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# Egocentric versus Allocentric Spatial Ability in Dentistry and Haptic Virtual Reality Training

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*Summary: The current study investigates the role of egocentric and allocentric spatial abilities in the field of dentistry. Whereas allocentric ability requires spatial transformation from a stationary point of reference, egocentric spatial ability is tied to the sensory-motor system, and it requires changing one's imagined perspective in space. Experiment 1 investigates the role of different spatial abilities in a tooth preparation exercise. Experiment 2 investigates the interaction of allocentric and egocentric spatial abilities with the effectiveness of haptic virtual reality training. The results show that only egocentric spatial ability was a significant predictor of success in tooth preparation. In addition, an egocentric spatial ability test was the reliable predictor of success in more complex (indirect vision) tasks during haptic virtual reality training. Our results indicate the need for the development of finer measures of the specific spatial skills that might be needed for different dental specializations. Copyright © 2013 John Wiley & Sons, Ltd.*

Dental practice involves visualization of spatial relations and anatomical structures that are not always visible. Thus, it is not surprising that the importance of spatial abilities for dental professionals has long been recognized. In the USA, the practice of assessing spatial abilities was introduced nationally in the 1950s as one of the components of the Dental Admission Test (DAT). It involved administering a battery of spatial and manual dexterity aptitude tests (e.g., the Chalk Carving Test, which required interpreting a diagram of a geometric design and carving the design accurately in a block of chalk). In 1972, the earlier spatial and dexterity tests were replaced in the DAT by the paper-and-pencil Perceptual Ability Test (PAT). The new test was adopted in the belief that spatial ability as measured by PAT has a direct relationship to a person's manual dexterity skills, that is, fine motor control and eye-to-hand fine motor coordination (DAT Users Manual, 2011).

The original validation studies by Graham (1972) demonstrated that PAT correlates with students' grades in preclinical operative classes, hands-on techniques in tooth preparation, and practical lab classes. The results from the subsequent research investigating predictive validity of PAT, however, were not consistent. Although a few studies (e.g., Bellanti, Mayberry, & Tira, 1972; Gray & Deem, 2002) reported high correlation between PAT and preclinical grades in first-year operative dentistry classes, a number of other studies found only weak to moderate correlations, suggesting that performance on PAT might not be a strong predictor of preclinical and clinical dental performance (Coy, McDougall, & Sneed, 2003; Curtis, Lind, Plesh, & Finzen, 2007; Hegarty, Keehner, Khooshabeh, & Montello, 2009; Oudshoorn, 2003; Ranney, Wilson, & Bennett, 2005; Sandow, Jones, Peek, Courts, & Watson, 2002). Moreover, Walcott, Knight, and Charlick (1986) reported that PAT failed to significantly predict individual psychomotor performance on the first-year operative dentistry exercises. Furthermore, several other studies (Manhold & Manhold, 1967; Wood, 1979) reported that tests of measuring manual dexterity skills (the original chalk-carving test or waxing test) correlated significantly more with performance in restorative dentistry than paper-and-pencil spatial tests, suggesting the spatial assessments cannot fully replace manual dexterity assessments during admission to dental schools.[1]

One possibility may be that only certain types of spatial processing are involved in dental practice. Graham (1974) reported a multiple factor structure for PAT—suggesting that it measures several components of spatial ability—and Ireland, Ripps, and Morgan (1982) reported that only the 3D subsection of PAT correlated with scores on preparing and restoring teeth in a manikin. Unfortunately, only a few studies have explored how other spatial tests, in addition to PAT, predict dental performance. Suddick, Yancey, Devine, and Wilson (1982) and Suddick, Yancey, and Wilson (1983) investigated the role of field dependence/independence in predicting clinical grades. They found that accuracy and response time on the Embedded Figures Test (identifying simple geometric figures 'embedded' in more complex figures) and the Inverted Tracing Test (mirror tracing of simple figures) were more closely correlated with clinical grades than PAT. Hegarty et al. (2009) developed a novel Object Cross-Section task that requires a participant to infer cross-sections from a picture of an unfamiliar 3D object, and they administered this task to dental students along with a number of other spatial tests, such as the Mental Rotation

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[1] Due to belief that PAT cannot fully replace fine motor skills testing, Canada, retained the carving dexterity examination. Also, PAT did not get acceptance in either Europe or Australia, where dental students are selected primarily on the basis of their academic performance, often combined with structured interviews and a number of different manual dexterity tasks such as carving a design in a block of chalk from a diagram or bending a piece of wire into a given complex shape (Boyle & Santelli, 1986; Deubert, Smith, Downs, Jenkins, & Berry, 1975; Spratley, 1992; Walcott et al., 1986).

Test (Vandenberg & Kuse, 1978), Visualization of Views Test (Eliot & Smith, 1983), and Abstract Reasoning Test (Bennet, Seashore, & Wesman, 1981). In their first study, all of the spatial ability measures were only moderately correlated with students' grades in restorative dentistry classes, and only the PAT had a significant (yet modest) correlation with students' grades in restorative dentistry in their second study (Hegarty et al., 2009).

Overall, the previous studies have not provided a clear understanding as to which components of spatial ability are critical for dental performance. Most of the previous attempts to find more predictive spatial tasks have been based on somewhat arbitrary selections of either existing spatial tests or the design of new tasks simulating elements of dental practice. Moreover, the above studies were based on a psychometric approach rather than being motivated by current cognitive theories of spatial processing.[2] The main goal of the current research was to investigate which components of spatial ability are important for dental performance, taking an experimental approach based on recent cognitive psychology and neuroscience studies on dissociation between *egocentric* and *allocentric* spatial processing.

Cognitive psychology and neuroscience research (e.g., Bryant & Tversky, 1999; Easton & Sholl, 1995; Klatzky, 1998; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999) distinguishes between two classes of spatial transformations: (1) object-based spatial transformations that involve an object-to-object or allocentric representational system and (2) egocentric perspective transformations that involve a self-to-object or egocentric representational system. The allocentric system codes information about the location of an object and its parts with respect to other objects. For instance, in a kitchen, the location of a refrigerator could be defined by its angle and distance from the sink and the stove. In contrast, the egocentric self-to-object system codes information about the location of an object and its parts with respect to the body axis of the self (left–right, front–back, up–down). In the egocentric system, the location of the refrigerator could be defined by its angle and distance from the location and facing direction of the observer. Information embedded in the allocentric representational system plays a central role in higher-order spatial cognitive processes like memory as well as in perceiving and transforming spatial representations from a fixed perspective (Burgess, 2006, 2008). The egocentric system is also involved in higher-order spatial processes (e.g., perceiving and transforming, and integrating spatial representations from different perspectives) and, in addition, is closely tied to visually guided motor actions and sensory-motor systems (Hu & Goodale, 2000; Whitney, Westwood, & Goodale, 2003).

