# Toward the Improvement of Image-Guided Interventions for Minimally Invasive Surgery: Three Factors That Affect Performance

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**Objectives:** The objectives were to measure the impact of specific features of imaging devices on tasks relevant to minimally invasive surgery (MIS) and to investigate cognitive and perceptual factors in such tasks. **Background:** Although image-guided interventions used in MIS provide benefits for patients, they pose drawbacks for surgeons, including degraded depth perception and reduced field of view (FOV). It is important to identify design factors that affect performance. **Method:** In two navigation experiments, observers fed a borescope through an object until it reached a target. Task completion time and object shape judgments were measured. In a motion perception experiment, observers reported the direction of a line that moved behind an aperture. A motion illusion associated with reduced FOV was measured. **Results:** Navigation through an object was faster when a preview of the object's exterior was provided. Judgments about the object's shape were more accurate with a preview (compared with none) and with active viewing (compared with passive viewing). The motion illusion decreased with a rectangular or rotating octagonal viewing aperture (compared with circular). **Conclusions:** Navigation performance may be enhanced when surgeons develop a mental model of the surgical environment, when surgeons (rather than assistants) control the camera, and when the shape of the image is designed to reduce visual illusions. **Application:** Unintentional contact between surgical tools and healthy tissues may be reduced during MIS when (a) visual aids permit surgeons to maintain a mental model of the surgical environment, (b) images are bound by noncircular apertures, and (c) surgeons manually control the camera.

## INTRODUCTION

Image-guided interventions are used increasingly in medical procedures (Peters, 2000) particularly in minimally invasive surgery (MIS) such as laparoscopy and colonoscopy (Church, 1995; Cotton & Williams, 1996; Tendick, Jennings, Tharp, & Stark, 1993). Surgeons operate through small incisions while they visualize the internal tissues with a camera or fiber-optic scope. MIS results in faster recovery times and less damage to healthy tissues as compared with open surgery (Tendick et al., 1993). Despite the benefits of such technologies for patients, there are drawbacks for surgeons (Treat, 1994). Specifically, perceptual-motor performance is degraded as compared with open surgery. Numerous studies have been conducted with the aim of improving the design of image-guided interventions for MIS, but few studies have measured the impact of design features on perceptual-motor performance. The objectives of the present study were to measure the impact of specific features of imaging devices on tasks relevant to MIS and to investigate cognitive and perceptual factors in such tasks. The results of three experiments suggest several avenues to pursue toward the improvement of image-guided interventions and the enhancement of patient safety.

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We begin with a review of four potential drawbacks of image-guided devices for MIS that were the basis for the experiments that follow: degraded depth perception, reduced field of view (FOV), degraded motion perception, and passive viewing.

## Degraded Depth Perception

To perform surgery effectively, it is critical for the surgeon to visualize the surgical tools relative to the area of treatment (Erhart et al., 1998). This requires effective depth perception. Imaging devices used in MIS result in degraded depth perception, as compared with those used in open surgery, for several reasons. For example, the image provided by the device is two dimensional; the depth cue of binocular disparity is not available (Tendick et al., 1993). Disparity results in the perception of depth and is important in tasks that require precise judgments about relative depth (Coren, Ward, & Enns, 1999). Furthermore, the image provided by the device typically represents a single perspective or vantage point, which also hinders depth perception. During open surgery, surgeons can extract depth information from numerous vantage points as they move their eyes and head to inspect the tissues. Without this capability in MIS, the surgeon must learn how to develop a 3-D mental map or mental model of the surgical site from the 2-D image (Chung & Sackier, 1998). Thus, the surgeon must perform mental transformations or mental rotations, which can contribute to errors, response delays, and mental workload (Wickens, 1999). In short, MIS requires different visuospatial skills and is more difficult to learn as compared with open surgery (Chung & Sackier, 1998; Haluck et al., 2001).

