since sonographers manually manipulate 2D and 3D sonographic images to generate multi-viewed logical, sequential renderings of an anatomical structure, it can be assumed that spatial ability is central to the perception and interpretation of these medical images. However, little is known about the relation between spatial ability and performance of sonographers. This study explores this possible relationship. Seventeen first-year sonography students were administered a spatial abilities test prior to their initial scanning lab coursework. The students’ spatial ability scores were compared with their scanning competency performance scores after the first 30 hours and after two semesters of instruction. A significant relationship between the students’ spatial ability scores and their scanning performance scores was found. This study suggests that the use of spatial ability tests for admission to sonography programs may improve student selection as well as assist programs in adjusting instruction and curriculum for students who demonstrate low spatial ability.

Keywords
spatial ability, sonography scanning, spatial ability testing

Sonography is a developed skill in which sonographers perform sonography scanning to produce sonographic images called sonograms. Sonographers image anatomical structures within patients to produce diagnostic images for the physician to interpret. Unlike other imaging modalities where the technologist positions the patient and the machine performs the imaging automatically, sonography is more subjective. It is an acquired skill that requires manual manipulation of the probe, or transducer, to produce the images while, at the same time, operating the ultrasound machine. The sonographer creates images that are 2D representations of 3D anatomical structures that are “slices” of the anatomical structure. These slices are commonly presented in a logical sequence to create a representation of the region of interest. In light of this task analysis, it can be assumed that learning sonography scanning may require a high level of spatial ability to create the sonograms.

Educational programs for sonographers often use traditional admissions criteria such as SAT or ACT scores, as well as grade point averages (GPA), or GRE scores, in selecting candidates for admission to their programs of study. However, through several years of observation of students in our program of study, we noted that some students learn to scan much faster than others, regardless of their academic achievement or aptitude scores. Although measures of aptitude and achievement may predict future success in didactic work, they did not illuminate a candidate’s aptitude for sonography scanning. Consequently, it can be assumed that all sonography schools may be faced with admitting candidates with high SAT or ACT scores and with exceptional incoming GPAs who perform well in didactic coursework yet struggle with learning sonography scanning.

An exploratory study focused on finding empirical evidence that an individual’s level of spatial ability may contribute to the process of learning sonography scanning was performed. The intent of the study was to examine the relationship between a student’s spatial test score and

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the student’s sonography scanning performance scores. If a positive relationship is found, then perhaps administration of a spatial ability test would be an appropriate predictor of a student’s aptitude for success in sonography scanning.

**Visual-Spatial Ability**

Visual-spatial ability refers to the neuro-psychological processing of spatial relations of image properties. Furthermore, it is defined as the “ability to generate, retain, retrieve, and transform well-structured images. Complex in nature, it is not a unitary construct, but rather exists in several forms,” with each emphasizing different aspects of the process of image generation, storage, retrieval, and transformation. Sonographers create relationships among the sonography images produced and give meaning to the anatomical structures they see on sonographic images. However, they rarely see the entirety of the anatomical object being scanned. Therefore, sonographers must be able to construct a series of images that logically represents the whole object. This requires an ability to mentally rotate and transform 2D images and create a series of views that represents the 3D structure.

The ability to perceive spatial properties occurs in a number of stages, from simple edge and surface encoding to more complex whole-object processing. Studies within the realm of neurophysiology have shown there is a hierarchy of visual-spatial abilities. The general classifications of visual-spatial abilities from low to high are as follows: (1) edge and surface extraction, (2) edge orientation encoding, (3) whole-object recognition, (4) imagery involving the spatial relations of object parts in 2D, and (5) imagery involving 2D and 3D whole-object spatial rotations and translations.

Some authors believe that spatial cognition is central to understanding medical images, including those produced by computed tomography (CT), magnetic resonance imaging (MRI), and radiography or x-ray. However, as of this writing, no empirical evidence has been identified in the literature that supports this assumption for sonography. The purpose of this study was to provide foundational empirical evidence in support of these assumptions, in which the following research questions were addressed: (1) what are the levels and variations of spatial abilities among the sonography students, and (2) what is the relationship between innate spatial ability test scores and student achievement in sonography scanning?