Research findings show that the dissociation between allocentric and egocentric representational systems exists in individual differences (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001).[3] That is, spatial ability (i.e., the ability to perceive spatial relations and manipulate objects in space) can be further divided into allocentric and egocentric subabilities. *Allocentric spatial ability* (traditionally called spatial visualization ability by psychometric researchers; Carroll, 1993; Eliot & Smith, 1983; McGee, 1979) is the ability to perceive spatial relations as well as imagine rotation or transformation of objects or arrays of objects from a stationary perspective. *Egocentric* or *perspective-taking* ability (also called *spatial orientation ability*; Kozhevnikov & Hegarty, 2001; McGee, 1979) is the ability to imagine a re-oriented self and perceive spatial relations from an imagined perspective. Although allocentric and egocentric spatial abilities are correlated (Kozhevnikov, Motes, Rasch, & Blajenkova, 2006), they are still distinct abilities. The dissociation between allocentric and egocentric spatial abilities is of great importance because research evidence indicates that these spatial abilities are responsible for success in different fields and show different relationships to real-world performance. In particular, the ability to perform egocentric spatial transformations has been found to predict performance on a variety of wayfinding tasks (e.g., Kozhevnikov et al., 2006). In contrast, allocentric spatial ability was found not to be a reliable predictor of wayfinding performance (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) but an important predictor in achievement in mathematics, physics, and engineering (Kozhevnikov, Motes, & Hegarty, 2007; Kozhevnikov & Thornton, 2006; McGee, 1979). Other complex spatial tasks, such as telerobotics, might require both allocentric ability to integrate the remote arm's movements from a single observer's view and egocentric ability to integrate information from different camera perspectives (Menchaca-Brandan, Liu, Oman, & Natapoff, 2007). Similarly, in dentistry, both spatial abilities might play a role. For instance, visualizing how different parts of the tooth would look from a fixed perspective might require allocentric processing, whereas the ability to integrate information about the tooth structure from different perspectives might rely more on egocentric processing. The differential roles of egocentric versus allocentric spatial abilities, however, have never been previously examined in dental research. Although PAT includes items measuring both components of spatial ability (e.g., PAT keyhole punching items require allocentric spatial transformations, whereas PAT top-front-end view items require egocentric spatial transformations; APPENDIX A), their contributions are usually not separated in the final score.

The goal of Experiment 1 was to more finely assess the roles of egocentric and allocentric spatial abilities in a manual dexterity task and specifically to determine which of these, if any, is important for predicting performance on a preclinical tooth preparation exercise (Class II amalgam

[2] Previous research in dental education has not made a clear distinction between the concepts of spatial ability, perceptual ability, motor ability, and manual dexterity. Dental researchers have described spatial ability as 'perceptual ability' and 'manual skills' (Ranney et al., 2005) as well as 'psychomotor', 'perceptual-motor', or 'sensorimotor' skills (Evans & Dirks, 2001), often unrelated to cognitive processes as compared to academic achievements (e.g., as in Gray, Deem, Sisson, & Hammrich, 2003). From a cognitive psychology point of view, spatial ability constitutes a part of general intelligence (Eliot & Smith, 1983), and although it involves perceptual components, this ability primarily relies on cognitive (image generation and transformation) and meta-cognitive (executive attention) functions (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) not directly related to psychomotor processes.

[3] The distinction between allocentric and egocentric spatial processing, which had been made in prior experimental and neuroscience studies, does not necessarily imply a difference in performance. That is, allocentric and egocentric manipulations could be different cognitive processes and rely on separate brain systems but tap the same underlying ability in the sense that when an individual is good at allocentric manipulation, he/she is also good at egocentric manipulation, and vice versa.

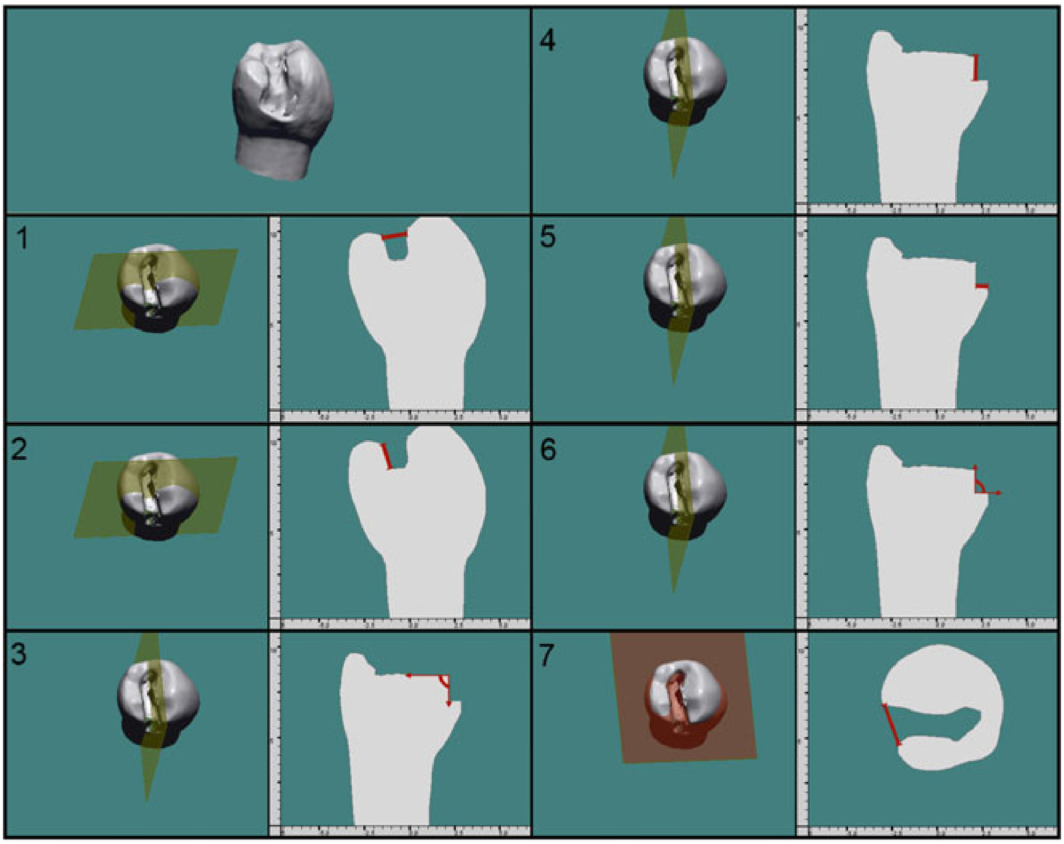



Figure 1. Class II amalgam tooth preparation task and seven criteria according to which students' tooth preparations were evaluated. Each criterion is the measured difference between a student's preparation and an 'ideal' preparation by an instructor, for the indicated distance (μm) or angle (°)

tooth preparation task).[4] The goal of Experiment 2 was to investigate the role of egocentric and allocentric spatial abilities on the efficacy of training dental students using an immersive virtual environment with haptic feedback technology. Simulation-based surgical training systems have emerged in the last several years as adjuncts in minimally invasive procedure training and the learning of new motor skills (Issenberg & Scalese, 2008; Scalese, Obeso, & Issenberg, 2008). In dentistry, haptic technology has been applied to various components of prosthetic laboratory phases and dental skill training (Buchanan, 2001, 2004; Konukseven, Önder, Mumcuoglu, & Kisnisci, 2010; Marras, Nikolaidis, Mikrogeorgis, Lyroudia, & Pitas, 2008). Although there is increasing evidence from experimental psychology that the use of immersive virtual realities and haptic technology may require more egocentric than allocentric spatial processing (Kozhevnikov & Garcia, 2011; Volcic & Kappers, 2008), little is known about how these virtual environments interact with students' spatial abilities.