Stereoscopic imaging was developed to enhance the surgeon's depth perception by providing binocular disparity information. However, 3-D camera systems do not resolve the issue of recovering 3-D structures from 2-D images (Gallagher, Cowie, Crothers, Jordan-Black, & Satava, 2003) and may not provide accurate depth information (Mitra, Lee, & Krile, 1990). Moreover, stereoscopic systems do not necessarily result in performance better than that provided by 2-D systems (Chan et al., 1997; McDougall et al., 1996; Tendick, Bhoyrul, & Way, 1997). Similarly, virtual endoscopy was developed to enhance depth perception by reconstructing 3-D anatomical images from computed tomography and magnetic resonance images (Levy, 1998). However, such reconstructions are limited in accuracy (Levy, 1998) and incorporate perspective rendering, which can introduce biases in visual performance (Ellis & Grunwald, 1989; McGreevy & Ellis, 1986). An alternative method under investigation is to insert more than one camera into the patient, which provides depth information from multiple points of view (DeLucia, Hoskins, & Griswold, 2004).

## Reduced FOV

In open surgery, surgeons view the tissues with a full FOV (about 90° vertically and 190° horizontally; Proctor & van Zandt, 1994). In MIS, FOV is reduced substantially (30°–70°; Tendick & Cavusoglu, 1997; Tendick et al., 1993). Tissues are viewed through an aperture or "keyhole." Surgeons reported that limited FOV contributes to task constraints and difficulties; relatedly, a loss of visual field can necessitate a conversion to open surgery (MacKenzie & Ibbotson, 2000). Furthermore, reduced FOV is associated with degradations in depth perception (DeLucia & Task, 1995) and spatial orientation (Dolezal, 1982). It has been proposed that reduced FOV interferes with the ability to develop a cognitive model of the environment (Dolezal, 1982), considered critical for MIS (Cao & Milgram, 2000). Indeed, it has been reported that problems with navigation and spatial orientation occur during endoscopy (Cotton & Williams, 1996) and virtual bronchoscopy (Summers, 1997). "Getting lost" is a common experience in MIS and includes uncertainty about the location of the scope within the tissues and about which direction to move the scope (Cao & Milgram, 2000). Such spatial disorientation can lead to unintentional contact between the surgical tools and healthy tissues, which increases the risk of complications.

## Degraded Motion Perception

When an object is viewed through an aperture, perceptual errors can occur. For example, Hochberg (1978) reported that when observers viewed a drawn object with a sequence of aperture views, errors occurred in judgments about the object's shape and the aperture's motion. Refer to Figure 1. Accurate shape information about anatomical

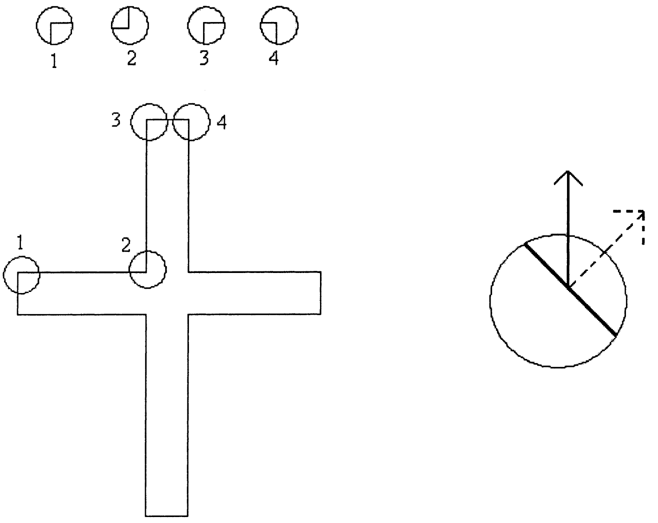


*Figure 1.* Left panel: Schematic representation of the displays used by Hochberg (1978). The circles (i.e., aperture) represent the parts of the cross figure that were visible to the observers as the aperture moved to different locations along the cross figure. Right panel: Schematic representation of the motion illusion attributable to aperture viewing. Although the oblique line actually moves upward (solid arrow), observers perceive it as moving perpendicular to its orientation (dotted arrow).

structures is crucial for surgical decision making and planning (Auer & Auer, 1998).