**Conceptual Framework**

The framework of this study embraces cognitive learning and constructivism with an emphasis toward generative learning. Constructivism is a philosophical explanation about the nature of learning. Some authors have extended this philosophy into a theory of learning, which has its roots in cognitive and social cognitive learning theories but with significant differences. In general, constructivists assert that the world can be viewed by individuals in many different ways. Knowledge is not something imposed on people from the outside; rather, it is formed from within. Therefore, each individual’s construction of knowledge is unique, based on personal beliefs and prior experiences. All knowledge is thus subjective to personal perceptions, worldviews, and innate abilities. There are many varieties of learning theories along the constructivist continuum, one of which is generative learning.

Generative learning theory is a cognitive approach to learning that draws from the constructivist philosophy and is most applicable to this study. First described by Wittrock, generative learning is a form of constructivism that is based on the neural aspects of brain functioning and the cognitive process of knowing. Learning strategies are those that create relationships and meaning through mental processes that “reorganize, elaborate, and reconceptualize information.” Mental structures formed by the learner that reflect reality are coupled with the learner’s prior knowledge and experiences, which then assist in the understanding and creation of relationships.

Generative learning is related to this phenomenon in that each time a study is generated, the sonographer must “learn” the anatomical configuration being studied and conceptually reorganize, elaborate, and reconceptualize the information provided by the acquired sonographic images. This study explores the relationship between an individual’s level of spatial ability and the student’s achievement in learning to scan.

**Visual-Spatial Ability Testing and Its Role in Occupations**

Spatial visualization tests are designed to evaluate an individual’s ability to mentally transform objects into alternate formations. Research on visual-spatial abilities (VSA) in relation to occupational aptitude has been done by a host of researchers. High scores on spatial ability tests have high correlation values within careers such as dentists, artists, engineers, industrial machine operators, draftsmen, designers, electricians, surgeons, and many others. Many of these careers require high scores on spatial ability tests for admission to their educational programs or prior to hire. Numerous studies from previous and recent research have linked the role of spatial cognition in medicine, especially in general surgery, laparoscopic surgery, and dentistry.
Several recent studies have looked at the role of innate spatial perception abilities among students in dentistry and general surgery. Wanzel et al.\textsuperscript{9} examined the influence of spatial abilities and manual dexterity on performance among dental students, surgical residents, and staff surgeons. Each group was administered the Vandenberg Mental Rotations Test\textsuperscript{11} to assess high-level spatial abilities and the Surface Development Test (SDT) for low-level spatial abilities.\textsuperscript{12}

Test results confirmed that high-level VSA is related to and could potentially predict initial student performance and product quality on spatially complex procedures, especially in laparoscopy procedures. High-level VSA test scores were more predictive of performance than the low SDT test scores, as well as the manual dexterity tests. Interestingly, those general surgery students who were identified with low spatial ability achieved results equal to surgical residents and staff surgeons after supplementary instruction on the specific technical tasks.

This important finding indicates that even though a novice with low spatial ability may initially exhibit low performance scores, additional instruction and deliberate practice can overcome low spatial ability and eventually increase the level of performance on the assigned tasks equal to the level of those with high spatial ability. In light of this finding, the authors do not support the use of high-level spatial ability testing for the selection of candidates for admission purposes into surgical or dental schools. Rather, the tests would be most beneficial in identifying those novice trainees who might benefit from supplementary instruction during their course of study.

Other recent studies have confirmed Wanzel et al.’s findings\textsuperscript{9} in general surgery, laparoscopic surgery, and dentistry.\textsuperscript{13–15} All found that high-level spatial ability testing can at least predict initial performance in these fields. Although the researchers used a different spatial relations test, all agreed that the VSA tests correlated most strongly with high initial student achievement. In contrast to Wanzel et al.’s conclusions, Keehner et al.\textsuperscript{13,14} and Risucci\textsuperscript{15} supported using spatial ability tests for selection of candidates, stating that the extra time and instruction necessary to overcome initial poor student achievement due to low innate spatial ability may not be practical with limited time and resources.

