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Chapter 11

The Role of Spatial Cognition in Medicine: Applications for Selecting and Training Professionals

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> I watched how she swabbed his chest with antiseptic, injected lidocaine, which is a local anesthetic, and then, in full sterile garb, punctured his chest near his clavicle with a fat three-inch needle on a syringe. The patient hadn't even flinched. She told me how to avoid hitting the lung. ("Go in at a steep angle" she'd said. Stay *right* under the clavicle"), and how to find the subclavian vein, a branch of the vena cava lying atop the lung near its apex. (Gawande, 2002, p. 53)

The previous account of a novice surgeon learning how to insert a central line is a dramatic demonstration of the importance of spatial cognition in medicine. All medical professions depend on a detailed understanding of anatomy, which involves such spatial concepts as the shape of anatomical structures (e.g., the lungs), where they are located relative to each other (e.g., "the subclavian vein lays atop the lung"), and how they are connected (e.g., "the subclavian vein is a branch of the vena cava"). When carrying out medical procedures the internal structures of the body are not directly visible, so that medical professionals have to rely on their mental spatial representations of these structures and awareness of human variability.

Spatial cognition is central to understanding medical images, including those produced by CT, MRI, X-Ray, and ultrasound. These medical images are essentially two-dimensional slices of three-dimensional objects. In interpreting medical images, specialists have to infer the three-dimensional structure of the anatomy of a specific patient on the basis of the two-dimensional view given in the image and their knowledge of anatomy. Interpretation of medical images, therefore, relies centrally on spatial representations and processes.

Surgery in particular relies strongly on internal representations and transformations of spatial information. The surgeon must develop a mental model of internal three-dimensional anatomy based on surface views or cross sections from X-ray, CT, MRI, or ultrasound images. From this three-dimensional model and a surgical goal, he or she must plan a strategy to navigate to the part of the anatomy to be operated on, often following natural paths provided by various types of ducts, recognizing landmarks provided by distinctive structures, and avoiding sensitive tissues such as large blood vessels. With the advent of minimally invasive techniques, the surgeon must rely on a video image of the internal anatomy showing anatomical structures from unusual angles never seen in anatomy textbooks, and must use instruments constrained by a fulcrum at their passage through the skin. Consequently, the performance of surgical tasks requires a broad range of spatial processes in order to plan, navigate, and reason using complex representations of space.

The importance of spatial thinking in medicine raises two questions that can be informed by research in spatial cognition. First, should spatial ability tests be used to select individuals for medical training? In fact, using spatial tests in this way is the practice in at least one medical specialty, dentistry. The admissions test used in dentistry schools in the United States includes a spatial abilities tests known as the Perceptual Aptitude Test, which includes items such as judging the relative sizes of angles, and imagining the folding and unfolding of pieces of paper (see examples in Fig. 11.1).

The decision to use this test in dentistry admissions reflects an *ability* model of individual differences in medical performance, that is, that success

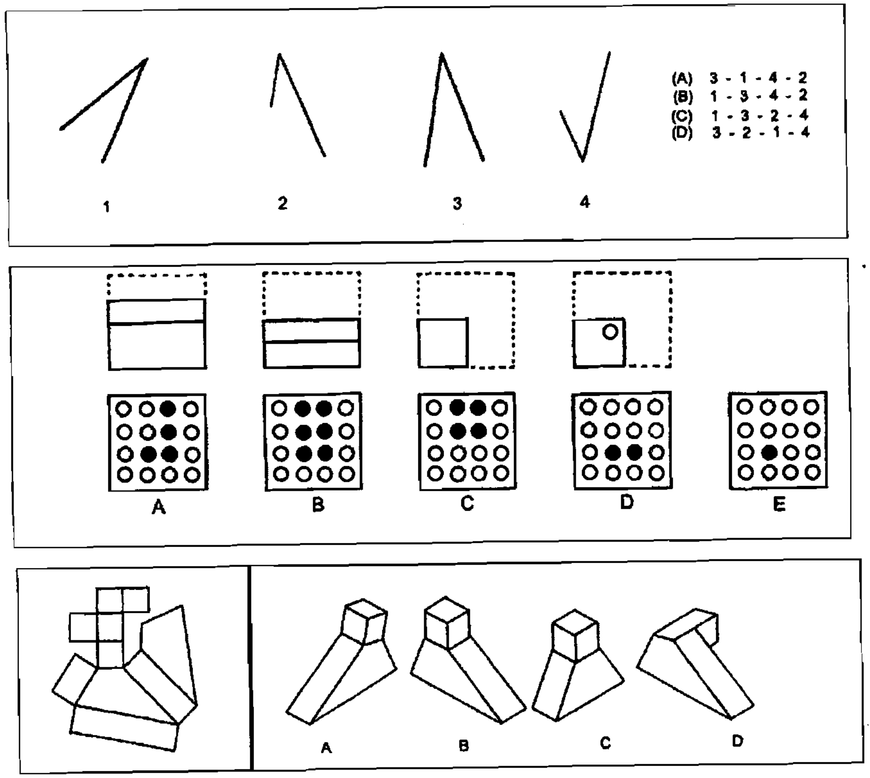

Fig. 11.1.
Examples of test items from the Perceptual Aptitude Test, which is a subtest of the Dental Admission Test. In the first example, the task is to order the angles in terms of size. In the second item the test-taker must choose which of the 5 options on the bottom would result if a piece of paper was folded, a hole was punched in the folded paper, and the paper was subsequently unfolded, as shown on top. In the third item, the test-taker must choose which of the shapes on the right would result if the figure on the right was folded into a three-dimensional object.

in the profession depends on domain-general abilities, notably spatial ability. The question of using spatial abilities to select individuals for training is also a topic of current debate in surgery (Gilligan, Welsh, Watts, & Treasure, 1999; Graham & Deary, 1991). However in surgery, the dominant model of performance is a *skill* model. As expressed by Gawande (2002):

> Surgeons, as a group, adhere to a curious egalitarianism. They believe in practice, not talent. ... To be sure, talent helps. ... nonetheless, attending surgeons say that what's most important to them is finding people who are conscientious, industrious, and boneheaded enough to keep practicing this one difficult thing day and night for years on end. (pp. 55–56)

The contrast between admissions policies in dentistry and surgery raises important questions about the relative contributions of spatial abilities and experience to performance in medicine, as well as questions about how these two factors interact.

A second question that can be informed by research in spatial cognition is that of how best to train medical personnel, especially given the availability of new technologies such as computer visualizations and virtual environments. Until recently, anatomy teaching has relied on resources such as printed diagrams, bench-top models, and cadaver dissection laboratories. Compared with today's technologies, however, these traditional learning materials have a number of limitations (Tendick et al., 2000). Diagrams are unavoidably restricted to two dimensions, generally entail only cardinal views, and bear little resemblance to real anatomy, while bench-top models are often useable only once, as they are of little value once they have been "dissected." Cadavers, although perhaps the most naturalistic of these materials, are rare commodities, whose use in medical schools is becoming increasingly restricted due to the expense of maintaining dissection laboratories. Unlike these traditional materials, computer visualizations are flexible, permitting the alteration of parameters such as anatomical variability, disease-state, or viewpoint perspective. They can also be reused with little cost. As a result, medical education has recently begun a dramatic shift towards introducing digital representations into its learning programs. In their statement on the future of medical training, the Association of American Medical Colleges (AAMC) states: "The capability of computing and communicating technologies to deliver high quality learning experiences to a diverse audience is one of the most promising aspects of computer-mediated education" (Florance, 2002, p. 1).