## EXPERIMENT 1

### Methods

Thirty-four participants (20 women) who had not yet been exposed to any practice of dentistry were recruited from a second-year predoctoral class (Harvard School of Dental Medicine—HSDM). The students took a 2-week course in a preclinical/laboratory environment involving a number of the manual dexterity exercises. At the beginning of the course, the students completed a 2-h Class II amalgam tooth preparation task (pretest). Shortly after the course, they were asked to complete the same tooth preparation task as a posttest. In addition, at the beginning of the course, all the participants were assessed on a number of computerized egocentric and allocentric spatial tasks. The students' PAT scores were also obtained from their dental school applications.

*Tooth preparation exercise*

The tooth preparation exercise is a manual task in which the students are presented with a plastic typodont model of a tooth having a distal cavity (Figure 1). The students are asked to remove the decayed tooth structure and create a form that promotes retention of restorative material to be inserted. The extension of tooth preparation depends on the size of the decay, and it could involve only the surface that contacts the opposing tooth (Class I preparation) or/and the surface of a neighboring adjacent tooth (Class II preparation). In the current experiment, the students were asked to complete a Class II amalgam tooth preparation task, which typically involves a more extensive tooth preparation, with more surfaces and complex forms, and requires greater manual dexterity than a Class I exercise. A maximum of 2 h was allowed for the task completion.

To evaluate students' performance on this task, both pretooth and posttooth preparations were laser scanned

[4] The Class II amalgam tooth preparation task involves fine motor skills and hand–eye coordination and is often referred to as 'the manual dexterity task' in dental practice (Deubert et al., 1975; Ranney et al., 2005).

(PREPassistant, KaVo Dental GmbH, Germany) to evaluate the amount of discrepancy compared with the 'ideal tooth' preparation. The discrepancy was analyzed on the basis of seven criteria described in Figure 1. Each criterion reflects difference between a student's preparation and an 'ideal' preparation by an instructor. Five of the criteria reflect the discrepancy in the size of the decay from different perspectives, and two of them indicate the angular discrepancy. The criteria are derived from the dental licensing board examination.

*Spatial assessments*

To measure students' spatial allocentric and egocentric abilities, two parallel versions of the Pointing Direction Task (Kozhevnikov et al., 2006) were administered. One of the versions, the *Perspective-Taking Ability* (PTA) task, assesses egocentric spatial ability, whereas the second version, the *Array Rotation Ability* (ARA) task, assesses allocentric spatial ability. In addition, all the participants were tested individually on a computerized *Mental Rotation Task* (MRT) (Shepard & Metzler, 1971) assessing the ability to perform allocentric transformations. The order of the tests was counterbalanced between participants.

*Pointing Direction Task.* Both versions of the task, PTA and ARA, involve similar task formats and stimuli; however, array rotation requires a person to anticipate the appearance of an array of objects after it is rotated (allocentric rotation tasks), whereas perspective-taking requires a person to anticipate the appearance of a fixed array after a change in the person's own perspective (egocentric orientation task). Although these tasks are logically equivalent, there is considerable evidence from spatial cognition research that both children and adults show different patterns of error for the two tasks, indicating the use of different cognitive transformations (Huttenlocher & Presson, 1979; Kozhevnikov et al., 2006; Wraga, Creem, & Proffitt, 2000). In particular, perspective-taking led to egocentric errors (i.e., confusion between left and right, front and back), whereas errors in array rotation were not systematic.

The egocentric spatial ability, PTA task (Kozhevnikov et al., 2006), consisted of 36 test trails. On each trial, the participants viewed a map of a town on the computer screen (Figure 2). A small figure representing a person's head indicated the starting location, where participants were to imagine themselves standing. The eyes of the figure were looking toward one of the five locations that represented the to-be-imagined facing location (imagined heading). Participants were to indicate the direction to a third (target) location from the imagined heading. Instructions appeared at the bottom of the screen, for example 'Imagine you are the figure. You are facing the university. Point to the airport.' Thus, participants were to imagine transforming their actual perspective (i.e., an aerial perspective of the character and the town) to that of the figure's perspective, and then the participants were to imagine pointing to the target from the figure's perspective. Accuracy and response times were measured.

The allocentric spatial ability, ARA task (Kozhevnikov et al., 2006), consisted of 36 test trials using similar stimuli to PTA; however, it required the participants to mentally rotate the array rather than to rotate an imagined self. A circle with an arrow pointing to one of the five target locations on the map indicated the starting point of the to-be-imagined vector (Figure 3). Participants were to imagine a second arrow pointing to one of the five target locations (e.g., 'Imagine a second arrow pointing to the airport'). Then participants were to rotate the vector composed from these two arrows until the first arrow pointed vertically up (i.e., was aligned with a vertical axis of the computer screen). After mentally rotating the arrows, the participants were to indicate the direction where the second imagined arrow would point.

All of the locations on the map, except for the starting, facing, and target locations, were randomly placed on each trial to prevent the memorization of the map and the verbal coding of objects' locations. The set of pictures representing different layouts and the method for responding were