**Spatial Ability Tests**

Spatial ability tests are designed to evaluate a person’s ability to mentally manipulate diagrams of objects into alternate formations. There exists a wide variety of tests related to each category of spatial ability, as noted above. The original Minnesota Paper Form Board Test was developed in the late 1920s by Likert and Quasha\textsuperscript{8} and was the first psychometric test assessing visual-spatial ability. The test measures the “ability that predicts performance in jobs requiring the capacity to visualize and mentally manipulate objects in space,” which correlates to assessing the fifth and highest category of visual-spatial ability of mental rotation and transformation of objects. According to the authors, an individual’s score can be marginally improved through specified training, but it is important to note that a dramatic improvement cannot be achieved through “practicing for the test” that affects interpretation of test results on the Revised Minnesota Paper Form Board Test.\textsuperscript{9}

A more recent version of the Revised Minnesota Paper Form Board Test (RMPFBT) is a well-designed measurement tool that has been reviewed and evaluated many times in its 75-year history. It is a spatial visualization test that targets the highest level of spatial ability skill category, which logically seems to be appropriate for the tasks necessary for sonography scanning, that of mentally rotating objects and understanding possible transformations. It is, in our opinion, an appropriate tool for assessing visual-spatial ability in sonography scanning.

The test is a 20-minute paper-and-pencil test that evaluates spatial abilities. It has an excellent split-half reliability score of .93, which measures internal test consistency. It also has a “test-retest” score of .85, which indicates high repeatability of the test with the ability to give consistent results over time. There are four alternate forms of the test, with a reliability of .85. Reliability refers to the accuracy and precision of a test and is an indication of the confidence one may place in a test score.\textsuperscript{8} Criterion-related validity, which means to provide an educated guess about an examinee’s potential for future success, has not been established for sonography but is .61 for dentistry. Construct validity measures the extent to which a test measures the trait it was designed to measure, which in this case is an individual’s spatial ability.\textsuperscript{16} For the RMPFBT, construct validity is reported to be .75, which means the test is an appropriate measure for spatial ability and would be an appropriate test for use in assessing spatial ability for sonographers.

**Method**

After obtaining permission from our institutional internal review board (IRB), a total of 17 sonography students divided into two groups were studied in this project. One group consisted of five first-year students enrolled in beginning cardiac sonography and 12 first-year students enrolled in beginning abdominal and OB/GYN. Fifteen participants were women and two were men. Both groups were studied for two semesters and were taught by different instructors. The RMPFBT was administered to each
statistically significant relationship between the scanning scores after the first 30 hours of instruction. In contrast, a very strong correlation occurred when the spatial test scores were compared with the two-semester averaged scores. The latter results indicate that high spatial ability test scores relate to student achievement in sonography scanning.

The tests were hand scored by the primary investigator at the end of each group’s respective project period to alleviate any unintended teacher coercion, grading, or scoring bias for the competency examinations of the students. All of the instructors of the participants in the study were blinded from the students’ individual spatial test scores at any time throughout the instructional period, as well as testing of the students’ scanning competency.

The study looked at two measures of the student’s competency scores. First, the students were given scanning competency tests at the end of the first 30 hours of instruction. In group 1, the 5 beginning cardiac students’ first competency scan consisted of obtaining the four basic 2D views of the heart, which included the parasternal long-axis, parasternal short-axis, apical, and subcostal views. For the second group of 12 beginning abdominal students, the first competency test was that of a scan of the aorta. The students used each other as models, and the instructor evaluated each student as he or she scanned in the laboratory setting, according to the performance objectives outlined in the Sonographer Clinical Assessment Book (SCAN), which is a commercially available assessment tool developed by the International Foundation for Sonography Education and Research (IFSER). Similarly, evaluations of student scanning were made according to the performance objectives stipulated in the SCAN. The students used each other as scanning models, and the instructor evaluated them in a laboratory setting.

The second portion of the study occurred at the end of two semesters of instruction, when all competency scanning scores were averaged for the entire period. The scores for both groups were combined and were then correlated with their respective scores on the RMPFBT. The independent variable, \( X \), is the spatial aptitude score, and the dependent variable, \( Y \), is the achievement or scanning score.