In this chapter, we first review previous literature demonstrating the role of spatial thinking in medical performance and training. We then outline the general approach of our research group to studying spatial cognition in medicine and describe progress on two current projects, one concerning the role of spatial thinking in laparoscopic surgery (i.e., minimally invasive surgery of the abdomen) and a second concerning the comprehension of cross-sectional diagrams and images, a skill that is important in many medical specialties.

PREVIOUS RESEARCH ON THE ROLE OF SPATIAL THINKING IN MEDICINE

Correlational Studies

As just discussed, the study of anatomy, one of the fundamental components of medical training, involves many spatial concepts. From a cognitive perspective, an important theoretical question concerns the nature of the mental representations that support anatomical knowledge and reasoning, for example, whether this knowledge is based on spatial or propositional representations. One type of evidence for spatial representations is that some students with low spatial abilities have a difficult time acquiring a spatial understanding of anatomy. For example, Rochford (1985) had experts classify questions from anatomy tests as either spatial or nonspatial and developed spatial ability tests that involved rotation, visualization, synthesis, and sectioning of geometrical shapes. The spatial ability tests reliably predicted achievement in anatomy classes, with low-spatial medical students attaining consistently lower marks than high-spatial individuals in both practical anatomy examinations and multiple-choice questions classified as spatially three-dimensional. By contrast, high- and low-spatial students performed equally well on tests of *nonspatial* anatomical knowledge. Although some low-spatial students were able to acquire a spatial understanding of anatomy with time, others never acquired this understanding. These findings imply that spatial abilities may be central in constructing an accurate spatial mental model of anatomy (see also Provo, Lamar, & Newby, 2002).

A similar relationship has been established within the field of dentistry, with spatial reasoning predicting success in the anatomically demanding fields of operative dentistry, endodontics, anatomy, and dental anatomy (Just, 1979). In fact, the dentistry profession has recognized the importance of spatial abilities for some time, and since the late 1940s, the Dental Admission Test (DAT) of the American Dental Association, used to select people for admission to dentistry school throughout the United States, has included a pencil-and-paper test of spatial ability known as the Perceptual Aptitude Test (Dailey, 1994; Peterson, 1947). Originally, the DAT also included a more practical Chalk Carving test, which involved interpreting a diagram of a detailed design and carving the design accurately in a block of chalk. However, in 1972, following extensive research (Graham, 1972), the chalk carving test was eliminated so that the current practice is to measure spatial abilities on the basis of paper-and-pencil tests alone. The question of whether a more practical perceptual-motor test adds to the prediction of success in dentistry schools remains controversial (Dailey, 1994).

One of our primary interests is the role of spatial cognition in the performance of surgery. For some years, the literature has indicated a relationship between spatial ability and operative skills in traditional (open) surgery. For example, Schueneman, Pickleman, Hesslein, and Freeark (1984) administered a comprehensive battery of psychometric tests to surgical residents and measured operative skills. Their data identified a cluster of cognitive functions underlying a factor that they labeled *complex visuo-spatial organization*. Surgical residents' scores on this factor proved to be a more reliable predictor of operative skill than either psychomotor ability or personality factors. Similarly, scores on tests of spatial relations have been shown to predict the performance of surgical trainees on a microsurgery task (Murdoch, Bainbridge, Fisher, & Webster, 1994), and several studies have demonstrated a correlation between surgical skills and performance on the embedded figures test (Gibbons, Baker, & Skinner, 1986; Gibbons, Gudas, & Gibbons, 1983; Steele, Walder, & Herbert, 1992).

More recently, Wanzel, Hamstra, Anastakis, Matsumoto, and Cusimano (2002) compared performance on a spatially complex surgical procedure to performance on six standardized visuo-spatial tests, ranging in complexity from relatively simple 2-D items such as the snowy pictures test (Ekstrom, French, Harman, & Dermen, 1976) to more complex 3-D visualization items such as the form board (Ekstrom et al., 1976) and mental rotation tests (Vandenberg & Kuse, 1978). They found that only the latter two tests predicted performance on the surgical procedure, which they interpreted as evidence for the involvement of 3-D visualization processes in the surgery task. The correlations were strongest for the most spatially complex surgical procedure. Furthermore, only the high-spatial participants were able to successfully transfer their learning to a more complex version of the procedure. One possible explanation of these findings is that processes such as visualization, mental rotation, and spatial orientation help to support and maintain a mental model of anatomical structure during surgical procedures, and to "envisage an end product before the procedure is started" (Wanzel et al., 2002, pp. 230).

Experimental Studies

Given students' difficulties in developing mental models of anatomy, medical educators have struggled to find ways of helping students to visualize anatomical structures in three dimensions (Provo, Lamar, & Newby, 2002; Russell-Gebbett, 1985). This research has used a variety of external models to aid students in the construction of internal representations (e.g., De Barros, Rodrigues, Rodrigues, Germano, & Cerri, 2001). A relatively recent development in teaching materials has been the introduction of computer models, that is, three-dimensional representations of anatomical structures, displayed on a computer screen, that can be rotated at will to view the structure from different perspectives. Many medical professionals believe that such computer models can significantly enhance education in medicine (Florance, 2002). For example, they may be particularly effective for low-spatial individuals, as providing external visualizations of anatomy may compensate for their inability to visualize these structures internally, or working with these visualizations may enhance visualization skill.

However, rather than compensating for the difficulties experienced by low-spatial students in learning anatomy, or enhancing their abilities, initial studies showed that 3-D visualizations can be more problematic for learners with low spatial ability. In a study where multiple views of 3-D anatomy were presented to medical students via a rotating computer model, a subsequent test of anatomical knowledge showed a significant disadvantage for individuals with poor spatial abilities (Garg, Norman, Spero, & Maheshwari, 1999). For these students, learning was effective only if the display was restricted to a simple depiction entailing just two cardinal views, suggesting that overly complex 3-D computer visualizations may actually impair spatial understanding for low-spatial individuals.

A follow-up study revealed that the effects of spatial ability can be moderated by the characteristics of the computer simulation. In this study, spatial understanding was enhanced when learner-controlled rotation was permitted via a hand-held mouse. When allowed to "rotate" the model themselves and select the views of interest, the students were able to encode the multiple views. This finding suggests that learner control contributes to the successful integration of complex spatial information (Garg, Norman, & Sperotable, 2001), a result that mirrors findings from more basic research on object recognition. Harman, Humphrey, and Goodale (1999) and James et al. (2002) found faster recognition (although not greater accuracy) for objects that had been actively manipulated during a learning phase, compared to objects that had been viewed passively, even when the quality of the visual information available from active and passive viewing was held constant using a yoked-pairs design.

Research on learning anatomy also provides information about the nature of internal spatial representations of 3-D structures. A current debate in research on object recognition concerns whether internal representations of 3-D objects are viewpoint-independent structural descriptions, or whether they consist of viewpoint dependent representations of previously experienced or canonical views (Tarr & Bultoff, 1998). Garg and colleagues hypothesized that the main advantage of learner control lay in the fact that it allowed the viewer to focus on key views of a part of the anatomy, rather than in its potential for displaying multiple views. In a third experiment, Garg, Norman, Eva, Spero, and Sharan (2002) tested this hypothesis by comparing an unconstrained multiple-views interactive model with a simplified version that only allowed views within 10 degrees deviation in either direction from six key views. They found no difference in the effectiveness of these two models, and showed that even the unconstrained group spent the majority of their learning time viewing the key views. In the posttask reports, 88% of participants described a strategy in which they answered the question by recalling a key view and then mentally rotating this mental image into the same orientation as the test item (cf. Tarr & Pinker, 1989), suggesting that their spatial representations were viewpoint-dependent.