Aperture viewing also is associated with an illusion of motion known as the *aperture problem* (Bruce, Green, & Georgeson, 1996). As shown in Figure 1, when a contour moves behind a fixed aperture, observers misperceive it as moving perpendicular to the contour's orientation. This illusion may occur because the receptive fields of motion detectors are limited. Consequently, motion detectors that are tuned to, or prefer, a particular orientation or direction respond as if the motion were perpendicular to the contour, even though other motions could result in the same visual information (Bruce et al., 1996; Sekuler, Watamaniuk, & Blake, 2002). Furthermore, when a contour moves behind an aperture, visual information about motion that is parallel to the contour's orientation is not available. Only perpendicular motion components are detectable.

The aperture problem is relevant to MIS because, given the reduced FOV, the camera must be moved to visualize different locations within a surgical site. The tissues and instruments visualized on the monitor appear to move behind a stationary aperture. Consequently, the surgeon may misperceive the direction of motion. Adjustments of the camera based on illusory motion can lead to unintentional contact between the surgical tools and healthy tissues, which increases the risk of complications. The aperture problem may be exacerbated when an assistant moves the camera for the surgeon, discussed next.

## Passive Viewing

In laparoscopic and thoroscopic procedures, the camera is controlled by an assistant rather than the surgeon (Haluck et al., 2001; Holden, Flach, & Donchin, 1999; Tendick & Cavusoglu, 1997). In other endoscopic procedures, the surgeon can control the camera but, in practice, often needs both hands to control the various functions of the scope (e.g., the insufflator, which expands the body with air). In this case, an assistant feeds the scope at the surgeon's instruction (Church, 1995; Cotton & Williams, 1996). This dissociation between action and perception (Flach, 1990) may disrupt perceptual-motor performance. Furthermore, disorientation, fatigue, and nausea can occur when a camera's movement is not controlled by the observer (Holden et al., 1999; Tendick et al., 1997).When changes in visual information are not attributable to the observer's own movements, viewing is considered *passive*. When changes in visual information are a direct consequence of the observer's actions, viewing is considered *active*

(Flach, 1990). Empirical studies suggest that active viewing or exploration can facilitate performance in various tasks (Gibson, 1962; Harman, Humphrey, & Goodale, 1999; Stappers, 1989). The implication is that image-guided surgery can be enhanced when the surgeon controls the camera.

### Objectives

Numerous studies have been conducted with the aim of improving the design of image-guided interventions for MIS and other medical procedures (Erhart et al., 1998; Peters, 2000; Summers, 1997; Williams, Guy, Gillies, & Saunders, 1993). However, few studies have measured the user's performance with the technologies or the effects of specific design features on cognitive, perceptual, and motor performance (for examples, see Cao, 2001; Holden et al., 1999; Tendick et al., 1993). That is, little effort has been devoted to human factors issues pertinent to the use of image-guided interventions (Peters, 2000). Such issues have been recognized increasingly as important to patient safety and to the design of medical devices (Kohn, Corrigan, & Donaldson, 2000; Rachlin, 1995; Sawyer, 1997; U.S. Food and Drug Administration Center for Devices and Radiological Health, 1997, 1999; Woods, 2000). Therefore, the objectives of the present study were to measure the impact of specific features of imaging devices on tasks relevant to MIS and to investigate cognitive and perceptual factors in such tasks.

We focused on three questions. First, does a mental model of 3-D space affect navigation performance when FOV is limited? Second, when a moving target is viewed through an aperture, does the shape of the aperture influence the apparent direction of the target's movement? Third, does active control during navigation result in better judgments of 3-D space than does passive viewing? We conducted three experiments to address these questions and found that mental models, aperture shape, and active control can influence performance on tasks relevant to MIS. Our results suggest several avenues to pursue toward the improvement of image-guided interventions for MIS.