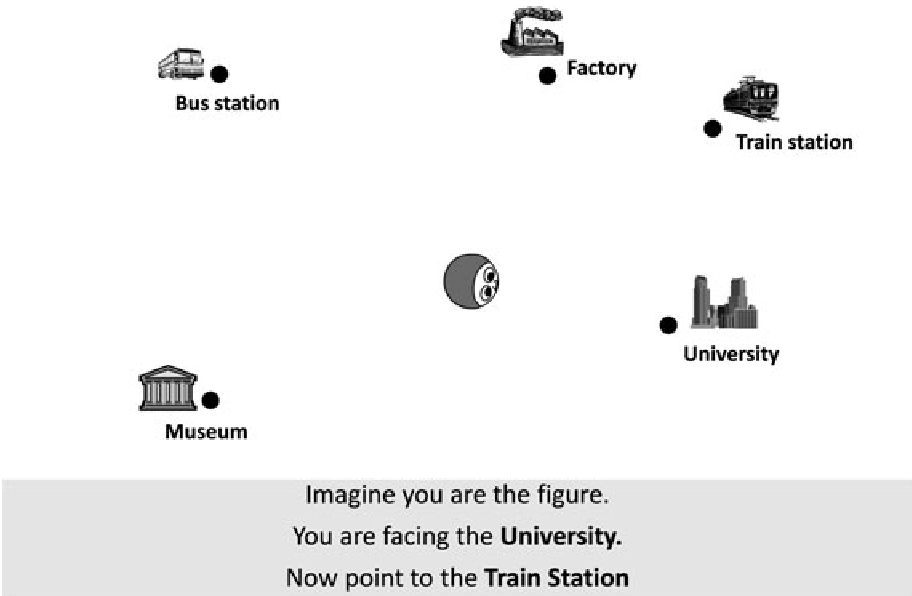



Figure 2. Example of a test trial from the Perspective-Taking Ability task

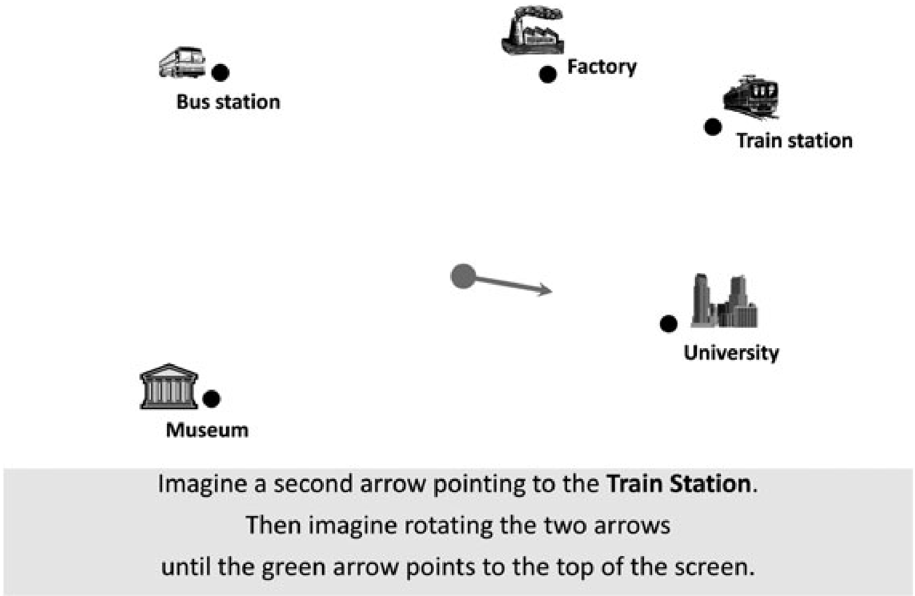



Figure 3. Example of a test trial from the Array Rotation Ability task

identical for both versions of the task. The imagined orientations (PTA task) and the angles between the direction of the green arrow and the vertical axis of the computer screen (ARA task) varied from 100° to 260° in increments of 20°. The correct response on all trials was one of four pointing directions: right-front (RF; 45° to the right), right-back (RB; 135° to the right), left-back (LB; 135° to the left), and left-front (LF; 45° to the left). To indicate the pointing direction, participants were to click on one of the arrows on a computer screen which represented four possible pointing directions (LF, RF, LB, RB); they were positioned to preserve the spatial configuration (e.g., the arrow representing the LF direction was placed on the left and above the arrow representing RB direction). Both accuracy and response times were measured.

*Mental Rotation Task (MRT).* In this allocentric task, participants observed pairs of three-dimensional geometric forms presented on the computer screen. The forms were rotated from 20° to 180°, either in the picture plane or in depth (Figure 4). On half of the trials, the second figure was a rotated version of the original stimulus, whereas on the other half of the trials, the figure was a rotated, mirror-reversed version of the original stimulus. Participants were to decide whether the two figures were the same or different. Participants

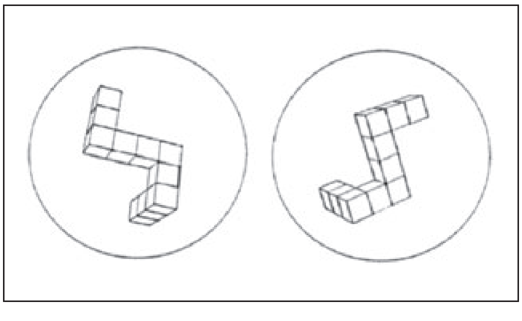


Figure 4. Example of a test trial from the Shepard and Metzler Mental Rotation Task

received eight training trials with feedback before starting the task. There were 36 test trials overall consisting of one 'same' and one 'different' trial for each of the different degrees of rotation. Both accuracy and response times were measured.

## Results and conclusions

### *Tooth preparation exercise*

For the tooth preparation exercise, each student received seven scores according to seven criteria shown in Figure 1 (lower scores indicate more accurate performance). The correlational analysis between students' scores on the seven criteria revealed that criterion 3 and criterion 6 were highly correlated with each other ($r = .54$, $p = .03$), while showing no significant correlations with other criteria, indicating that these two criteria might measure a different manual dexterity skill. Indeed, criteria 3 and 6 do not require estimates of size or a shift in perspective but rather precision in defining an exact angle. In contrast, criteria 1, 2, 4, 5, and 7 require representing spatial relations and distances between parts of complex 3D shapes. Thus, we averaged criteria 3 and 6 into one criterion of manual dexterity—M-I criterion—and the other five measures (criteria 1, 2, 4, 5, and 7) into a second criterion of manual dexterity skill—M-II.

We used repeated measures ANOVAs to investigate whether the students improved their performance on their M-I and M-II dexterity scores after the 2-week preclinical/laboratory course. The results showed that there was a significant improvement in their M-II scores between pretest and posttest sessions for all the students [$F(1, 32) = 7.25$, $p < .01$]; however, there was no significant improvement in M-I ($F < 1$). Possibly, improvement in the ability to accurately represent angles (i.e., eye-accuracy) is less susceptible to manual dexterity training than the ability to accurately represent the spatial relations and distances between parts of 3D shapes.

The descriptive statistics for M-I and M-II criteria and all spatial assessments are presented in Table 1. For spatial

Table 1. Descriptive statistics for the tooth preparation task (combined criterion statistics M-I, M-II) and the spatial assessment tests

| | | Units | Mean | *SD* |
|---|---|---|---|---|
| M-I | Pretest | Angular deviation (°) | 31.51 | 14.68 |
| | Posttest | Angular deviation (°) | 25.53 | 9.52 |
| M-II | Pretest | μm | 0.39 | 0.11 |
| | Posttest | μm | 0.32 | 0.09 |
| PTA | Accuracy | Proportion correct | 0.85 | 0.21 |
| | RT | Seconds | 14.58 | 7.43 |
| ARA | Accuracy | Proportion correct | 0.89 | 0.16 |
| | RT | Seconds | 11.82 | 5.53 |
| MRT | Accuracy | Proportion correct | 0.63 | 3.05 |
| | RT | Seconds | 4.26 | 0.45 |

assessments, all the response time (RT) data were screened for outliers (RTs ± 2.5 *SD* from an individual subject's mean RT were deleted; 4.6% out of all correct responses).

*Computation of visual-spatial efficiency*

Previous studies indicated the existence of speed-accuracy trade-off during visual-spatial task performance (e.g., an individual might show high accuracy at the expense of unusually slow response time, RT, and vice versa; Lohman & Nichols, 1990). In order to avoid confounds arising from speed-accuracy trade-offs, we used a measure of spatial processing efficiency for all the computerized spatial assessment tests that involved dividing each subject's proportion of correct responses by his or her average RT. A logarithmic transformation, ln(RT), was used to normalize the RT data that are typically positively skewed. Thus, the efficiency measure we report refers to the number of correct responses made by the subject in one unit of time, ln (seconds). This integrated measure of accuracy and RT has been used by other spatial cognition researchers as well to investigate the efficiency of visual-spatial processing and avoid the speed-accuracy confound (Kozhevnikov, Louchakova, Josipovic, & Motes, 2009).