A question that emerges from this result is whether this viewpoint dependency reflects a fundamental limitation in our ability to construct fully three-dimensional spatial representations, whether it is due to familiarity with certain views from anatomy textbooks, or whether it reflects the shape of the anatomy (such as the carpal bones of the wrist, which might have an obvious front and back, etc.). Similar patterns of exploration have been found for novel nonanatomical objects. In studies using novel computer-generated structures, participants who were allowed to freely rotate the structures during learning actually chose to spend most of their time on a small number of views around the primary axis of rotation, principally the "front" and "side" views, making small movements, either side of these views (Harman et al., 1999; James et al., 2002). Thus, this phenomenon is not restricted to anatomical structures and does not merely reflect prior familiarity with certain views.

In summary, previous literature has provided evidence that spatial ability is related to success in learning anatomy and procedures in surgery and dentistry. There has also been some research suggesting a promising role for 3-D computer visualizations in medical training; however, not all interfaces to such visualizations are equally effective, and, in some circumstances, their comprehension may depend on spatial ability. If spatial ability is critical for comprehending 3-D computer visualizations, an important challenge will be supporting low-spatial learners in using these resources as they become more widespread in educational settings. Studies in other domains have shown that targeted training programs using computer visualizations can improve spatial comprehension among individuals. For example, this approach has been successful in reducing the gender discrepancy traditionally found in disciplines that make heavy demands on spatial abilities, including engineering specialties such as computer-aided 3-D visualization and design (Hsi, Linn, & Bell, 1997; Sorby, 1999; Ullman & Sorby, 1995).

OUR RESEARCH FOCUS

Our research on spatial cognition and medicine has focused on two specific medical skills: the manipulation of an angled laparoscope in minimally invasive surgery, and the ability to imagine cross sections of 3-D anatomy-like structures. In studying these medical skills, our research has examined three issues.

First, we have studied the relations between spatial abilities, other cognitive and motor abilities, and spatial skills in medicine. In this line of research, we have examined how medical professionals compare to the general population with respect to spatial ability, how spatial and other abilities are related to medical performance, and how these relations are moderated by practice and expertise.

Second, we have studied how the skills can be trained with interactive visualizations and virtual reality. Three-dimensional computer visualizations are often characterized as having the potential to augment or amplify cognition (Card, MacKinlay, & Schneiderman, 1999; Norman, 1990) with "remarkable potential to help students learn" (Gordin & Pea, 1995, p. 276). However, as we have seen from the research of Garg and colleagues (Garg et al., 1999, 2001, 2002), not all visualizations are equally effective, and we currently know relatively little about how learners interact with visualizations and how to best design these visualizations to aid in the acquisition of spatial mental models (e.g., of anatomy) or spatial skills (e.g., navigation in surgery).

Third, we have examined interactions between spatial abilities and the availability of interactive visualizations in training. There are at least three possible ways in which interactive visualizations may affect individuals of different abilities. First, such visualizations may "augment" performance equally for high-spatial and low-spatial individuals, so that students of all abilities are helped equally. Second, they may compensate for low spatial abilities, so that training with computer visualizations improves the performance of low-spatial learners more than that of high-spatial learners. In this case, differences between high- and low-spatial learners will be attenuated by computer visualizations. Third, spatial ability might be a necessary prerequisite for learning from computer visualizations, in which case visualizations would have a greater facilitating effect on the performance of high-spatials (referring to individuals with high spatial ability) than low-spatials (referring to individuals with low spatial ability). In this case, use of visualizations should magnify performance differences between high- and low-spatial individuals.

STUDIES OF SPATIAL ABILITIES IN LAPAROSCOPIC SURGERY

Our studies in the domain of surgery have focused on spatial abilities and skills in minimally invasive surgery. This type of surgery became feasible in the late 1980s with the development of the miniature video camera. It is becoming the technique of choice for more and more procedures, as it offers significant advantages for patients, such as lower postoperative morbidity rates and faster recovery times. In minimally invasive surgery, operative procedures are conducted from just outside the body, avoiding the need for a large incision. In *laparoscopy* (minimally invasive surgery of the abdomen), several small openings or ports are created in the patient's abdominal wall, each large enough to accommodate a narrow tube or cannula. Through one of these, a *laparoscope* (a camera mounted on a long tube with internal optics) is passed into the abdominal cavity. Long-handled surgical instruments are inserted through the other ports. The laparoscope transmits a video image from inside the abdomen to a monitor, which the surgeon uses to guide activities and maneuver instruments at the operative site.

Although clinically beneficial for the patient, these methods pose a substantial challenge to the surgeon (Tendick et al., 2000). For one thing, the available perceptual information is highly restricted. The operative space cannot be viewed directly, nor can it be explored with the hands. Although the operative site is visible via the laparoscope, the 2-D image provided on the monitor lacks binocular depth cues and so differs substantially from that of open surgery. The camera angle also varies from moment to moment so that the perspective of the anatomy shown on the monitor typically deviates from that of the surgeon. A further challenge comes from the laparoscope's angled lens (see Fig. 11.2). If surgeons used a laparoscope with a straight objective lens, the only area visible would be that located directly in front of it. Insertion through the abdominal wall creates a fulcrum that limits the laparoscope's range of possible motion, so a straight lens would provide an overly restricted range of viewing perspectives. For many procedures, this limitation is overcome with an objective lens fitted at an angle (e.g., 45°) with respect to the laparoscope's longitudinal axis. This expands the field of view considerably and allows the surgeon to look from underneath, above, and partly around internal structures as the scope is rotated. However, it also alters the relationship between perceptual and motor events. Surgeons new to angled laparoscopy must master these novel relationships.