## EXPERIMENT 1

Previous studies have suggested that reduced FOV results in degraded performance in part because it impairs an observer's ability to develop a mental map or mental model of the environment. As noted earlier, when observers viewed a drawn object with a sequence of aperture views, they misjudged the object's shape and the aperture's motion (Hochberg, 1978). Performance improved when a plan view of the object preceded the aperture views. Presumably, observers could "fit" each aperture view into a mental schema or map developed from the plan view (Hochberg, 1978). In MIS, anatomical knowledge helps surgeons navigate the scope when visual cues are not available (Summers, 1997), and shape information is important for spatial orientation in endoscopic navigation (Cao, 2001). Surgeons may use anatomical knowledge such as shape to develop a mental model (Cao & Milgram, 2000). The purpose of Experiment 1 was to measure the potential benefits of a mental model in navigation.

### Method

*Participants.* The observers were 24 Texas Tech University undergraduate students, who received credit toward a psychology course for their participation. All had normal or corrected visual acuity and were naive as to the hypotheses of the experiment.

*Apparatus and displays.* Fundamentally, the colon can be considered as a hollow tube (Baillie, 1991). We created three objects from plastic tubes that were identical in length (90.5 cm) and contained a mesh-like texture. As shown in Figure 2, one tube was straight and the others were curved. The shapes of the curved tubes were similar to the letter *S* or an inverse of the letter *S* (i.e., approximately mirror images of each other). The tubes were attached to a 76.20- × 91.44-cm sheet of transparent Plexiglas that rested within a wooden frame or housing structure. The wooden frame was covered with black cloth so that the tubes could not be observed directly while the participants were performing the task. Illumination was located inside the frame so that the observers could see the tubes through the imaging device. The tubes were illuminated by six portable fluorescent lamps, each 20 W. Three lamps were located above the tubes, and three were located below the tubes. The imaging device was a Pro-Vision PV-300 flexible fiber-optic borescope with a 40° FOV and nonarticulating tip. The fiber-optic

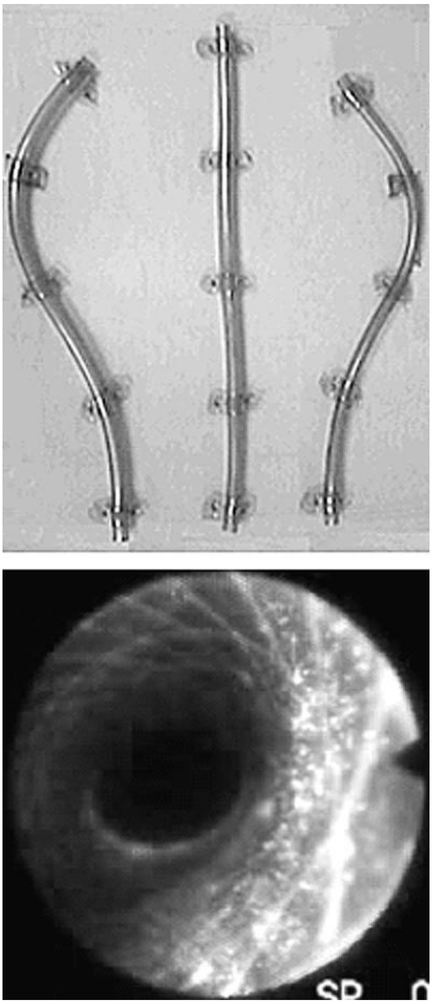


*Figure 2.* Experiments 1 and 3. Top panel: Top view of the tubes. Bottom panel: Example of an image provided by the borescope in Experiment 3.

cable was 914.4 mm in length and 10.5 mm in diameter.

*Procedure.* We instructed observers to feed the borescope through the object (they were not told that the object was a tube) until they reached a cardboard target. They were told to reach the target as rapidly as possible and that they would be timed. Before each trial, the tip of the borescope was positioned inside one end of the tube in front of a green cardboard target placed into a slit in the tube. When the experimenter instructed the observer to begin, the scope passed through this target, and the experimenter began a timer when the target moved. The destination target was located in the opposite end of the tube and was textured with a black-on-white grid pattern. The experimenter stopped the timer when the destination target moved. This constituted the task completion time (Cao, 2001; Tendick et al., 1997). We used these targets so that task completion time was based on the same travel distance of the scope for all observers.