*Correlational analysis*

The relationships between visual-spatial efficiency on the spatial assessment tests and the performance on the tooth preparation exercise were examined using Pearson product-moment correlations (Table 2). All the correlations between the spatial ability assessments and pre-M-I and post-M-I were non-significant (ranging from $r = -0.1$ to 0.18) and thus are not included in Table 2.

As can be seen from Table 2, the performance on the tooth preparation exercise as measured by the M-II variable has a significant correlation on the pretest only with the egocentric spatial ability as measured by the PTA efficiency ($p < .01$). Neither of the correlations between pretest M-II and the allocentric ability tasks were significant ($p = .14$ for correlation with MRT and $p = .42$ for correlation with ARA).

In order to compare the effect of allocentric versus egocentric abilities on pretest tooth preparation, multiple regression analysis was conducted with PTA, MRT, and ARA as predictors and pretest M-II as the dependent variable. Using the enter method, a significant model emerged [$F(3, 33) = 2.97$, $p < .05$] with adjusted $R$ square = .15. In this model, only PTA was a significant predictor (beta = −0.45, $p = .01$), whereas neither of the allocentric tasks significantly predicted performance on the tooth preparation exercise ($p = 0.6$ for MRT and 0.4 for ARA).

As for PAT, it is significantly correlated with PTA ($p < .05$), which is not surprising taking into account that some of PAT items measure egocentric ability (e.g., 'top-front-end view'). In addition, PAT tends to positively correlate with both allocentric spatial tasks (ARA and MRT). As for PAT's correlation with the pretest M-II ($r = -.25$, $p = 0.15$), it is consistent with the previous literature, although it did not reach significance for the current sample. However, the semipartial correlation between PAT and pretest M-II becomes close to zero ($sr = -.01$) after partialling out the effect of PTA efficiency. This suggests that it is mostly egocentric items in PAT that contribute to its predictive validity in tooth preparation.

Most of the correlations between the spatial ability assessments and M-II became several times weaker in the posttest. As for PTA, it shows only marginal correlation with post-M-II ($p = .06$).

*Conclusions*

Overall, the results showed that egocentric spatial ability is the most reliable predictor for tooth preparation. PTA

Table 2. The Pearson product-moment correlations among mean performances on the tooth preparation exercise (combined criterion statistic M-II) and the spatial assessment tests (visual-spatial efficiency)

| | M-II pretest | M-II posttest | PAT | PTA | ARA | MR |
|---|---|---|---|---|---|---|
| M-II pretest | — | .32* | −.25 | −.45*** | −.14 | −.26 |
| M-II posttest | | — | .03 | −.32* | −.25 | −.11 |
| PAT | | | — | .38** | .28 | .24 |
| PTA | | | | — | .29* | .25 |
| ARA | | | | | — | .32* |
| MR | | | | | | — |

***$p < .01$(two-tailed)
**$p < .05$ (two-tailed)
*$p < .10$ (two-tailed)

explains about 20% of variance on the tooth preparation exercise pretest and 10% on the posttest, in contrast to allocentric ability tests which are not reliable predictors of performance on the tooth preparation exercise. As for PAT, it explains about 6% and 0% of variance in pretest and posttest tooth preparation exercises, respectively. Semipartial correlation analysis suggests it is mostly egocentric items in PAT that contribute to its predictive validity in tooth preparation.

The fact that all the correlations between M-II and spatial assessments became reduced from pretest to posttest could be attributed to several factors. The first is that the performance on the M-II posttest might have reached a ceiling level, as the students gained all the knowledge required for the tooth preparation. The second is that after the students have acquired all the procedural knowledge about how to prepare the tooth, the role of spatial cognitive processing has diminished. Indeed, previous research that investigated correlations between spatial ability and surgical skills has also shown that the role of spatial abilities can diminish as skills become increasingly automatic (Keehner, Lippa, Montello, Tendick, & Hegarty, 2006).

Figure 5. SensAble PHATOM Omni® haptic device used for training

## EXPERIMENT 2

### Method and materials

Seventeen volunteers out of the 34 students who participated in Experiment 1 were then randomly selected for additional haptic training. The haptic training was completed individually and lasted for 2 h and 30 min. The students selected for haptic training completed five exercises using a haptic device (SensAble PHANTOM Omni, Figure 5). These exercises trained participants to remove the maximum amount of various geometric shapes, within predetermined width and depth boundaries using the haptic device. In total, students were exposed to five exercises of the manual dexterity module of the Individual Dental Education Assistant (IDEA) software: (1) straight-line direct vision, (2) circle direct vision, (3) heart-shape direct vision, (4) line—indirect vision, and (5) rectangle—indirect vision (see examples in Figure 6). Indirect vision (IV) refers to the fact that the software gives an indirect view of the task object that is like looking at the object in a hand-held mirror. The position and orientation of the virtual mirror is controlled by the user with the haptic device in a manner that is similar to the way a dental mirror is used to inspect a tooth. The software detects any areas that extend beyond the specified outlines and measures the amount of over-preparation. Tutorials and demonstrations were performed by one of the investigators, and students were allowed two practice sessions in order to become familiar with the haptic environment.

There were several measurements in relation to performance on each haptic task. First, students performed a number of attempts (trials) until they were able to complete the exercise within the time allotted for each task (e.g., straight line—1.20 min, circle—1.10 min, heart shape—1.30 min,

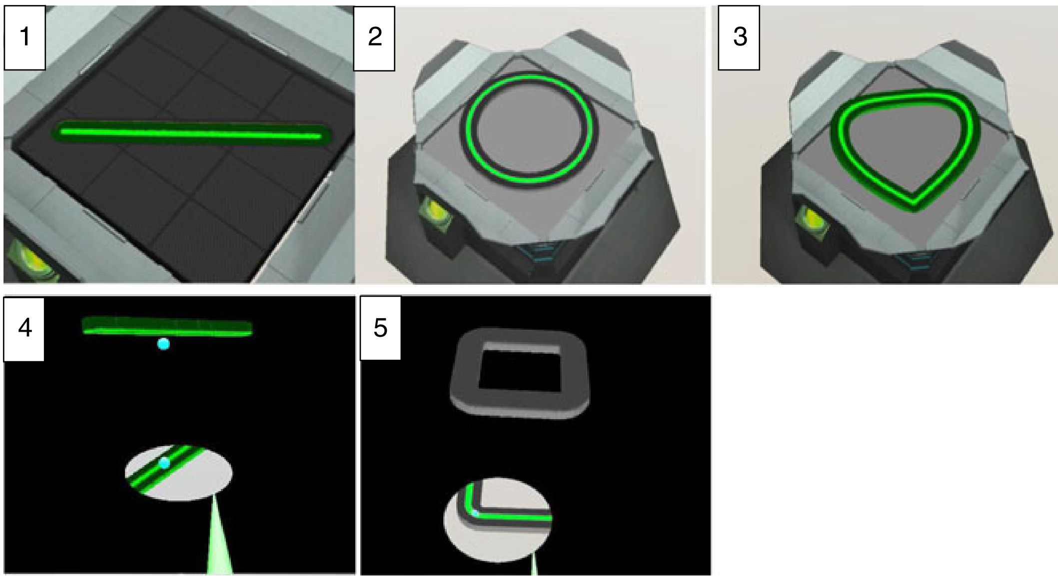



Figure 6. Example of exercises used for haptic training (1, straight-line direct vision; 2, circle direct vision; 3, heart-shape direct vision; 4, line indirect vision; 5, rectangle indirect vision). The ‘material’ to be removed in the exercises was indicated in green

IV line—1.20 min, IV square—1.30 min). Their accuracy (percent completed) and amount of time to complete each exercise across all attempts were recorded.

