Visuospatial Anatomy Comprehension: The Role of Spatial Visualization Ability and Problem-Solving Strategies

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The present study explored the problem-solving strategies of high- and low-spatial visualization ability learners on a novel spatial anatomy task to determine whether differences in strategies contribute to differences in task performance. The results of this study provide further insights into the processing commonalities and differences among learners beyond the classification of spatial visualization ability alone, and help elucidate what, if anything, high- and low-spatial visualization ability learners do differently while solving spatial anatomy task problems. Forty-two students completed a standardized measure of spatial visualization ability, a novel spatial anatomy task, and a questionnaire involving personal self-analysis of the processes and strategies used while performing the spatial anatomy task. Strategy reports revealed that there were different ways students approached answering the spatial anatomy task problems. However, chi-square test analyses established that differences in problem-solving strategies did not contribute to differences in task performance. Therefore, underlying spatial visualization ability is the main source of variation in spatial anatomy task performance, irrespective of strategy. In addition to scoring higher and spending less time on the anatomy task, participants with high spatial visualization ability were also more accurate when solving the task problems. Anat Sci Educ 00: 000–000. © 2013 American Association of Anatomists.

Key words: gross anatomy education; spatial ability; visualization; learning; medical education; problem-solving strategy; mental rotations; identification; localization

INTRODUCTION

One of the primary goals of healthcare and medical education is to teach students how to perform clinical procedures with minimum risks and maximum benefits to patients. Since patients are three-dimensional (3D) entities, healthcare and medical education often involve learning and applying 3D information (Marks, 2000). A cornerstone in the foundation begins in anatomy courses, where, in addition to terminology, students learn visuospatial information, including the shape of anatomical structures, their respective positions in 3D space, and their location relative to other structures. When carrying out clinical procedures, often the internal structures of the patient's body are not directly visible, so that medical professionals have to rely on internal or mental representations of visuospatial anatomical information (Hegarty et al., 2007).

Learning visuospatial information is often considered a visual process, involving the visuospatial working memory (Clark and Paivio, 1991; Baddeley, 1992; Mayer and Sims, 1994; Miyake et al., 2001). Processing information in visuospatial working memory is strongly influenced by spatial ability (Miyake et al., 2001). Spatial ability refers to an individual's ability to search the visual field, apprehend the forms, shapes, and positions of objects as visually perceived, form mental representations of those forms, shapes, and positions, and manipulate such representations "mentally" (Carroll, 1993). In other words, an internal representation of a

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perceived object or scene must be created and maintained in such a way that mental manipulations are possible. As the acts of creating, maintaining, and manipulating internal representations all require different but important abilities, several sub-factors of spatial ability have been identified and together they form the broad concept of spatial ability. These sub-factors include: visualization (Vz), spatial relations (SR), closure speed (CS), closure flexibility (CF), and perceptual speed (P) (Carroll, 1993).

Although there are several sub-factors of spatial ability, the factor that has been shown to influence anatomy learning is visualization (Vz), also known as spatial visualization (Garg et al., 1999a,b, 2001, 2002; Nguyen et al., 2012). Spatial visualization refers to an individual's ability to apprehend, encode, and manipulate visuospatial representations in two- or three-dimensions (Carroll, 1993). Like any ability, Vz varies significantly with the general population. Some people can store and process visuospatial information with ease, while others have difficulties performing these cognitive processes. Cognitive analysis of performance on tests of Vz suggests that differences in Vz reflect variations in speed of processing visuospatial information (Mumaw and Pellegrino, 1984; Salthouse, 1996), visuospatial working memory capacity (Shah and Miyake, 1996; Miyake et al., 2001), and strategies for processing visuospatial information (Just and Carpenter, 1985; Cohen, 2005). Compared to low Vz individuals, those with high Vz are faster at carrying out mental operations, have more working memory resources for storing and processing visuospatial information, and adopt more efficient strategies for solving Vz problems.