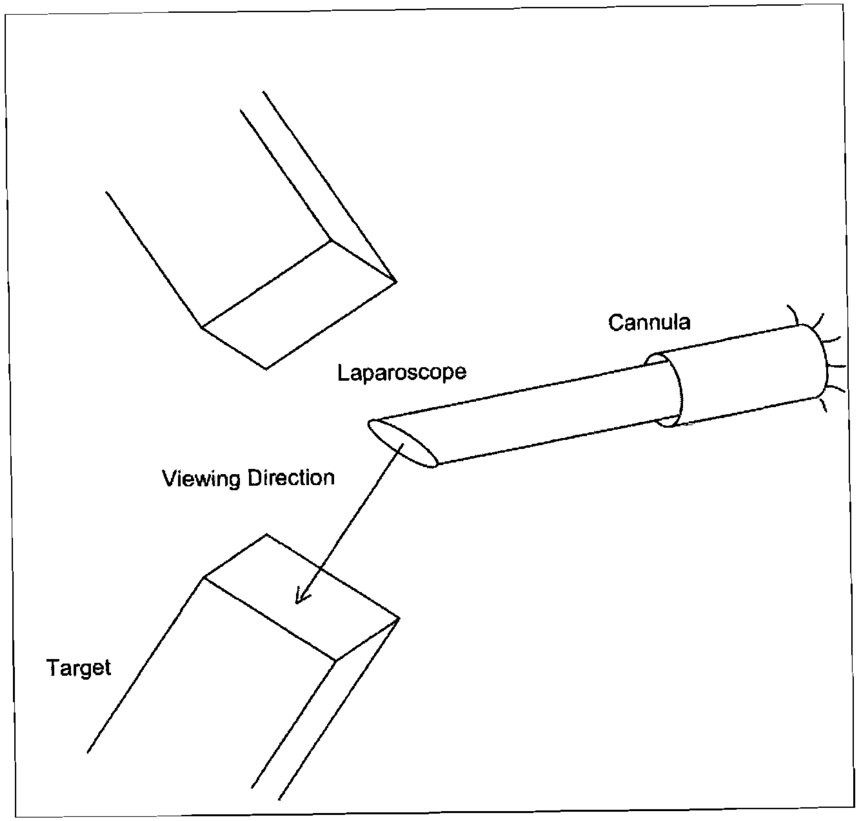

Fig. 11.2.
Illustration of an angled laparoscope. The laparoscope is inserted through a cannula, which constrains its motion to four degrees of freedom. The lens is angled with respect to the longitudinal axis of the laparoscope.

Given this analysis, it is not surprising that spatial ability is correlated with surgery performance under laparoscopic conditions. In a study of surgeons attending a laparoscopic skills training course, Risucci, Geiss, Gellman, Pinard, and Rosser (2001) reported significant correlations, ranging from .2 to .5, between skill in simulator-based laparoscopic performance (dexterity drills and suturing trials), and spatial tests including mental rotation, form completion, and touching blocks (from the *Cognitive Laterality Battery*, Gordon, 1986). In a study with undergraduates using a virtual reality simulation and abstract targets to assess laparoscope control skills, Eyal and Tendick (2001) found significant correlations, ranging from .4 to .6, with tests of spatial ability, including card rotations, perspective-taking, and paper folding. In a study of the effects of camera angle, Keehner, Wong, and Tendick (2004) asked participants to perform a maze-drawing task using only a laparoscope to guide the movements of an instrument (no direct view). The angle of the laparoscope was manipulated, placing it at 90°, 180°, or 270° offset, or in the same orientation as the participant (0°, or no offset). They found a large main effect of camera angle, with performance deteriorating when the laparoscope was offset (largest decrement at 180°). Spatial ability affected performance, with high-spatial individuals performing significantly better overall than low-spatials, and spatial ability interacted with camera offset, such that low-spatial participants were significantly more affected by greater camera offset.

Do Surgeons Have Higher Spatial Ability?

The first question we asked in our research was how the spatial abilities of surgeons compare to the norms on spatial ability tests for college students. Although individuals are not selected for surgical training on the basis of spatial ability, we might expect surgeons to have higher spatial abilities for two reasons. First, there is now considerable evidence that spatial abilities can improve with practice and training (e.g., Baenninger & Newcombe, 1989; Hsi, Linn, & Bell, 1997; Newcombe, Mathason, & Terlicki, 2001; Sorby, 1999; Ullman & Sorby, 1995), so that it is plausible that practicing spatial thinking in the context of surgery improves one's spatial abilities. Second, surgeons may self-select for spatial ability (high-spatial individuals may choose this spatially demanding specialty, low-spatial individuals may drop out of this specialty, or both). In our initial studies (Keehner, Tendick, et al., 2004) we tested the spatial abilities of surgery trainees and practicing surgeons using the Paper Folding Test (Ekstrom et al., 1976). The surgeons performed no better (and, in fact slightly, worse) than the college norms for the test. This study provided no evidence that practicing surgery increases one's spatial ability or that surgeons self-select for spatial abilities. However, a limitation of this study is that there was only time to administer one spatial ability test. Another study that used a battery of tests found higher scores by surgeons on some visual-spatial tests (Risucci, 2002).

How Does Practice Moderate the Relation Between Spatial Abilities and Surgery?

The second question we asked in our research was how the relationship between spatial ability and performance in minimally invasive conditions

might be moderated by practice. Previous research on spatial abilities in this field has used beginning surgeons with relatively little experience, such as trainees or residents. Findings on the relationship between cognitive abilities and surgical skills have been assumed to apply equally to more experienced practitioners, yet it may not be valid to extrapolate to this population. One possibility is that experience attenuates individual differences, bringing the performance curves of high-and-low performing individuals closer together over time. Fig. 11.3a shows hypothesized learning curves consistent with this possibility. A second possibility is that the learning curves of participants follow the same trajectory, regardless of their starting points, producing parallel patterns of skill development that maintain initial differences, as shown in Fig. 11.3b. A third possibility is that spatial abilities become more important as expertise develops, in which case experience should widen the gap between high- and low-performing participants, as shown in Fig. 11.3c. This issue clearly has important practical implications for recruitment and training. If initial differences in performance endure or increase with practice, it may be important to select people for medical training on the basis of their spatial abilities, whereas if individuals of all abilities can attain the same level of skill with practice, selection is not necessary.

We conducted two studies that assessed the relation between spatial abilities and experience in surgery. The first was a cross-sectional study of surgeons attending laparoscopic training courses at the University of California, San Francisco (Keehner, Tendick, et al., 2004). The attendees fell into two groups: *high experience* (attending an advanced laparoscopic skills course) and *low experience* (attending an introductory skills course). The latter group had abundant experience in open techniques, but had undertaken few, if any, minimally invasive procedures. We used the Paper Folding Test (Ekstrom et al., 1976) to assess spatial visualization abilities, and their *in vivo* operative skills were rated by at least two independent expert observers. Spatial test scores were significantly correlated with operative skills among the low experience group ($r = .39$, $p < .01$). However, the correlation was small and not significant among the high-experience group, who were considerably further along the learning curve ($r = .02$). Our results were similar to those obtained by Wanzel et al. (2003), who found correlations of .41 to .73 between surgical skill ratings and scores on spatial tests (mental rotation and surface development) among surgical novices but not among experienced surgeons (surgery residents and staff surgeons). Findings such as these are consistent with previous research on skill acquisition, which suggest that the effects of cognitive abilities on performance diminish with practice (Ackerman, 1987, 1988). They are consistent with the hypothetical curves shown in Fig. 11.3a, but not those shown in Fig. 11.3b and 11.3c.