Observers viewed the tube's interior through the eyepiece of the borescope; the image was similar to that shown in Figure 2. Half of the observers viewed one tube's exterior for 5 s prior to each trial while the other tubes were covered (preview condition). The remaining observers were not provided with a preview. There was a delay between the end of the preview and the start of navigation (iconic memory was ineffective for this task). We assumed that the preview would result in a memory of the tube that would serve as a mental model during navigation. Our assumption is based on previous reports that navigation performance relies on mental models of the environment or internal representations of spatial information (Cao, 2001; Tendick & Cavusoglu, 1997; Tendick et al., 2000). However, our study was not designed to test whether observers internalized the tube's shape per se. Therefore, we use the term *mental model* in the broadest sense, encompassing any form of internal representation, mental schema, or memory.

We measured three aspects of performance. First, we measured task completion time. Second, after each trial, we instructed observers to report the number of turns that the scope made during navigation. Third, we measured shape identification. From a sheet with 17 drawings, observers picked the one that they thought matched the object most closely. The drawings are shown in Figure 3. We counted the number of trials that resulted in correct responses and converted this to a percentage accuracy score. The probability of selecting the correct shape by guessing alone was 1/17 or 5.88% on any given trial. This represents *chance* performance. The highest attainable accuracy in this task was 100%.

Observers were informed that they would be asked to describe various properties of the tubes, such as shape and size. The specific nature of the questions became apparent after the first trial. Thus, the presentation order of the tubes was counterbalanced across observers. Observers viewed each tube twice, viewing all three tubes