Individual differences in Vz have been shown to influence success in anatomy (Rochford, 1985; Guillot et al., 2007; Hegarty et al., 2007; Fernandez et al., 2011; Lufler et al., 2012; Nguyen et al., 2012) and proficiency in anatomically related fields such as surgery (Anastakis et al., 2000; Wanzel et al., 2002) and radiology (Provo et al., 2002; Luursema et al., 2006, 2008; Hegarty et al., 2009; Vorstenbosch et al., 2009; Luursema and Vervey, 2011). Rochford (1985) demonstrated that spatial ability is associated with achievement among medical students taking anatomy. Low Vz students (i.e., those who failed the battery of geometrical spatial exercises) scored consistently lower marks than their high Vz counterparts on both practical anatomy examinations and spatial multiple-choice questions. In contrast, high- and low-Vz individuals performed equally well on tests of non-spatial anatomical knowledge. Lufler et al. (2012) found similar results when assessing medical students at Boston University School of Medicine. High Vz participants were twice as likely than low Vz participants to score greater than 90% on practical examinations and on both practical and written examinations. More recently, Nguyen et al. (2012) demonstrated significant correlations between Vz and performance on a novel task called the spatial anatomy task (SAT). Subjects with high Vz scored higher and spent less time on SAT than subjects with low Vz. Findings such as these suggest that there is a strong spatial component to the way anatomical information is mentally represented. It also implies that low Vz individuals may have greater difficulty acquiring, representing, and manipulating mental representations of anatomy.

While the positive influence of Vz on anatomy task performance is known, the underlying cognitive mechanisms of spatial reasoning and the strategies that students employ to solve spatial problems in anatomy are less well understood. Anecdotal evidence suggests that differences in task performance may be due to strategic differences in the way high- and low-Vz learners approach answering the spatial task problems in anatomy (Rochford, 1985). It was suggested that these differences may include: (a) sectioning—visualizing a given section through an object, (b) translating—perceiving the apparent changes in the shape of an object when it is rotated in three-dimensions, (c) rotating—retaining in imagination the relative positions of the structures of a given body undergoing rotations in space, and (d) visualizing—synthesizing mentally the orthogonal sections of a given object to form an image of the whole (Rochford, 1985). However, to the best of our knowledge, no investigators have empirically tested the idea that multiple strategies could be used to solve spatial problems in anatomy, and that differences in strategies adopted by high- versus low-Vz individuals contribute to differences in anatomy task performance.

Although the role of strategy preference for spatial problem solving in anatomy has not been studied extensively in the past, strategy preference has been investigated in other disciplines, including chemistry, mathematics, and physics. Stieff et al. (2012) demonstrated that students employ multiple strategies when solving chemistry problems. Males prefer to reason with mental imagery, while females used multiple alternative strategies. Furthermore, students with low Vz prefer to use alternative strategies more frequently than those with high Vz. Hegarty and Kozhevnikov (1999) found that success in mathematical problem solving is positively related to the use schematic representations (encode spatial relations of objects) and is negatively related to the use of pictorial representations (encode visual appearance of objects). The authors also demonstrated that schematic imagery is associated with high Vz. Kozhevnikov et al. (2007) demonstrated that students' solutions to kinematics problems are related to Vz. Students with high Vz were more likely to construct schematic representations, take into account and successfully integrate several motion parameters, and reorganize one spatial problem representation into another coordinated, corresponding representation. By contrast, students with low Vz were more likely to construct pictorial representations, consider a single motion parameter at a time, and to hold multiple, uncoordinated representations of the same problem. While the relationship between Vz and strategy preference for problem solving in chemistry, mathematics and physics has been investigated, the relationship between Vz and problem solving in anatomy has yet to be studied.

The purpose of this study was to examine the problem-solving strategies of learners to determine whether differences in strategies adopted by high- and low-Vz subjects contribute to variation in visuospatial anatomy comprehension. Visuospatial anatomy comprehension was assessed using the same spatial anatomy task (SAT) reported in one of our previous studies (Nguyen et al., 2012). However, in addition to score and time spent on the SAT, the current study also included accuracy of SAT response (or proportion correct) as a third measure of performance.

This study aimed to address with the following questions: Are there multiple strategies used to solve the SAT questions? Does strategy choice of high- versus low-Vz individuals influence success on the SAT? Anecdotal evidence from use of the SAT suggested that multiple strategies could be used to solve inherent questions. For example, when solving the mental rotations questions participants could imagine rotating the anatomical figure or translating themselves. Rotation could be performed on the whole figure or part of the figure.

Participants could use verbal processes (talking to themselves) and/or perceptual-motor processes (moving themselves or surrounding objects) to assist with mental rotation, or just rely only on visualization processes. Therefore, it was hypothesized that multiple problem-solving strategies will be employed when answering the SAT questions, and that differences in strategies adopted by high- versus low-Vz subjects will contribute to differences in SAT task performance.

MATERIALS AND METHODS

Participants

Students from Western University enrolled in a science or social science program during September 2011 to December 2011 were invited to participate in the study. This study was granted ethics approval by The Research Ethics Board at Western University (protocol 17332E). There were no exclusion criteria for this study. Participation in the study was completely voluntary and students could opt out at any time during the course of the study.