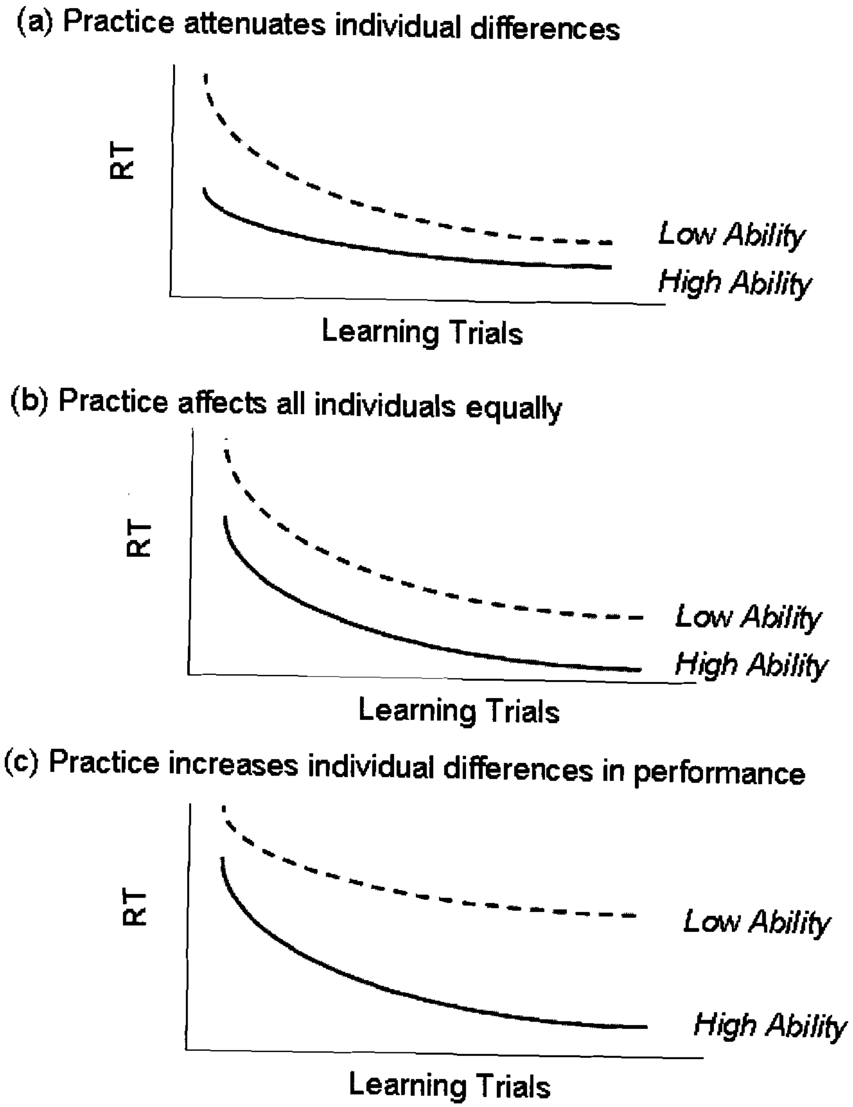

Fig. 11.3.
Illustrations of learning curves reflecting three possible ways in which practice might moderate the relation between spatial abilities and surgery. These show time to complete a skill, so that lower values represent better (faster) performance.

A limitation of the study with surgeons was its cross-sectional design. In addition to experience, the two groups of surgeons in that study differed on several other factors such as age and availability of laparoscopic techniques at the time of their initial training in surgery. Furthermore, due to the demands on surgeons' time, the study was conducted under relatively uncontrolled conditions, and there was only enough time to administer one test of spatial ability. In our second study in this domain, we devised a controlled, laboratory-based longitudinal learning study, using graduate and undergraduate students in a variety of nonmedical disciplines as participants (Keehner, Lippa, Montello, Tendick, & Hegarty, 2006). This design allowed us to observe the developmental trajectory of ability–performance relations over time. Over a series of 12 learning trials, scheduled over 3 weeks, participants learned to operate a simulated angled laparoscope, and we observed the ability–performance correlations at different points on the learning curve. The task required no surgical or anatomical expertise; the participants learned to maneuver the scope to geometric targets in space, represented via a desktop virtual environment. However we also established that the prior knowledge and experience of laparoscopic surgeons transferred to performance on our simulation, confirming that it depended on common skills with laparoscopic surgery. In addition to spatial abilities, we administered tests of general reasoning ability and perceptual-motor abilities to gain a broader understanding of the cognitive abilities on which surgical performance might depend.

A striking result of this study was that despite large initial differences (some of which may have been due to differences in cognitive and motor abilities), all individuals attained proficiency on the laparoscope task. Even those individuals who experienced considerable difficulty in the beginning were able to acquire the skill with practice. For example, the absolute difference between the best and worst performing participants was approximately 80 seconds per target at the beginning of practice but only 10 seconds per target at the end, and the group standard deviation diminished 89% between Session 1 and Session 12. Thus the learning curves for high- and low-spatial individuals followed the pattern of the hypothetical curves shown in Fig. 11.3a. This attenuation of individual performance differences is large even when compared to previous studies of skill acquisition. In a comprehensive review of 24 skill acquisition studies, Ackerman (1987) found that interindividual variability (group SDs at the beginning and end of training) reduced over trials by an average of 34%.

Zero-order correlations indicated that spatial ability measures were related to initial performance and persisted throughout the learning trials, despite the attenuation of individual differences in task performance. The latter finding contrasts with our earlier study with surgeons (Keehner, Tendick, et al., 2004), and suggests that spatial ability has an effect on performance, even after considerable practice. In reconciling the discrepancy between these two studies, it is important to note that the earlier study with surgeons entailed a variety of different skills, whereas the laboratory study focused specifically on the skill of operating an angled laparoscope. In addition, to fully understand how spatial abilities relate to performance on this task, it is also important to examine the effects of a broader range of abilities.

What Is the Relation of Other Abilities to Surgical Performance?

In addition to spatial abilities, we measured general ability via the Abstract Reasoning task of the Differential Aptitude Test battery (Bennet, Seashore, & Wesman, 1981) and three measures of perceptual-motor abilities (described later). Consistent with previous research (e.g., Lohman, 1996; Marshalek, Lohman, & Snow, 1983), general ability was correlated with spatial ability (correlations with different spatial ability measures ranged from .45 to .56). These correlations raise the question of whether the relation between spatial ability and performance of surgical skills reflects spatial ability per se, or whether it reflects the common variance of spatial ability and general ability. An examination of correlations with performance at different points along the learning curve indicated that although general ability was correlated with initial performance, this correlation diminished with practice. Further analyses revealed that the early correlation between spatial ability and performance actually arose from variance shared by both spatial and general ability. By contrast, the later correlation with spatial ability was due to the variance unique to spatial visualization ability alone, that is, *not* shared by general intelligence.

We interpreted these findings in terms of the distinction between general intelligence, which reflects the operation of the central executive component of working memory, and spatial visualization ability, which reflects a more specific visuospatial representational system (e.g., Baddeley, 1986; Kosslyn, 1980; Logie, 1995). One of the key roles ascribed to the central executive is the control of attentional resources, to maintain task goals, inhibit distracting information, and schedule different sub processes required to accomplish complex tasks (Engle, Kane, & Tuholski, 1999; Miyake & Shah, 1999). These types of executive processes are more important at the beginning of training (Ackerman, 1988; Shiffrin & Schneider, 1977), so the *shared* variance between spatial and general intelligence (which reflects the strategic component of

spatial tests) was correlated with *early* task performance. By contrast, the variance unique to the spatial tests (which reflects the ability to maintain and accurately transform spatial information (e.g., Miyake, Rettinger, Friedman, Shah, & Hegarty, 2001) appears to have become more important after some training in using the laparoscope, once participants had developed a consistent strategy.

We measured the perceptual-motor ability of our participants with three tests. A test of manual dexterity determined pure motor performance (which was uncorrelated with laparoscopic performance), and a pursuit rotor task and choice reaction-time task assessed the ability to coordinate and relate perceptual and motor events (control precision and response orientation, cf. Fleishman, 1962). Consistent with the widespread notion that skill learning passes from a cognitive or declarative stage through an associative stage to an autonomous or procedural stage (Anderson, 1982; Fitts, 1964; James, 1890; Shiffrin & Schneider, 1977), it is generally found that perceptual-motor abilities become relevant only at the later autonomous stage of skill acquisition (e.g., Ackerman 1988, 1992). However, we found the opposite data pattern. Participants with high perceptual-motor ability (measured by pursuit rotor and choice reaction-time performance only) outperformed participants with low perceptual-motor ability at the beginning of the laparoscope task, and this advantage vanished as practice increased. As suggested by the correlation between general intelligence and initial performance, the laparoscopic skill does involve executive strategic components early in learning and these may have been shared somewhat with the perceptual-motor tasks, particularly choice reaction time (Szmalec, Vandierendonck, & Kemps, 2005). However, the fact that participants with better perceptual-motor ability have an advantage at the beginning of training also indicates that at least part of the laparoscopic skill may also require nondeclarative processes that are initiated by simply performing the task repeatedly.