### Results

This study examined the spatial ability of each student to assess how the scores vary among the students. The minimum aptitude score of all the participants for spatial ability was 34, and the maximum score was 55. Normative data have not been established for the occupation of sonography for the RMPFBT. As an example for comparison, normative data for grade 12 women indicate that a score of 34 would be in the 15th percentile and a score of 55 would be in the 90th percentile. Therefore, the beginning sonography students as a whole had a very wide range of spatial ability. The relationship between students’ spatial aptitude measure and their achievement was measured at two times: after 30 hours of instruction and two semesters of instruction. The combined performance scores of the two groups after the first 30 hours ranged from 52% to 98% (see Table 1).

Regression analysis was done for student performance after 30 hours and resulted in a marginal Pearson Product-Moment correlation coefficient (\( r \)) of .264, which is the measure of the linear relationship of the two variables. In other words, it represents the simple relationship between the spatial ability test scores and the scanning competency scores as reflected by their scanning scores. The coefficient of determination, or \( r^2 \), which is the proportion of the total variance in the scanning scores (\( Y \)) that can be associated with the spatial ability scores (\( X \)), was .070. This means that the spatial test scores can account for only 7% of the variation in the students’ scanning scores, which is quite low. The adjusted \( r^2 \) for having a sample \( N < 30 \) was .008. The standard error of the estimate was 10.9081.

The standard error of the estimate is the standard deviation of the variance of the residuals along the regression line. The residuals, or deviations, are the departures from \( Y \) and predicted \( Y \), or the difference between the value the model predicts and the value of the observed data on which the model is based. Ideally, we want the departures or residuals to be as small as possible, and therefore, the smallest standard error of the estimate is desirable for

<table>
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<th>Variance</th>
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a predictive test, and in this case, the departures are quite large. The standard deviation of the residuals equals the standard error of the estimate. In essence, it is a measure of how representative a sample is of a population.

Often with regression analysis, an F test or an analysis of variance (ANOVA) is performed. ANOVA compares the variance of the regression model with the variance of the residuals, or deviations (see Table 2). Traditionally, ANOVA is used in experimental research, and regression is used in correlation research. The ANOVA procedure in regression can be used to test the hypothesis that the independent variable, in this case the spatial test scores, will account for a statistically significant proportion of the variance in the dependent variable, or the students’ scanning scores. An ANOVA does not, however, tell anything about the individual contribution of the variables in the model.

Spatial test scores and scanning competency scores for all students in the first part of the study were compared. Ideally, it is desirable to have the results of the “Sig.” column of the ANOVA to be less than .05. Our results for this part of the study indicate that because the “Sig.” number is very large (.30), the results are not statistically significant (see Table 2).

For the second part of the study, regression analysis was done for the combined student performance after two semesters of instruction. In contrast to results after 30 hours of instruction, the Pearson Product-Moment correlation coefficient was .60. In social science research, .60 indicates a strong relationship between the two variables or between the spatial ability scores and the students’ competency scanning scores.

The coefficient of determination, \( r^2 \), was .36. This tells us that spatial ability can account for 36% of the variation in student achievement. In social science research, this statistic is quite significant and also shows a strong relationship between spatial ability and the scanning competency scores. The adjusted \( R^2 \) for having a sample less than 30 was .349, and the standard error of the estimate was 3.8859 (see Table 3).

Again, a one-way ANOVA was done to determine if a statistically significant proportion of the variance of the dependent variable, scanning scores, is associated with the independent variable, the spatial ability scores (see Table 4). We found a statistically significant association for the variables after two semesters of instruction (see Table 4).

This suggests a much stronger relationship between the spatial scores and student performance when looking at the two-semester average (see Figures 1 and 2).

The power of a statistical test refers to the ability of a test to detect a hypothesized effect. The value of .80 has generally been accepted as the minimum standard. Power is greatly affected by sample size and can therefore be increased by increasing the sample size. The statistical power of this study is .83, indicating a sufficient sample size for the study.

**Discussion**

Our first research question asked, what were the levels and variations of spatial abilities among the sonography students? The first-year students had a very wide range of
spatial ability, ranging from 34 to 55, with the scores being distributed consistently throughout the range. The second research question explored the relationship between the RMPFBT spatial ability scores and the performance scores recorded after 30 hours of instruction and then after averaging all the competency scores for the two semesters. Unexpectedly, a marginal Pearson correlation of .264 was found after the first 30 hours of instruction, whereas a strong correlation of .60 was found with the average of the two-semester performance scores. We had anticipated exactly the opposite result. In the literature, other investigators have reported strong correlations with spatial ability and task performance after initial instruction, then weaker relationships due to mediating aspects of extended instruction and practice.