The spatial assessments of the students obtained in Experiment 1 were used for the analysis in Experiment 2.

### Results and conclusions

In order to evaluate performance in the haptic training, we computed 'haptic task efficiency' for each haptic exercise as: the percentage of the task completed accurately in a unit of time. Mean efficiency was computed for each haptic task for each participant across all attempts after initial training on the task. The first haptic task (straight-line) efficiency was calculated separately because this was a preliminary exercise that only required cutting a simple line, whereas the other tasks required manipulating geometric shapes that were more complex. The efficiencies for haptic tasks 2 and 3 were averaged because both tasks were of similar complexity and required direct vision (Haptic DV). The efficiencies for haptic tasks 4 and 5 were also averaged because both tasks required indirect vision (Haptic IDV).

Table 3 shows correlations among the visual-spatial efficiencies observed in the different spatial assessments and haptic task efficiencies. Haptic task 1 (line task) seems to be a simple task, and performance on this task is not correlated with performance on the more complex Haptic DV and Haptic IDV tasks. Overall the results show a pattern of increasing correlations between PTA efficiency and haptic efficiency with increasing haptic task complexity, reaching significance for Haptic IDV ($r = .52$, $p = .03$). Neither of the correlations between Haptic IDV and allocentric ability tasks reached significance ($p = .11$ for correlation with ARA, and $p = .40$ for correlation with MRT).

In order to compare the effect of allocentric versus egocentric abilities on the Haptic IDV task, multiple regression analysis was conducted with PTA, MRT, and ARA tasks as predictors and Haptic IDV task efficiency as the dependent variable. Using the enter method, a significant model emerged [$F(3,\ 16) = 3.51$, $p < .05$] with adjusted $R$ square = .31. In this model, only PTA was a significant predictor (beta = .68, $p < .05$) whereas neither MRT nor ARA task significantly predicted performance on the Haptic IDV tasks ($p$s > . 27).

*Conclusions*

The current results suggest that only egocentric ability as measured by PTA is a reliable predictor of success in haptic training tasks, particularly for more complex tasks that require indirect vision. Similar to telerobotics tasks where egocentric ability is required to integrate information from different camera perspectives (Menchaca-Brandan et al., 2007), integration of different perspectives required by indirect vision tasks in the haptic simulator seem to rely mostly on egocentric spatial transformations, where an observer is required to imagine moving himself/herself to different position in relation to the target object.

## DISCUSSION

The current research shows that egocentric spatial ability is an important component of spatial ability for predicting dental performance. In Experiment 1, only an egocentric ability assessment (PTA), but not allocentric assessments (MRT and ARA), significantly predicted performance on the tooth preparation exercise. The results of Experiment 2 extend these findings, showing that performance in a haptic simulator was also significantly related only to egocentric ability.

These results may be explained by current cognitive neuroscience and psychology theories, according to which allocentric and egocentric spatial processing are governed by distinct cognitive and neurological processes (e.g., Klatzky, 1998; Zaehle et al., 2007). The literature suggests that it is egocentric frames of references that are tied to perceptual and sensory-motor systems and that the formation of egocentric representations is based on our experiences with goal-directed manual manipulation with objects (Gilmore & Johnson, 1997). Hu and Goodale (2000) argued that human motor actions directed towards objects are 'computed within an egocentric frame of reference,' in contrast to perception, which does not require control of motor actions and could be based on allocentric reference frames. Thus, it is not surprising that it is the egocentric frame of reference that might be crucial for manual dexterity tasks such as tooth preparation and haptic training, which are heavily based on hand–eye coordination and fine motor skills.

Furthermore, although egocentric spatial processing is closely tied to the sensory-motor system, it also relies on higher-level spatial cognitive processes (e.g., imagining and mentally integrating visual-spatial information from different perspectives), which seem to be important for both tooth preparation exercises and haptic training. The tooth preparation exercises in our study involved such egocentric high-level cognitive processes as visualizing how the parts of the tooth would look from different orientations and integrating the views into one 3D image of a tooth. Similarly, the indirect vision exercises during haptic training involved visualizing the object from a hand-held mirror view. This

Table 3. The Pearson product-moment correlations among performance on the haptic tasks (haptic task efficiency) and the spatial assessment tests (visual-spatial efficiency)

| | Haptic 1 | Haptic DV | Haptic IDV | PAT | PTA | ARA | MR |
|---|---|---|---|---|---|---|---|
| Haptic 1 | — | .01 | .07 | .36 | .37 | .32 | .35 |
| Haptic DV | | — | .57** | .32 | .43* | .40 | .03 |
| Haptic IDV | | | — | .27 | .52** | .40 | .21 |

**$p < .05$ (two-tailed)
*$p < .10$ (two-tailed)

could explain significant correlations reported in our experiments between these tasks and egocentric but not allocentric spatial ability tests. This explanation is further supported by our informal interviews with expert dentists, who reported that during similar dental procedures they usually visualize themselves in different positions relative to the tooth rather than mentally rotating it. At the same time, other dental practices, such as comprehending a dental radiograph, diagnostics, judgment, and decision-making about appropriate dental treatments, might rely more on allocentric than egocentric spatial transformations. For example, it might be important for root canal specialists to imagine the invisible 3D structure of a root canal from a stationary allocentric perspective. Further research is needed to identify measures of the specific spatial skills that are required for different dental specializations and procedures.

Interestingly, in Experiment 1, the relationship between egocentric spatial ability and the tooth preparation task was significant only for pretest, and it is decreased on the posttest after students completed manual dexterity training. This may indicate that acquisition of expertise encourages procedural skills, which somewhat decreases the importance of egocentric spatial processing. Indeed, many schools believe that manual dexterity is a trainable skill rather than a fixed ability, and thus it should not be used as a requirement for dental admission. There is also substantial evidence that studying dentistry significantly improves manual skills (Luck, Reitemeier, & Scheuch, 2000). This idea is consistent with studies that reported that the relationship between PAT and dental students' preclinical and clinical performance diminished with years of dental practice (Coy et al., 2003; Poole, Catano, & Cunningham, 2007). It should be noted, however, that the above studies investigated the relationship between spatial ability and dental performance that is primarily related to manual dexterity. Dental performance that involves higher-order cognitive skills (e.g., diagnostics) may be less likely to become automatic, even after extensive training. Future research is needed to investigate how the correlation with spatial abilities changes with experience in dentistry, not only in manual dexterity tasks but also in other tasks involving higher-order cognitive skills (decision-making, judgment).