Conclusions and Applications

In conclusion, our research has shown that spatial visualization abilities, as measured by standardized tests, predict performance in the domain of laparoscopic surgery. However, in spite of this correlation, current practicing surgeons do not have exceptional spatial abilities. Should we use spatial ability tests to select people for surgery training, as is the practice in dentistry? Our studies caution against this policy for two reasons. First, they suggest that interindividual variation is diminished with practice, and that individuals of all ability levels can acquire surgical skills.

Consistent with previous literature on ability–skill interactions (Ackerman, 1988), large initial differences in performance, which were correlated with spatial, perceptual-motor, and general ability were mostly overcome by practice. Second, our studies suggest that general intelligence and perceptual-motor abilities may be more important than spatial ability at the beginning of training. Most importantly, our studies demonstrate the importance of assessing the effects of abilities throughout the learning curve, because the effects of these abilities may change with practice. (Ackerman, 1988; Fleishman & Rich, 1963; Parker & Fleishman, 1961; Shiffrin & Schneider, 1977).

Although our results are more supportive of a skill model than an ability model of performance in surgery, even at the end of learning some variability among learners remained, and this variance was related to individual differences in spatial ability. For practitioners considering the issue of whether to prescreen surgery trainees on spatial abilities (Gilligan et al., 1999; Graham & Deary, 1991) an important question is whether this variability has practical significance for performance in the context of real surgery. Given the result of our earlier study, that spatial ability did not predict the general performance of experienced surgeons, it will also be important to conduct longitudinal studies of training in other aspects of minimally invasive surgery besides that of operating an angled laparoscope.

In addition to its applications in the area of personnel selection, a second application of our research in this domain is the demonstration that a surgical skill can be trained using an interactive virtual environment. When experienced surgeons interacted with our laparoscopy simulation, they performed at the level of the novices after 12 days of practice, suggesting that the simulation assessed skills acquired in real surgical practice (Keehner, Lippa, et al., 2006). This suggests the feasibility of using virtual environments for training real laparoscopic skills. Currently, the dominant method for surgical training is the apprenticeship model, in which trainees practice their skills on real patients, supported by more experienced practitioners. Besides the obvious risks to the patients, this requires the presence of an instructor, and can be a highly variable and unpredictable training mode. As virtual technologies become more advanced, it will be possible to create simulations of any disease or anatomical variation. Students will be able to interact with these simulations in their free time, without the need for an instructor present and without risk to patients. Even experienced surgeons might use these simulations to practice an unusual type of procedure that they are required to perform for the first time. Virtual environment technology therefore offers much promise for improving medical training in the future. However, in order to develop simulations that will be effective in training, we need to better understand how individuals interact with and learn from such materials. We now turn to another line of research that focused on this issue.

STUDIES OF COMPREHENDING 3-D ANATOMICAL STRUCTURES

Our second line of research examines the ability to interpret and generate 2-D representations of 3-D objects. The ability to interpret 2-D representations is important in learning anatomy, because cross-sectional drawings are used extensively in anatomy textbooks and learning materials. It is also central to interpreting MRI, ultrasound, and x-ray images, which provide the user with 2-D slices of 3-D anatomy. Interpreting these medical images is a challenging task that develops over years of experience for a radiologist. Although these imaging techniques are available to other medical personnel, they are often underused. For example, in discussions with surgeons, we have learned that although ultrasound can be useful as a navigational aid in surgery, most surgeons do not use it because they have never mastered the spatial skills necessary to manipulate the ultrasound probe and anticipate what 2-D images will result when they place and move the ultrasound probe over different anatomical regions.

Medical educators are currently exploring 3-D computer visualizations as alternatives to traditional anatomical teaching materials (e.g., Florance, 2002; Garg et al., 1999, 2001). The essential question here is whether and how viewing and interacting with *external* visualizations, presented on a computer screen, can enhance the development of *internal* visualizations. Despite much optimism, our understanding of how learners interact with computer visualizations is limited. Although often assumed to enhance cognition, it is not clear that such resources are effective for all learners. For example, novices do not always have the metacognitive skills necessary to interact effectively with these visualizations (Hegarty, 2004; Lowe, 1999, 2004; Rieber, Tzeng, & Tribble, 2004). Furthermore, the interface to the visualizations can be a source of extraneous cognitive load (Sweller, van Merrienboer, & Paas, 1998). The question of how much interactivity to allow users is therefore an issue of current debate. Our experiments examined the efficacy of anatomical visualizations, given various characteristics of the learner and the interface.

The task in our experiments was to imagine a cross-section of a three-dimensional object. To control for prior knowledge of anatomy, participants were presented with a fictitious anatomy-like structure. The structure was egg-shaped and included internal ducts that branched in

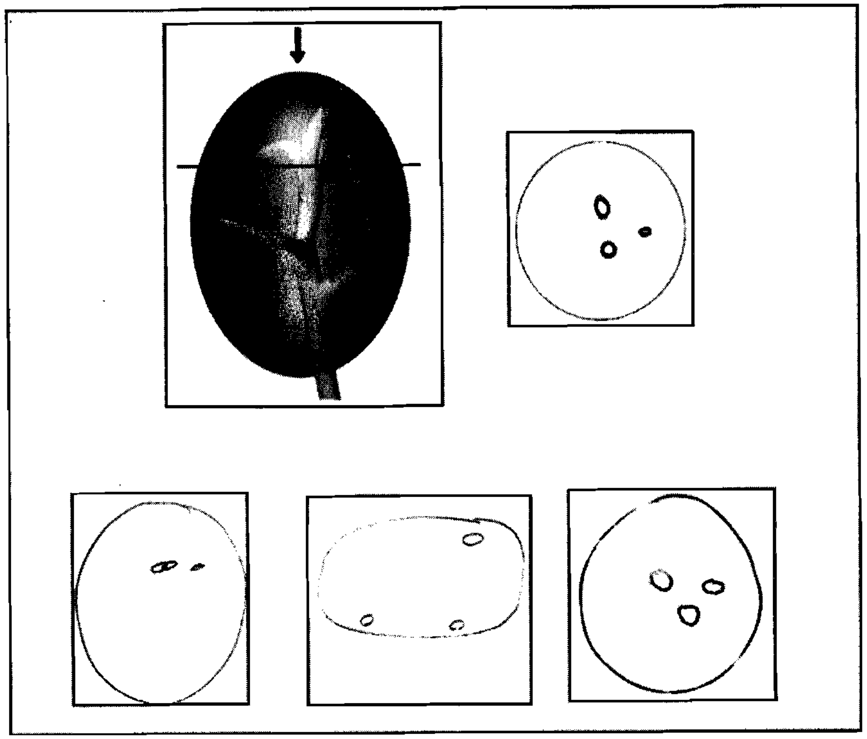

Fig. 11.4.
Example of a trial of the cross-section task, showing the correct answer and examples of drawings made by three participants.

different directions (see Fig. 11.4). A superimposed vertical or horizontal line on the printed images indicated where participants should imagine the structure had been sliced through. The task was to draw the cross-section that would result. While they were performing this task, the participants had access to a 3-D computer visualization of the anatomy-like structure that could be rotated around its horizontal and vertical axes, but which did not show the cutting plane.