A potential explanation of our findings is the different experiences of both study groups. Performance scores of the 12 students in the abdominal group were clustered together after the first 30 hours of instruction and then diverged throughout the two semesters as the scanning competencies became more difficult. In contrast, the performance scores of the 5 students in the cardiac class varied widely after the first 30 hours and then converged throughout the two semesters as the weaker students caught up with the competency levels of the stronger scanners. This variation in student learning and instructional experiences and associated performance scores may have skewed the scores for the first 30 hours. More study is needed, whereby controls for varied student experiences during the initial instructional period are examined.

A mix of abdominal and cardiac classes was combined in this study to increase the number of participants in order to achieve a sufficient sample size for the number of independent variables in the study, which is one. For simple regression using one independent variable measuring student achievement on scanning scores, the sample size must equal about 15 to 20 participants. Criterion-related validities as low as .20 may justify the use of a test in a selection program. Of central importance to this study was the question regarding the relationship between spatial ability test scores and student achievement in sonography scanning, for which positive results were demonstrated. There are several significant limitations in this study. One is that only 17 students participated, all enrolled in a single sonography program at one university. Of the 17 participants, 15 were female, with only 2 being male. A more balanced representation would be more advantageous in the role of gender, spatial ability, and cognitive learning. However, recent findings in the literature have shown that men generally perform better than women, with no statistically significant difference between male and female scores on the Revised Minnesota Form Board Test. Research using other spatial ability tests has demonstrated only a one-point difference in favor of males.

The students’ scanning scores were averaged over a two-semester period to mediate the myriad potential factors that can affect a student’s scanning competency score. Some of these factors may include a student not feeling well the day of competency testing, test anxiety, motivational influences, teacher-student relationships, and a host of other unforeseen factors that can affect college students. Most of the participants were traditional-aged students in their junior year of college.

A final limitation to the study lies in the fact that this research study cannot account for an individual’s level of psychomotor skills. Sonography scanning is an acquired skill through many hours of individual diligent practice. An individual’s level of eye-hand coordination is certainly a factor in learning how to scan. If a person possesses a high level of spatial ability within the visual system, the level of psychomotor skills could affect an individual’s scanning score. The use of a spatial ability test that combines testing for psychomotor skills would be most appropriate for future study. These types of tests usually
require a trained professional to administer and were cost prohibitive for this study. Nevertheless, in our opinion, the positive results of this study should not be ignored and provide foundational empirical evidence on which to build for future research.

Future study should control subjectivity by having enough participants to be studied as one group, using one instructor, and possibly implementing a spatial ability test that incorporates psychomotor skill evaluation. Use of the SCAN was very beneficial for providing well-accepted performance standards for student evaluation. Drawing the sample population from a single homogeneous study group would reduce instructor and student variances in the rather subjective art of competency scanning evaluations.

**Conclusion**

The results of this small pilot study indicate that a positive relationship exists between spatial ability testing and student achievement when comparing student competency scanning scores and spatial test scores over a span of two semesters of instruction. This may imply that spatial aptitude testing may be appropriate for the screening of candidates for admissions purposes, along with the use of other traditional criteria, such as GPA, SAT, ACT, or Graduate Record Examination scores. It may also be important to adjust instructional pedagogical techniques and even curriculum to address the needs of students with low spatial abilities.

Another study is planned to determine validation of our initial findings, with some of the above-stated limitations being addressed. A much larger, more diverse sample population size will be used, as well as including several different learning environments from a wide variety of sonography educational programs. We invite other educational institutions with sonography programs to join us for further exploration of this interesting phenomenon.

**Declaration of Conflicting Interests**

The author(s) declared no potential conflicts of interest with respect to the authorship and/or publication of this article.

**Funding**

The author(s) received no financial support for the research and/or authorship of this article.

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![Figure 2. Regression scatter plot for the students’ two-semester averaged scanning scores compared with their spatial ability test scores. The graph shows a strong linear relationship between the two variables.](image-url)
References