Performance Measures

Mental rotations test (MRT). The standardized MRT (Vandenberg and Kuse, 1978; Peters et al., 1995) was used to assess participants' Vz. The task involved mentally rotating three-dimensional block figures. The task consisted of 24 items. Each item was made up of one target figure and four option figures (two are rotated images of the target and two are distractors). Participants had to determine as quickly and accurately as possible which two of the four option figures were rotations of the target figure. Participants were given 360 sec (180 sec for each subset of 12 questions, separated by a break) to complete as many questions as possible. A credit was given if both correct stimuli were identified. The maximum score on the MRT was 24.

Spatial anatomy task (SAT). A novel task pertaining to the visuospatial properties of three tubular anatomical structures (i.e., the mediastinal aorta, trachea, and esophagus) was used to assess spatial anatomical knowledge (Nguyen et al., 2012). The task consisted of three parts, and each part comprised of 10 multiple-choice questions. Part 1 involved the mental rotations of the anatomical structures, Part 2 involved the identification of the structures in two-dimensional cross-sections, and Part 3 involved the localization of planes corresponding to selected cross-sections. Example items from Parts 1, 2, and 3 are shown in Figure 1. For each part, participants were given 120 sec to complete as many questions as possible. A countdown timer appearing on the top right-hand corner of the computer screen recorded the amount of time participants spent on the task. For Part 1 (mental rotations questions), a single credit was given if both correct stimuli were identified. For Part 2 (identification questions) and Part 3 (localization questions), a credit was given for each correct answer.

Self-reflective questionnaire. A 22-item questionnaire was used to collect general information about how participants approached answering the SAT questions. The questionnaire queried strategies used during mental transformation as well as strategies used while answering the questions. The questionnaire consisted of 21 multiple-choice questions and one opened-ended question (Question 2). The questions were based on previous pilot testing of students to determine common language and approaches used while answering the SAT. Example items from the self-reflective questionnaire are presented in the Appendices A and B.

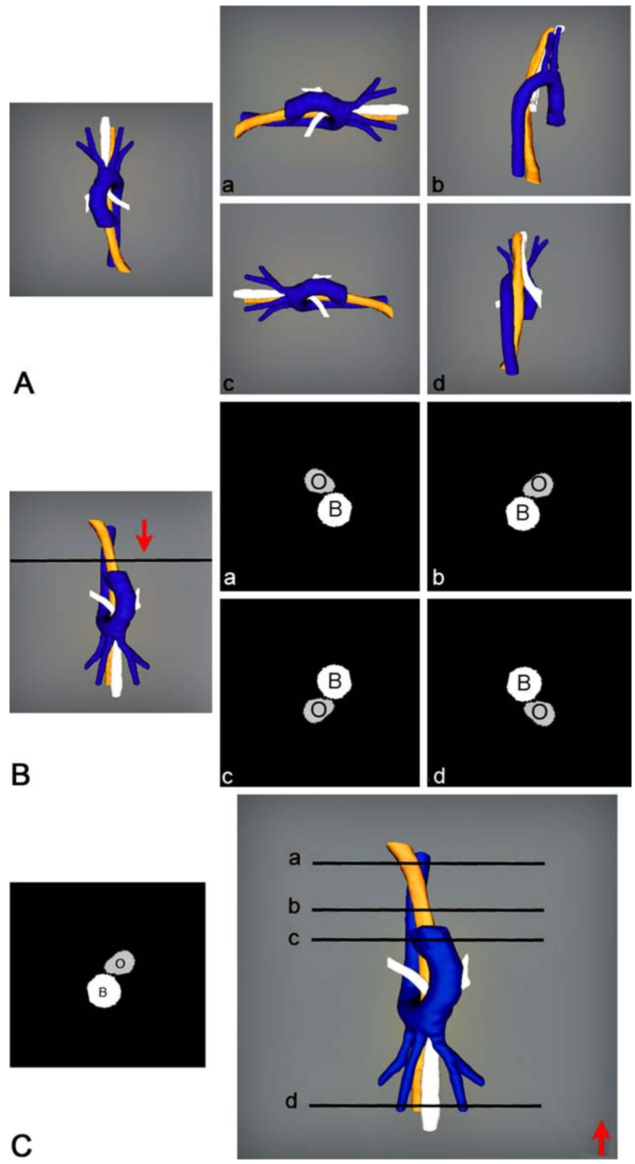

Figure 1.

Example items from the spatial anatomy task (SAT); **A**, mental rotations problem; **B**, identification problem; and **C**, localization problem. Reproduced with permission from Nguyen et al. (2012).