To perform the cross-section task, a person must first construct an internal representation of the three-dimensional structure from the information presented in the diagram. He or she must then imagine slicing the object and removing the section in front of the cut plane. Third, the person must imagine changing his or her perspective so that it is perpendicular to the cut plane. (An alternative strategy at this stage is to mentally rotate the sliced object, so that the cut plane now faces the observer). Finally, he or she must draw the imagined cross-section from this perspective.

There are several ways in which an interactive 3-D visualization might aid an observer in performing this task. First, in contrast to a static 2-D view, which provides only pictorial depth cues, rotating the 3-D visualization provides depth cues such as motion parallax, accretion, and deletion, which provide more information about the relative locations of the parts of the structure. This additional depth information should aid in constructing an accurate internal representation from the external visualization. In addition to these cues (which are provided by any rotation of the object), there may be further benefits if the viewer is allowed to actively control the visualization. *Active control* refers to situations where people can decide when, how much, and in which way to move themselves or another (real or simulated) object. A possible general benefit of active control is that monitoring of efferent commands provides another source of spatial information about movements. The correspondence of visual and motor information may provide especially strong cues about spatial properties (e.g., Christou & Bülthoff, 1999; Feldman & Acredolo, 1979; Philbeck, Klatzky, Behrmann, Loomis, & Goodridge, 2001; Wang & Simons, 1999). A more specific benefit of active control in the context of the cross-section task is that the observer can rotate the object in the visualization to the orientation from which he or she must imagine the cut plane, thus reducing some of the discrepancy between the view shown on the computer monitor and the view that he or she must imagine. However, using the interactive visualization in this way depends on metacognitive understanding of the task and how the visualization can be used most productively, and previous research suggests that such metacognitive understanding is often lacking (Hegarty, 2004; Lowe, 1999, 2004; Rieber et al., 2004).

Fig. 11.3 shows an example of a trial from our experiments, including the correct answer and examples of the drawings of three different participants for this trial. We measured accuracy on four aspects of the drawings: (1) the number of ducts drawn, (2) the outside shape of the slice, (3) the spatial relationship between the ducts and outside shape (i.e., location of the ducts within the slice), and (4) the spatial relationships among the ducts (this measure was only relevant if there were two or more ducts sliced through). Each drawing was scored as "correct" or "incorrect" on each measure according to predetermined scoring criteria. Two autonomous raters independently scored a sample of trials and their overall rate of agreement was 94%.

In general, individuals drew slices that contained the correct number of ducts (Cohen, Hegarty, Keehner, & Montello, 2003; Keehner, Cohen, Hegarty, & Montello, 2004). Accuracy on this measure was generally around 90% in all of our experiments. However, they often drew the outside shape of the slice incorrectly (accuracy on this measure ranged from about 60% to about 85% in different conditions across the experiments). Only a minority of participants drew all ducts in their correct locations with respect to each other and with respect to the outside shape. Performance in different conditions across our experiments ranged from 25% to 70% correct for the measure of duct location, and from 30% to 70% on the measure of duct relations. Thus, although participants could generally infer the correct number of ducts in a slice (which could be determined by a nonspatial strategy of counting the number of ducts intersected by the cutting plane), they had difficulty visualizing the shape of the slice, and the relative locations of the ducts, both within the slice and with respect to each other. In other words, there were large individual differences in performance on the drawing task.

Effects of Spatial Ability and Interactivity

In several experiments, we examined the effects of spatial ability and interacting with 3-D computer visualizations on performance of the cross-section drawing task. In Experiment 1 of this series, 34 students were allowed to freely rotate a 3-D visualization of our anatomy-like object while performing the drawing task (Cohen et al., 2003). In this and all experiments in this series, spatial ability was measured using the Mental Rotation Test (Vandenberg & Kuse, 1978) and a modified version of Guay's Visualization of Views test (Eliot & Smith, 1983); we created a composite measure of spatial ability by taking the mean of the *z*-scores for these two measures. The measure of performance on the cross-section task we report here is the mean of the *z*-scores for the 4 measures of drawing performance described earlier. We found that spatial ability correlated significantly with drawing accuracy ($r = .72$, $p < .001$). The drawings of some low-spatial participants suggested that they did not fully understand what a cross-section means. For example, some low-spatial participants did not draw the outside shape of the object, or drew a combination of a cross-section and an exterior view of the structures, an error that has also been observed in studies with children (Piaget & Inhelder, 1948; Russell-Gebbett, 1985).

We conducted a follow-up protocol study with three high-spatial participants and three low-spatial participants to better understand what information they encoded from both the static and animated views, and their strategies for using the external visualization in the cross-sectional

drawing task. Preliminary analyses indicated that while performing the cross-section task, high-spatial participants used the animation more often and more strategically. They were also more likely to mention spatial features of the imagined or drawn slice. Low-spatial participants appeared to have difficulty mapping the features of the stimulus figure onto the animation, and reported that they felt disoriented once they moved the animation, whereas high-spatial participants could easily identify the correspondence between two-dimensional and three-dimensional representations (Cohen, 2005).

The fact that high-spatial participants used the animated model more often (and more effectively) than low-spatial participants raised the possibility that additional information provided by the 3-D visualization, rather than spatial ability per se, was responsible for the superior performance of high-spatial participants. That is, because high-spatials rotated the computer visualization more, they had more access to the additional depth cues that it provided, and they were more likely to have seen the structure from the perspective that they had to imagine.

We conducted a second study in which we varied whether participants were allowed to interact with the computer visualization (Cohen et al., 2003). Participants were assigned to one of two conditions: an interactive condition similar to Experiment 1, and a noninteractive condition in which they viewed a continuously rotating visualization but were unable to manipulate it. All participants in this condition were exposed to the additional depth cues provided by the animation, but they were unable to control the rate or direction of rotation, so that they could not rotate it at will to the perspective from which they had to imagine the sliced object. In addition, because some low-spatial participants in Experiment 1 appeared to misunderstand the requirements of the cross-section task, we provided more instruction to participants about what is meant by a cross-section by showing participants an instructional animation that illustrated how to draw a cross section of an apple.

If the superior performance of high-spatials (observed in Experiment 1) is solely due to better use of the visualization, we should observe an effect of spatial ability only in the interactive condition of Experiment 2. On the other hand, if spatial ability is related to the ability to imagine a cross-section, we should observe an effect of spatial ability in both conditions. The results of Experiment 2 indicated that spatial ability was equally correlated with performance in the two conditions ($r = .55$, $p < .01$). In addition, exposure to an interactive visualization was associated with superior performance on the drawing task.