The results of Experiment 2 indicate that egocentric ability may play a crucial role in haptic training especially for more complex tasks, such as indirect vision tasks, that require integration of multiple perspectives. The results indicate that it is important to study the role of individual differences in training in haptic environments. Although these new training environments may be very appealing to users, they are not necessarily efficient. For example, Gray et al. (2003) reported that the expected significant correlation between performance on a simulator and performance in the second preclinical restorative technique laboratory was not found. The results of the current study show that one reason for inconsistent findings could be a large variation in students' egocentric and allocentric spatial abilities that influences the effectiveness of learning and training in virtual environments. This raises a question for future studies as to whether haptic environments are equally beneficial for training students of low versus high egocentric spatial abilities.

Finally, our results indicate the need for revising PAT as part of the dental school admission test. As mentioned before, PAT is composed of both allocentric and egocentric items. For instance, such PAT items as imagining a flat sheet folded into a 3D object and the paper folding test (imagining how a sheet would look if it were folded, pierced, and unfolded) are purely allocentric and require transforming an image from a fixed perspective. Other parts of PAT require adopting different egocentric perspectives (e.g., 3D subsection). However, the number of egocentric and allocentric items are not equal, and furthermore, the admissions process for dental schools does not differentiate between them but rather depends on one composite score. On the basis of our study, a reasonable recommendation for the future development of dental admission assessments would be to separate different sub-scores of PAT (allocentric and egocentric) and look at their predictive power separately.

Another problem with current admission is that solving PAT problems may be achieved by verbal–analytical strategies. For example, there are existing non-spatial analytical techniques for 'cracking' PAT (e.g., http://predds.net/pat-techniques/) which are popular among matriculants, suggesting that both allocentric and egocentric components of PAT can be solved analytically. Moreover, as reported in cognitive psychology literature, most of the tests designed to measure spatial egocentric ability are often solved allocentrically by mentally rotating the stimulus rather than by reorienting oneself (Barratt, 1953; Carpenter & Just, 1986; Carroll, 1993). Recent studies suggested that one of the few relatively reliable instruments to measure egocentric spatial ability is the perspective-taking test (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Kozhevnikov et al., 2006), which was used in the current study. Thus, we suggest that introducing more advanced and finer-grained methods of assessments of spatial ability—and specifically egocentric spatial ability tests, such as two-dimensional and three-dimensional perspective-taking tasks (see Kozhevnikov & Garcia, 2011, for a review)—would be an important step in predicting dental performance.

## REFERENCES


Barratt, E. S. (1953). An analysis of verbal reports of solving spatial problems as an aid in defining spatial factors. *Journal of Psychology*, *36*, 17–25.

Bellanti, N. D., Mayberry, W. E., & Tira, D. E. (1972). Relation between selected predictor variables and grades in fixed prosthodontic laboratory. *Journal of Dental Education*, *36*(12), 16–21.

Bennet, G. K., Seashore, H. G., & Wesman, A. G. (1981). *Differential aptitude tests—Space relations test*. Sidcup, UK: The Psychological Corporation.

Boyle, A. M., & Santelli, J. C. (1986). Assessing psychomotor skills: The role of the Crawford small parts dexterity test as a screening instrument. *Journal of Dental Education*, *50*(3), 176–9.

Bryant, D. J., & Tversky, B. (1999). Mental representations of spatial relations from diagrams and models. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 137–156.

Buchanan, J. A. (2001). Use of simulation technology in dental education. *Journal of Dental Education*, *65*(11), 1225–31.

Buchanan, J. A. (2004). Experience with virtual reality-based technology in teaching restorative dental procedures. *Journal of Dental Education*, *68*, 1258–1265.

Burgess, N. (2006). Spatial memory: How egocentric and allocentric combine. *Trends in Cognitive Sciences*, *10* (12), 552–557.

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, *1124*, 77–97.

Carpenter, P. A., & Just, M. A. (1986). Spatial ability: An information processing approach to psychometrics. In R. J. Sternberg (Ed.), *Advances in the Psychology of Human Intelligence*, Vol. 3 (pp. 221–253). New Jersey: LEA.

Carroll, J. (1993). *Human cognitive abilities: A survey of factor analytical studies*. New York: Cambridge University Press.

Coy, K., McDougall, H., & Sneed, M. (2003). Issues regarding practical validity and gender bias of the perceptual abilities test (PAT). *Journal of Dental Education*, *67*, 31–37.

Curtis, D. A., Lind, S. L., Plesh, O., & Finzen, F. C. (2007). Correlation of admissions criteria with academic performance in dental students. *Journal of Dental Education*, *71*, 1314–1421.

DAT Users Manual (2011). Dental admission testing program user's manual. Report 3.

Deubert, L. W., Smith, M. C., Downs S., Jenkins, C. G. B., &Berry, D. C. (1975). The selection of dental students: A pilot study of an assessment of manual ability by practical tests. *British Dental Journal*, *139*(9), 357–61.

Easton, R. D., & Sholl, M. J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(2), 483–500.

Eliot, J., & Smith, I. M. (1983). *An international directory of spatial tests*. Windsor, Berks: Nfer-Nelson.

Evans, J. G., & Dirks, S. J. (2001). Relationships of admissions data and measurements of psychological constructs with psychomotor performance of dental technology students. *Journal of Dental Education*, *65*, 874–882.

Gilmore, R. O., & Johnson, M. H. (1997). Body-centered representations for visually-guided action emerge in early infancy.*Cognition*, *65*, B1–B9.

Graham, K. S. (1972). Substitution of perceptual-motor ability test for chalk carving in dental admission testing program. *Journal of Dental Education*, *36*, 9–14.

Graham, J. W. (1974). Factor analysis of the perceptual-motor ability test. *Journal of Dental Education*, *38*, 16–19.

Gray, S., & Deem, L. (2002). Predicting student performance in pre-clinical technique courses using the theory of ability determinants of skilled performance. *Journal of Dental Education*, *66*, 721–727.

Gray, S. A., Deem, L. P., Sisson, J. A., & Hammrich, P. L. (2003). The predictive utility of computer-simulated exercises for preclinical technique performance. *Journal of Dental Education*, *67*(11), 1229–33.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*, *32*, 175–191.

Hegarty, M., Keehner, M., Khooshabeh, P., & Montello, D. R. (2009). How spatial abilities enhance, and are enhanced by, dental education. *Learning and Individual Differences*, *19*, 61–70.

Hegarty, M., Richardson, A. E., Montello, D. R., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence*, *30*, 425–447.

Hu, Y., & Goodale, M. A. (2000). Grasping after a delay shifts size-scaling from absolute to relative metrics. *Journal of Cognitive Neuroscience*, *12*, 856–868.

Huttenlocher, J., & Presson, C. C. (1979). The coding and transformation of spatial information. *Cognitive Psychology*, *11*, 375–394.