Study Design

After informed written consent, participants completed the required tasks on an individual basis at a computer in a quiet laboratory setting. All participants completed the MRT as a baseline measure of Vz and then the SAT as a baseline measure of spatial anatomical knowledge. Immediately after completing the SAT, participants completed the self-reflective questionnaire. Matlab (The MathWorks, Natick, MA) was

Table 1.

Descriptive Statistics for the Mental Rotations Test (MRT) and Spatial Anatomy Task (SAT)

Participants	MRT score	SAT score	Time spent on the SAT (in sec)	Accuracy of SAT responses
All ($N = 42$)	11.98 ± 5.83	15.57 ± 5.74	327.39 ± 37.47	0.67 ± 0.17
Male ($N = 18$)	14.83 ± 6.12[a]	16.5 ± 7.19	318.52 ± 42.76	0.68 ± 0.19
Female ($N = 24$)	9.89 ± 4.49	14.88 ± 4.40	334.05 ± 32.32	0.67 ± 0.15

[a]Statistical significance at $P < 0.05$.

used for the implementation of the MRT and SAT. Participants' responses to individual items on MRT and SAT were automatically recorded. The amount of time (in seconds) spent on the SAT was also recorded. Upon completion of the MRT and SAT, all participants completed a pencil and paper version of the self-reflective questionnaire.

Data Analyses

Descriptive statistics for the MRT and SAT were computed. Continuous variables were described as means and standard deviations. Ordinal variables were described as frequencies and percentages. Separate independent t-tests were used to determine if males and females differ on the MRT and SAT.

Separate Pearson's correlation analyses were used to assess the relationship between age and MRT scores, age and SAT performance, MRT scores and SAT performance, and different parts of the SAT (Parts 1, 2, and 3). Performance on the SAT included scores, time, and accuracy of SAT responses. Accuracy was calculated as the number of SAT questions solved correctly divided by the number of questions attempted. For example, if a participant attempted six questions and got three of them correct then the accuracy for this participant was 0.5 or 50%.

Responses to the self-reflective questionnaire (i.e., all questions except Question 2) were examined and multiple-choice questions with more than two option choices were pooled to produce two response categories. For example, Question 1 (see Appendix A) had five option choices before pooling: options "a," "b," "c," "d," and "e." After pooling, Question 1 had the two option choices (see Appendix B). In this example, all individuals who stated that they mentally rotated the entire tube figure were grouped into one pooled category (a), while those who stated that they did not mentally rotated the entire tube figure were grouped into the second pooled category (b).

Based on the obtained MRT scores, participants were equally distributed into one of three Vz groups—low Vz ($N = 14$), intermediate ($N = 14$), or high Vz ($N = 14$). Subsequently, separate 2 × 2 chi-square (χ^2) tests were used to determine whether responses to any of the pooled items on the self-reflective questionnaire were significantly different for subjects in the high Vz ($N = 14$) and low Vz ($N = 14$) groups. Removal of the intermediate group was done to exclude the potential for overlap occurring about the overall mean of MRT scores. This further dichotomizes individuals of high- and low-Vz and enables conclusions to be drawn as to whether high- and low-Vz individuals adopt significantly different problem-solving strategies. Yate's (continuity) corrections were used when the expected count frequency in a cell was small (i.e., <5) to reduce the chances of a Type 1 error. Finally, responses to Question 2 (see Appendix) on the self-reflective questionnaire were examined to determine which feature(s) of the anatomical model was used to assist with the mental rotations.

RESULTS

Descriptive Statistics

Forty-two students within a science ($N = 40$) and social science ($N = 2$) program at Western University participated in the study. Science students are either in the process of completing or have completed a university level anatomy course, while the social science students had never taken anatomy. Participants were between 20 and 45 years of age (mean age $= 25.38 \pm 5.86$). There were 24 (57.1%) female participants. All participants provided written consent to participate.

Descriptive statistics are presented in Table 1. Participants' MRT scores were normally distributed with a mean score of 11.98 ± 5.83. Participants' SAT scores were also normally distributed with a mean score of 15.57 ± 5.74. The average time participants spent on the SAT was 327.39 ± 37.47 sec, and accuracy of SAT responses was 0.67 ± 0.17. Analysis with sex revealed that males scored significantly higher on the MRT than females, $t(40) = 3.01$, $P < 0.05$, Cohen's $d = 0.92$. Mean MRT scores for males and females were 14.83 ± 6.12 and 9.83 ± 4.59, respectively. Differences in sex did not contribute to variations in SAT scores, $t(40) = 0.91$, $P > 0.05$, time spent on the SAT, $t(40) = -0.60$, $P > 0.05$, or accuracy of SAT responses, $t(40) = 0.81$, $P > 0.05$.