We conducted two additional experiments to examine the roles of active control and quality of visual information provided by the interactive condition of Experiment 2. There were at least two differences between the interactive and noninteractive conditions in that experiment. First, the interactive condition provided more active control of the visualization, so that users could determine when to rotate the visualization, at what speed, and to what orientations in space, and received efferent feedback from their actions. A second difference was that as a result, those in the interactive condition saw different views of the 3-D anatomy-like structure, and presumably saw views that were more useful for performing the cross-section task. In Experiments 3 and 4, participants (N = 30 in each condition) were randomly allocated to one of two conditions. The *active* group was allowed to rotate the computer visualization at will. The *passive* group had no control over the movements. Using a yoked-pairs design, the manipulations performed by the active participants were recorded and later played back to the passive participants, so that both members of each pair received exactly the same visual information.

In Experiment 3, participants interacted with the 3-D visualization using keyboard controls, such that they were only allowed to rotate the visualization in one dimension (x, y, or z) at a time. There was no main effect of condition, indicating that the performance of active and passive participants did not differ significantly. Although overall performance means did not differ between the active and passive groups, the correlation between spatial ability and performance was attenuated in the active condition (r = .30, n.s) compared to the passive condition (r = .54, p < .01). Low-spatial individuals tended to perform better in the active condition, but the trend was for high-spatials to have poorer performance in this condition.

A limitation of Experiment 3 was that the keyboard interface to the visualization was not intuitive and may have taken participants' attention away from the main task (cf. Sweller et al., 1998; Wilson & Peruch, 2002). In Experiment 4, people interacted with the visualization by means of an *InterSense Inertiacube* 3-degrees-of-freedom motion sensor mounted inside an egg-shaped casing. As participants held and manipulated the egg, their movements were translated directly to the on-screen visualization in real time, providing total freedom of movement and a more naturalistic sense of control. In this experiment, there was again no difference in performance between active and passive participants. Furthermore the effects of spatial ability were attenuated for both groups in this experiment (active condition: r = .29, n.s.; passive condition: r = .25, n.s.). These results suggest that the benefits of interactive control may arise primarily from the fact that it permits access to the most informative views of the object for this task, and that the same benefits may be possible even without active control, provided these informative views of an object are presented. Preliminary analyses of how students interacted with the 3-D visualization indicated that the most common pattern was to rotate the visualization to the view that they were asked to imagine, which was indeed the most informative view for the task (Keehner & Khooshabeh, 2005).

Conclusions and Applications

In summary, we have argued that the ability to mentally relate 2-D and 3-D representations of anatomical structure is central to both learning anatomy and interpreting medical images. To date our research has focused on the ability to infer a two-dimensional representation (a cross section) from a three-dimensional image and indicates that spatial ability is highly related to this ability. That is, when students were exposed to an animation of an anatomy-like object, which provided motion-based depth cues, but were not allowed to control this animation, performance was highly correlated with spatial ability. In a recent experiment, we found a similar degree of correlation between spatial ability and performance in a task that involved choosing the correct cross section from a number of alternatives, indicating that the correlation is due to variance in ability to imagine the cross-section and not just drawing ability. These results again raise questions about selection of individuals for medical training. If low-spatial participants have difficulty relating 2-D and 3-D representations of anatomical structures, perhaps it is a good idea to use spatial ability tests to select individuals for medical training, as is the practice in dentistry.

However, our research also has important implications for training, and suggests that the right training and the right interface may attenuate the importance of spatial ability in mentally relating 2-D and 3-D representations of anatomy. We found that interaction with a 3-D visualization can benefit performance on the cross-section task. This benefit appears to occur because individuals who interact with a 3-D visualization using an intuitive interface can rotate it to orientations that are most useful for task performance. Active control or interactivity per se (i.e., the correspondence between visual and motor feedback) does not benefit spatial understanding. Thus, if the visual information is held constant as in our yoked-design studies, interactivity does *not* benefit spatial understanding. Rather, providing people with an intuitive interface induces them to interact so that they get more useful (better quality) information. It appears to be the quality of information available to a learner that is most important for task performance.

Our research on relating 2-D and 3-D representations is limited in that to date we have focused on the ability to infer a 2-D representation (a cross-section) from 3-D static and animated diagrams. In future research, it is important to study the converse inference, how people infer the 3-D structure of an object from 2-D views, such as cross sections. In addition, it is important to examine whether and how interacting with computer models can aid in learning anatomical structure, that is, in constructing spatial mental models of anatomy that can be recalled in the absence of any external visualization. Although we have not yet studied anatomy learning directly, our research is highly consistent with previous research on anatomy learning (Garg et al., 1999, 2001). A general conclusion of this research is that not all interactive visualizations are helpful and there are important conditions that must be met in order for them to be effective. First, it is important that low-spatial individuals fully understand the spatial task that they are being asked to perform with the aid of the visualization. Low-spatial individuals may have difficulty understanding spatial concepts such as a cross-section from verbal instruction alone, and without this understanding, may not be able to use an interactive animation productively. Second it is important to provide an intuitive interface to the visualization (see Hutchins, Hollan, & Norman, 1986). When the interface to an external visualization is highly intuitive or naturalistic, the effects of spatial ability are attenuated, suggesting that the external visualization can compensate for low-spatial visualization abilities.

CONCLUSIONS

We have examined various aspects of performance in medicine, including learning anatomy, performing minimally invasive surgery, and using medical imagery technologies. Informal task analyses of these activities suggest that they rely considerably on spatial mental models and imagined spatial transformations. Consistent with this view, there is much evidence from both past research and our own research that task performance in a variety of medical specialties is correlated with spatial ability.

In this chapter, we have considered the implications of these findings for selection and training of medical professionals. First, we questioned whether spatial ability tests should be used to select individuals for medical training. In general our research suggests that this might not be necessary. Although high-spatial individuals appear to have an advantage early in training in medical skills, all individuals seem to be able to acquire the necessary skills (at least in the domains we have examined), and the effects of ability diminish with training. Therefore, it seems that spatial and related abilities are less important than extensive practice in predicting performance.

More generally this research raises the question of whether individual differences in medical performance are best viewed in terms of an *ability* model or a *skill* model of individual differences. Abilities are typically thought of as being relatively general (e.g., spatial, verbal, reasoning) and fairly immutable, whereas skills are thought to be very task-specific and determined by experience and practice. In fact, however, the distinction between ability and skill may be somewhat artificial. An important goal of future research will be to determine the extent to which training in specific spatial skills in medicine and other professions generalizes to other spatial thinking activities, that is, whether only specific spatial skills or more general spatial abilities can be trained.

We have also addressed possible applications of spatial cognition research in education and training, especially using new technologies such as interactive visualizations and virtual environments. The results of these studies suggest a promising role for new information technologies in medical education and training. For example, they have shown that when low-spatial participants are provided with appropriate task instructions and an intuitive interface, external visualizations can help compensate for poor internal visualization skills. In addition, virtual environment simulations can be an effective training medium for perceptual-motor skills in medicine, eliminating risk to patients. More generally, as the use of computer visualizations grows across curricula in many other domains, our research will have broader educational impacts beyond medicine in a variety of domains that depend on spatial visualization skills, including engineering (Hsi, Linn, & Bell, 1997; Sorby et al., 1999; Ullman & Sorby, 1995), geology (Kali & Orion, 1996), biology (Russell-Gebbett, 1985), and physics (Kozhevnikov, Hegarty, & Mayer, 2002). Our findings regarding training have applications for a broad audience of not only medical educators, but for all professionals involved in advocating, generating, or implementing new information technologies in education.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grants 9980122 and 0313237. We thank Frank Tendick, Paul Brown, Eric Herbrandson, and Charles Goodacre for many fruitful discussions about the spatial challenges of medicine and for providing software, stimuli, and participants for our research.

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