Ireland, E. J., Ripps, A. H., & Morgan, K. S. (1982). Stereoscopic vision and psychomotor learning in dental students. *Journal of Dental Education*, *46*, 697–698.

Issenberg, S. B., & Scalese R. J. (2008). Simulation in health care education. *Perspectives in Biology and Medicine*, *51*, 21–46.

Keehner, M., Lippa, Y., Montello, D. R., Tendick, F., & Hegarty, M. (2006). Learning a spatial skill for surgery: How the contributions of abilities change with practice. *Applied Cognitive Psychology*, *20*, 487–503.

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial cognition—An interdisciplinary approach to representation and processing of spatial knowledge* (Lecture Notes in Artificial Intelligence 1404) (pp. 1-17). Berlin: Springer-Verlag.

Konukseven, E. I., Önder, M. E., Mumcuoglu, E., & Kisnisci, R. S. (2010). Development of a visio-haptic integrated dental training simulation system. *Journal of Dental Education*, *74*, 880–891.

Kozhevnikov, M., & Garcia, A. (2011). Visual-Spatial Learning and Training in Collaborative Design in Virtual Environments. In X. Wang, & J. Jen-Hung (Eds.), *Collaborative design in virtual environments* (pp.17-26). Intelligent Systems, Control and Automation: Science and Engineering, Vol. 48. Springer: Netherlands.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition 29*(5), 745-756.

Kozhevnikov, M., & Thornton, R. (2006). Real-time data display, spatial visualization ability, and learning force and motion concepts. *Journal of Science Education and Technology*, *15*, 113–134.

Kozhevnikov M., Louchakova O., Josipovic Z., & Motes M. A. (2009). The enhancement of visuospatial processing efficiency through Buddhist deity meditation. *Psychological Science*, *20*(5), 645–653.

Kozhevnikov, M., Motes, M., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Sciences*, *31*, 549–579.

Kozhevnikov, M., Motes, M., Rasch, B., & Blajenkova, O. (2006). Perspective-taking vs. mental rotation transformations and how they predict spatial navigation performance. *Applied Cognitive Psychology*, *20*, 397–417.

Lohman, D. F., & Nichols, P. D. (1990). Training spatial abilities: Effects of practice on rotation and synthesis tasks. *Learning and Individual Differences*, *2*, 67–93.

Luck, O., Reitemeier, B., & Scheuch, K. (2000). Testing of fine motor skills in dental students. *European Journal of Dental Education*, *4*(1), 10–4.

Manhold, J. H. Jr., & Manhold, B. S. (1967). Predictive value for four year performance of individual parts of the Dental Aptitude Test. *Journal of Dental Education*, *31*(1), 62–70.

Marras, I., Nikolaidis, N., Mikrogeorgis, G., Lyroudia, K., & Pitas, I. (2008). A virtual system for cavity preparation in endodontics. *Journal of Dental Education*, *72*(4), 494–502.

McGee, M. G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin*, *86*, 889–918.

Menchaca-Brandan, M., Liu, A. M., Oman, C. M., & Natapoff, A. (2007). Influence of perspective-taking and mental rotation abilities in space teleoperation. *2nd ACM/IEEE Conference on Human-Robot Interaction* (HRI 07), Washington, DC.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology. General*, *130*, 612–640.

Oudshoorn, W. C. (2003). The utility of Canadian DAT perceptual ability and carving dexterity scores as predictors of psychomotor performance in first-year operative dentistry. *Journal of Dental Education*, *67*(11), 1201–1208.

Poole, A., Catano, V. M., & Cunningham, D. P. (2007). Predicting performance in Canadian dental schools: The new CDA structured interview, a new personality assessment, and the DAT. *Journal of Dental Education*, *71*(5), 664–676.

Ranney, R. R., Wilson, M. B., & Bennett, R. B. (2005). Evaluation of applicants to predoctoral dental education programs: Review of the literature. *Journal of Dental Education*, *69*, 1095−1106.

Sandow, P. L., Jones, A. C., Peek, C. W., Courts, F. J., & Watson, R. E. (2002). Correlation of admission criteria with dental school performance and attrition. *Journal of Dental Education*, *66*(3), 385–92.

Scalese, R. J., Obeso, V. T., & Issenberg, S. B. (2008). Simulation technology for skills training and competency assessment in medical education. *Journal of General Internal Medicine*, *23*, 46–49.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*(3972), 701–703.

Spratley, M. H. (1992). Regression analysis of dexterity tests and dental students' practical examination results. *Australian Dental Journal*, *37*(6), 461–6.

Suddick, R. P., Yancey, J. M., Devine, S., & Wilson, S. (1982). Field dependence-independence and dental students' clinical performance. *Journal of Dental Education*, *46*, 227–232.

Suddick, R. P., Yancey, J. M., & Wilson, S. (1983). Mirror-tracing and embedded figures tests as predictors of dental students' performance. *Journal of Dental Education*, *47*, 149–154.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotation, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*, 599–604.

Volcic, R., & Kappers, A. M. L. (2008). Allocentric and egocentric reference frames in the processing of three-dimensional haptic space. *Experimental Brain Research*, *188*, 199–213.

Walcott, A. M., Knight, W. G., & Charlick, R. E. (1986). Waxing tests as predictors of students' performance in preclinical dentistry. *Journal of Dental Education*, *50*, 716–21.

Whitney, D., Westwood, D. A., & Goodale, M. A. (2003). The influence of visual motion on fast reaching movements to a stationary object. *Nature*, *423*, 869–873.

Wood, W. W. (1979). Grade averages and DAT scores as predictors of performance in dental school. *Journal of Dental Education*, *43*, 630–632.

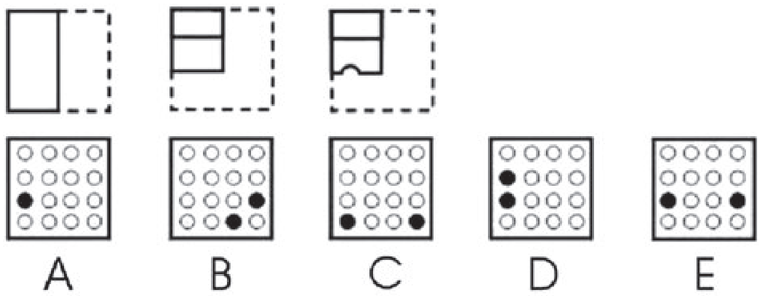
Wraga, M., Creem, S. H., & Proffitt, D. R. (2000). Updating displays after imagined object- and viewer rotations. *Journal of Experimental Psychology: Learning, Memory, and Cognition 26*(1), 151–168.

Zacks, J., Rypma, B., Gabrieli, J. D. E., Tversky, B., & Glover, G. H. (1999). Imagined transformations of bodies: An fMRI investigation. *Neuropsychologia*, *37*, 1029–1040.

Zaehle, T., Jordan, K., Wüstenberg, T., Baudewig, J., Dechent, P., & Mast, F. W. (2007). The neural basis of the egocentric and allocentric spatial frame of reference. *Brain Research*, *1137*, 92–103.

## APPENDIX A

PAT keyhole punching




PAT top front end view