Correlations

There were no significant correlations between age and MRT scores, $r(42) = 0.17$, $P > 0.05$, age and SAT scores, $r(42) = 0.23$, $P > 0.05$, age and time spent on the SAT, $r(42) = 0.03$, $P > 0.05$, or age and accuracy of SAT responses, $r(42) = 0.13$, $P > 0.05$.

Correlations between MRT scores and the three measures of SAT performance are presented in Table 2. The analyses revealed a significant positive correlation between MRT scores and SAT scores, $r(42) = 0.72$, $P < 0.001$, a significant negative correlation between MRT scores and time spent on the SAT, $r(42) = -0.70$, $P < 0.001$, and a significant positive correlation between MRT scores and accuracy of SAT responses, $r(42) = 0.52$, $P < 0.001$.

Table 2.

Correlations Between the Mental Rotations Task (MRT) and Spatial Anatomy Task (SAT)

	MRT scores	SAT scores	Time spent on the SAT	Accuracy of SAT responses	SAT scores Part 1	SAT scores Part 2	SAT scores Part 3
MRT scores	1						
SAT scores	0.72[a] (0.51)	1					
Time spent on the SAT	−0.70[a] (0.48)	−0.67[a] (0.45)	1				
Accuracy of SAT responses	0.52[a] (0.27)	0.87[a] (0.75)	−0.44[b] (0.19)	1			
SAT scores Part 1	0.44[b] (0.20)	0.77[a] (0.60)	−0.53[a] (0.28)	0.60[a] (0.36)	1		
SAT scores Part 2	0.67[a] (0.44)	0.76[a] (0.58)	−0.58[a] (0.32)	0.66[a] (0.44)	0.34[c] (0.11)	1	
SAT scores Part 3	0.56[a] (0.32)	0.80[a] (0.64)	−0.45[c] (0.21)	0.77[a] (0.59)	0.44[b] (0.19)	0.44[b] (0.20)	1

Numbers in parentheses represent r^2 values.
Statistical significance at
[a]$P < 0.001$,
[b]$P < 0.01$,
[c]$P < 0.05$.

Table 2 also demonstrates that scores on the MRT correlated significantly with scores on each part of the SAT. Participants who scored high on the MRT tended to score high on SAT Part 1 (mental rotations questions), $r(42) = 0.44$, $P < 0.01$, Part 2 (identification questions), $r(42) = 0.67$, $P < 0.001$, and Part 3 (localization questions), $r(42) = 0.56$, $P < 0.001$. Correlations between the different parts of the SAT were also significant. Participants who scored high on SAT Part 1 tended to score high on SAT Part 2, $r(42) = 0.34$, $P < 0.05$, and Part 3, $r(42) = 0.44$, $P < 0.01$. Those who scored high on SAT Part 2 tended to score high on Part 3, $r(42) = 0.44$, $P < 0.01$.

Strategy Reports and Chi-Square Tests

Based on participant MRT scores, a tertiary split was performed to categorized participants into three Vz groups: high ($N = 14$), low ($N = 14$), and intermediate ($N = 14$). Mean MRT scores for the high Vz, low Vz and intermediate Vz groups were 18.79 ± 3.36, 6.14 ± 2.63, and 11.00 ± 1.09, respectively.

The numbers of responses for each answer option as selected by participants in the high and low Vz groups for each multiple-choice question posed on the self-reflective questionnaire are presented in Supporting Information. Variation in participants' responses to the self-reflective questionnaire suggests that there were in fact a number of different ways participants approached answering the SAT questions.

When answering SAT Part 1 (mental rotations questions), 23 (82%) participants imagined rotating the tube figure and 5 (18%) imagined translating themselves about the figure (*Question 3*). Mental transformations consisted of rotating the entire tube figure, 15 (54%), or some part of the figure, 13 (46%) (*Question 1*). Verbal processes were implemented by 6 (21%) participants to aid mental transformation (*Question 4*), and motor processes were used by 9 (32%) subjects (*Question 5*). Approximately 15 (50%) participants developed a specific approach to solving the mental rotations questions (*Question 8*). Twenty-one (75%) participants scanned the option figures systematically—trying the first, then the second, etc. (*Question 6*). Once a match had been found, 12 (43%) participants compared the rest of the option figures to target figure while 16 (67%) compared the rest of the options to the match figure (*Question 7*). Twenty-one (75%) participants were most concerned with getting the right answers and 7 (25%) were concerned with completing as many questions as possible within the given time frame (*Question 9*).

Concerning SAT Part 2 (identification questions), 22 (79%) participants imagined transforming the tube figure and 6 (21%) imagined translating themselves (*Question 11*). All participants (100%) performed the initial transformation on the tube figure rather than on a cross-sectional image (*Question 10*). Verbal processes were used by 6 (27%) participants to assist with mental transformation, and motor processes were used by 10 (36%) participants (*Question 14*). Twenty (71%) participants developed a specific approach to solving the task questions. All, but two, (93%) participants scanned the cross-sectional images systematically (*Question 12*). During the task, 21 (75%) participants were concerned with getting the right answers and 7 (25%) were concerned with completing as many questions as possible within the given time frame (*Question 16*).

When answering SAT Part 3 (localization questions), 24 (86%) participants performed the initial mental transformation on the intact tube figure and 4 (14%) on one of the cross-sectional images (*Question 17*). Verbal processes were used by 6 (21%) of participants to assist with mental transformation (*Question 18*), and motor processes were used by 7 (25%) participants (*Question 20*). Twenty-two (79%) participants developed a specific approach to solving the localization problems (*Question 21*). Twenty-three (87%) scanned the horizontal/vertical lines inherent in the diagrams systematically while

Table 3.

Relationship Between Vz, Problem-Solving Strategy, and Identification Task Performance for Question 15

	Total		Developed a strategic approach to solving the identification questions		Tried a number of different approaches	
	High Vz	Low Vz	High Vz	Low Vz	High Vz	Low Vz
N	14	14	13	7	1	7
Score on SAT Part 2	8.07 ± 1.73^{a}	4.50 ± 2.47	8.08 ± 1.80	4.57 ± 2.37	8	4.43 ± 2.70
Time spent on SAT Part 2	88.45 ± 23.7^{a}	118.66 ± 3.82	86.03 ± 22.79	118.03 ± 5.20	120	119.3 ± 1.87
Accuracy of SAT Part 2 responses	0.97 ± 0.06^{a}	0.66 ± 0.22	0.98 ± 0.46	0.70 ± 0.25	0.8	0.62 ± 0.18

[a]Statistical significance at $P < 0.05$.
SAT, spatial anatomy task; Vz, visualization.

the other 5 (18%) scanned the lines in a non-systematic way. During this task, 25 (89%) participants were concerned with getting the right answers and 7 (11%) were concerned with completing as many questions as possible within the given time frame (*Question 9*).

Subsequent chi square test analyses revealed an ability difference for question 15, $\chi^2(1, 28) = 4.38$, $P < 0.05$ (see Supporting Information). Table 3 shows the relationship between Vz, strategy preference for Question 15, and identification task performance. More high Vz subjects (93%) than low Vz subjects (50%) developed a strategic approach to solving SAT Part 2 (identification questions). The remaining eight participants utilized multiple approaches. Compared to low Vz participants, those with high Vz scored higher, $t(26) = 4.43$, $P < 0.001$, spent less time, $t(26) = -4.71$, $P < 0.001$, and were more accurate when responding to SAT Part 2 questions, $t(26) = 5.02$, $P < 0.001$. However, there appears to be no difference in the performance of high and low Vz subjects who reported developing a strategic approach to answering the identification questions versus those who tried multiple approaches.

Examination of Question 2 ("*Please explain or mark on the image below which tube(s) or tube feature(s) you used when making the comparison*") revealed that participants relied on visually salient or distinguishing features of the anatomical figure to assist with the mental rotations task problems. Fourteen (50%) participants were attentive to the curvature of the blue tube (i.e., the arch of the aorta), 14 (50%) to the three branches arising from the curvature (i.e., the brachiocephalic trunk, common carotid and subclavian arteries), 6 (21%) to the branching of the white tube (i.e., bifurcation of the trachea), 8 (29%) to the thickness of the terminal ends of the white tube (the primary bronchi), 16 (57%) to the relative position of the orange and blue tubes (i.e., relation between the esophagus and descending aorta), and 4 (14%) to the position of the three tubes (i.e., between the esophagus, aorta, and trachea).

DISCUSSION

The present study examined whether (a) there are multiple strategies used to solve the spatial anatomy task (SAT), and (b) whether the strategy choice of high- versus low- Vz individuals influences task performance. Analysis by sex revealed that males scored significantly higher on the MRT than females. This result is in line with previous studies that have established the existence of sex differences in spatial abilities favoring males (Linn and Petersen, 1985; Masters and Sanders, 1993; Peters et al., 1995; Voyer et al., 1995; Langlois et al., 2013). Sex differences, however, did not contribute to variations in SAT scores, time spent on the SAT, or accuracy of SAT responses. Performance on the SAT performance was attributed to differences in participants' Vz. Compared to low Vz individuals, those with high Vz scored higher and spent less time on the SAT. This result replicates the results reported in our previous study examining the effects of Vz on SAT performance (Nguyen et al., 2012). But beyond scores and time spent on the SAT, the current study also demonstrated that high Vz individuals solved more of the attempted questions correctly than low Vz individuals. Overall, the results supports previous findings suggesting that Vz plays a significant role in the mental rotation of anatomical structures (Stull et al., 2009), identification of the structures in two-dimensional cross-sections (Provo et al., 2002), and localization of planes corresponding to selected cross-sections (Luursema et al., 2006, 2008; Luursema and Vervey, 2011). Since Vz partially reflects greater working memory capacity (Shah and Miyake, 1996; Miyake et al., 2001), which is necessary for storing and processing visuospatial information, this might explain why high Vz individuals were more efficient and accurate when solving the SAT problems. Since Vz also reflects speed of processing information (Salthouse, 1996), this might have affected speed of encoding the SAT problems, such that high Vz subjects were able to execute the relevant mental operations faster resulting in the significant time difference between high- and low-Vz subjects.

Since the SAT involves complex mental manipulations in two- and three-dimensions, it was predicted that multiple strategies could be employed to solve the task questions. Variation in participants' responses to the self-reflective questionnaire (see Supporting Information) suggests that there were in fact a variety of strategies participants used when answering the SAT questions. These differences can be categorized into two major operations—transformation and search. "Transformation" refers to the strategies used to transform a figure to bring its orientation into congruence with another figure, and "search" refers to the strategies used to find a pair of matching or corresponding figures. Differences in transformation strategies included: establishing a frame of reference participants used during transformation (*Questions 3 and 11*), utilizing visual features to guide transformation (*Questions 1 and 2*), the object selected for transformation (*Question 17*), and the use of visual, verbal, and motor processes to aid transformation (*Questions 4, 5, 13, 14, 18, and 20*). Differences in search strategies included: the images used when finding a pair of matching figures (*Question 7*) and the use of a systematic versus non-systematic approach to scanning the option figures/choices (*Questions 6, 12, and 19*). In addition to transformation and search, there were also differences in the overall strategies participants employed over the course of entire SAT. These differences included: the use of one versus multiple problem-solving strategies (*Questions 8, 15, and 21*) and the source of motivation when answering the task questions (*Questions 9, 16, and 22*).

Interestingly, chi-square test analyses of the multiple-choice questions revealed an ability difference on the strategy employed to solve SAT Part 2 (identification problems), but not SAT Part 1 (mental rotations problems) or Part 3 (localization problems). Concerning the identification problems, individuals with high Vz more frequently used a strategic approach to solving the identification problems, while those with low Vz tried a number of different approaches. This result is consistent with the results of Stieff et al. (2012) study that found students with low Vz prefer to use alternative strategies more frequently than those with high Vz. Although chi-square test analysis revealed a strategy difference between high and low Vz participants on the identification problems, further examination of the data (Table 3) suggests that strategy choice did not contribute to variation in identification task performance, and that task performance reflects participants' Vz.

Limitations

We recognize that the present study has some limitations. This study was conducted using a self-reflective questionnaire that was developed on expectations based on behavioral/cognitive studies (e.g., Kozhevnikov et al., 2002, 2005) and the authors' experience (Nguyen et al., 2012) with how people approach problem solving. However, the questionnaire was not explicitly validated. Previous behavioral and neuroimaging studies have identified three distinct types of cognitive styles for acquiring and processing information: one verbal and two visual (object and spatial) (Kozhevnikov et al., 2002, 2005). Verbalizers consist of people who prefer to use verbal-logical modes when attempting to solve problems. Object visualizers prefer to construct high-resolution mental images of individual objects, and spatial visualizers prefer to represent and transform spatial relations among objects. Future studies are warranted to establish the validity and reliability of the self-reflective questionnaire by (1) asking experts in the field of mental imagery to review the individual items on the self-reflective questionnaire and (2) correlating the scores obtained on the questionnaire with scores on a valid and reliable instrument measuring the same construct, such as the Object-Spatial Imagery Questionnaire (QSIQ; Blajenkova et al., 2006) or the Object-Spatial-Imagery and Verbal Questionnaire (QSIVQ: Blajenkova and Kozhevnikov, 2009). The results of this study were based on a sample size of 42, and after removing the intermediate Vz group in the chi-square (χ^2) test analyses we were left with 28 participants. As a result, the chance of finding a difference on any of the multiple-choice questions posed on the self-reflective questionnaire was diminished. Furthermore, when analyzing the data, statistical significance was based on an alpha value of 0.05. The authors did not correct for multiple comparisons when analyzing the data. Therefore, the chance of committing a Type 1 error is elevated. Future studies of this type are warranted to increase the sample size to enhance the ability to detect strategy differences between high- and low-Vz individuals. Further studies are also recommended to examine other learner characteristics that could influence performance on spatial anatomical tasks. Some plausible correlates that might cause differences in performance include general intelligence, conceptual knowledge, verbal ability, and academic major. Concerning academic major, Peter et al. (1995) showed that spatial abilities are lower in humanities majors compared to science majors, and Blajenkova et al. (2006) demonstrated that visual artists and humanities professionals utilized different problem-solving strategies than scientists. Unfortunately, due to the limited number of social science majors enrolled in this study ($N = 2$) it was not possible to establish whether academic major influence spatial ability and/or preference for problem-solving strategy.

CONCLUSION

The present study revealed that there are a number of different strategies employed by students when answering spatial anatomy task (SAT) questions. However, differences in strategies did not appear to contribute to SAT performance. Variation in SAT performance was due to participants' spatial visualization ability (Vz). In addition to scoring higher and spending less time on the SAT, high Vz participants were also more accurate when answering the task questions.

Given the importance of Vz in the comprehension of visuospatial anatomical information, questions arise about the extent to which Vz is mutable. There is evidence that Vz could be improved through practice with mental rotation exercises (Peters et al., 1995; Hoyet et al., 2009) and training with rotational videogames such as Tetris (Okagaki and Frensch, 1994; Terlecki et al., 2008). Therefore, early testing of anatomy students for their Vz may be recommended to identify students with low Vz (i.e., those who have greater difficulty acquiring, representing, and manipulating mental representations of anatomy). Intervention with the appropriate mental rotation exercises or videogames could then be remedial for these students to improve their Vz and to ensure that they have the best chance of acquiring sufficient understanding of visuospatial anatomical information.

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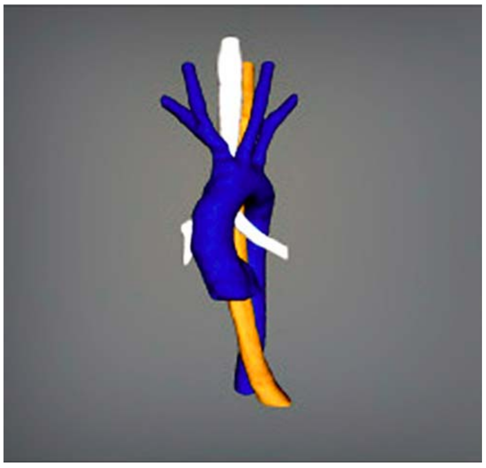
APPENDIX : A

EXAMPLE ITEMS FROM THE SELF-REFLECTIVE QUESTIONNAIRE

Question 1. While answering the **mental rotations task** questions:

a. I imagined rotating all three tubes in my mind while making the comparison
b. I imagined rotating two of the three tubes in my mind while making the comparison
c. I imagined rotating one of the three tubes in my mind while making the comparison
d. I imagined rotating part(s) of one or more tube(s) while making the comparison (e.g., the curvature of the blue tube, or the "Y" shape branch coming off the blue tube)
e. Other (explain)___________________________________

Question 2. Please explain or mark on the image below which tube(s) or tube feature(s) you used when making the comparison.



Question 16. While answering the **identification task** questions:

a. I was more concerned with getting the right answers than I was about the time limit
b. I was more concerned with getting all the answers completed than I was about getting the correct answers
c. I did not care how I did it
d. Other (explain)___________________________________

Question 20. While answering the **localization task** questions:

a. I used movements of my body (e.g., finger, head, and hand) and/or pencil to help me with the task
b. I did not use movements of my body (e.g., finger, head, and hand) and/or pencil to help me with the task
c. Other (explain)___________________________________

APPENDIX : B

EXAMPLE OF POOLED QUESTION FROM THE SELF-REFLECTIVE QUESTIONNAIRE

Question 1. While answering the **mental rotations task** questions:

a. I imagined rotating the entire tube figure in my mind while making the comparison
b. I imagined rotating part of the tube figure in my mind while making the comparison