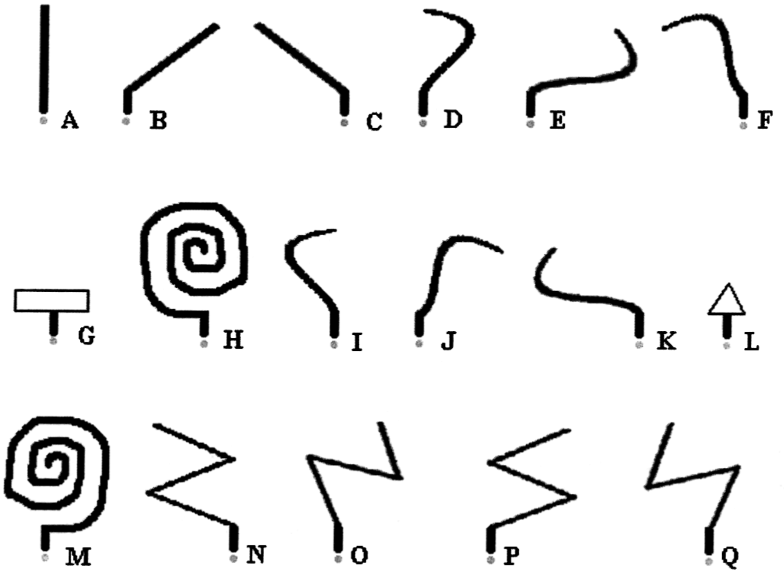


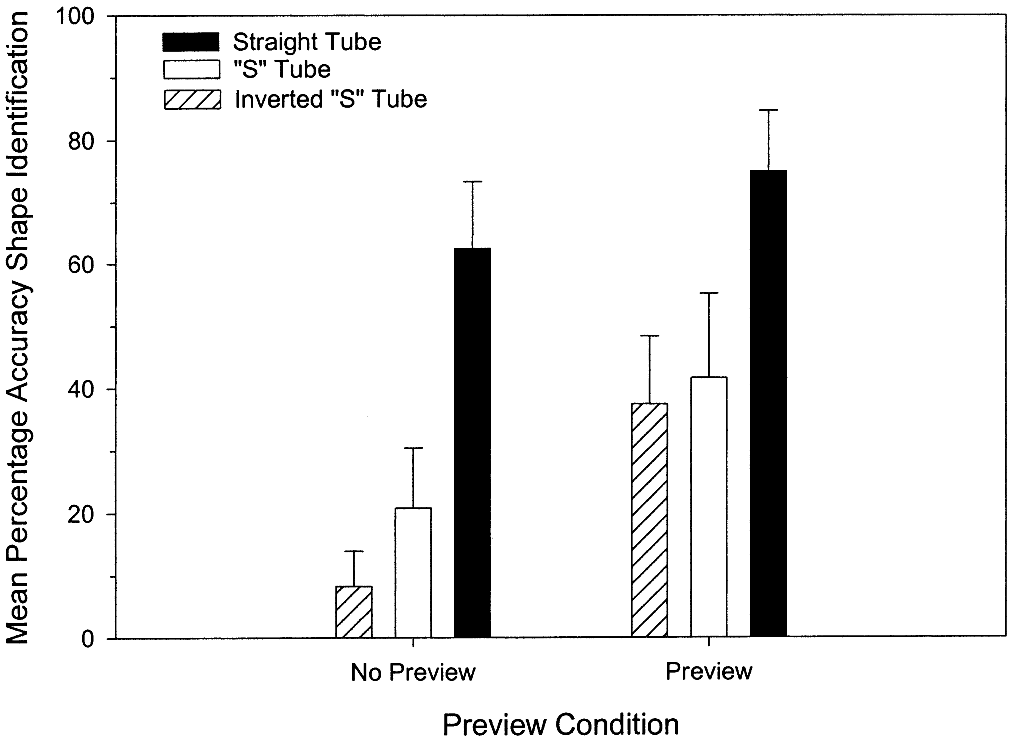
*Figure 3.* Experiments 1 and 3. Drawings of shapes that observers used in the shape-identification task. Shapes labeled A, I, and D, represent the straight, S shape, and inverted S shape, respectively.

once before viewing them again in the reverse order. Finally, prior to the experimental trials, observers were familiarized with the properties of the borescope. They fed the scope through each tube once without viewing the image.

## Results

Results are summarized in Figure 4 and suggest that navigation performance can be enhanced when observers can develop a mental model of the environment. Each dependent measure was analyzed separately with a 2 × 3 × 6 (Preview Condition × Tube Shape × Order) mixed analysis of variance (ANOVA) and Tukey's (HSD) post hoc tests. As expected, shape-identification judgments were more accurate when a 5-s preview of the tube was provided than when it was not (51% vs. 31%, respectively), $F(1, 12) = 5.23$, $p < .041$, $\omega^2 = 5.13\%$. The preview also resulted in faster task completion times, $F(1, 12) = 11.74$, $p < .005$, $\omega^2 = 27.24\%$ (means were 7.6 s and 11.6 s, respectively). Two-tailed t tests indicated that mean percentage accuracy in shape identification was significantly greater than chance probability for all three tubes if a 5-s preview was provided, $p < .023$, but that it was significantly greater only for the straight tube if a preview was not provided, $p < .0003$.

Unexpectedly, such benefits of the preview were not observed for percentage accuracy in the reported number of turns. Therefore, we analyzed the absolute error in reported number of turns, which is a less stringent measure of accuracy. Absolute error is a continuous measure of how much the observer's response deviates from the correct answer, whereas percentage accuracy measures how frequently observers report the correct (exact) answer. Nevertheless, analyses did not indicate an effect of preview condition on mean absolute error (for the inverted S shape, S shape, and straight shape, respectively, $M = .75$, .88, and .29 in the preview condition and $M = .54$, .42, and .42 in the no-preview condition). Two-tailed *t* tests indicated that the mean error was greater than zero, $p < .01$, for the curved tubes of both preview conditions but not for the straight tube. Finally, there was a main effect of tube shape on task completion time, $F(2, 24) = 29.49$, $p < .0001$, $\omega^2 = 14.19\%$, percentage accuracy of shape identification, $F(2, 24) = 14.71$, $p < .0003$, $\omega^2 = 21.66\%$, and percentage accuracy of reported number of turns, $F(2, 24) = 7.38$, $p < .005$, $\omega^2 = 14.01\%$. The straight tube resulted in the shortest task completion time, followed by the inverted S shape, and then the S shape. It also resulted in the greatest mean percentage accuracy in shape identification and in the reported number of turns.



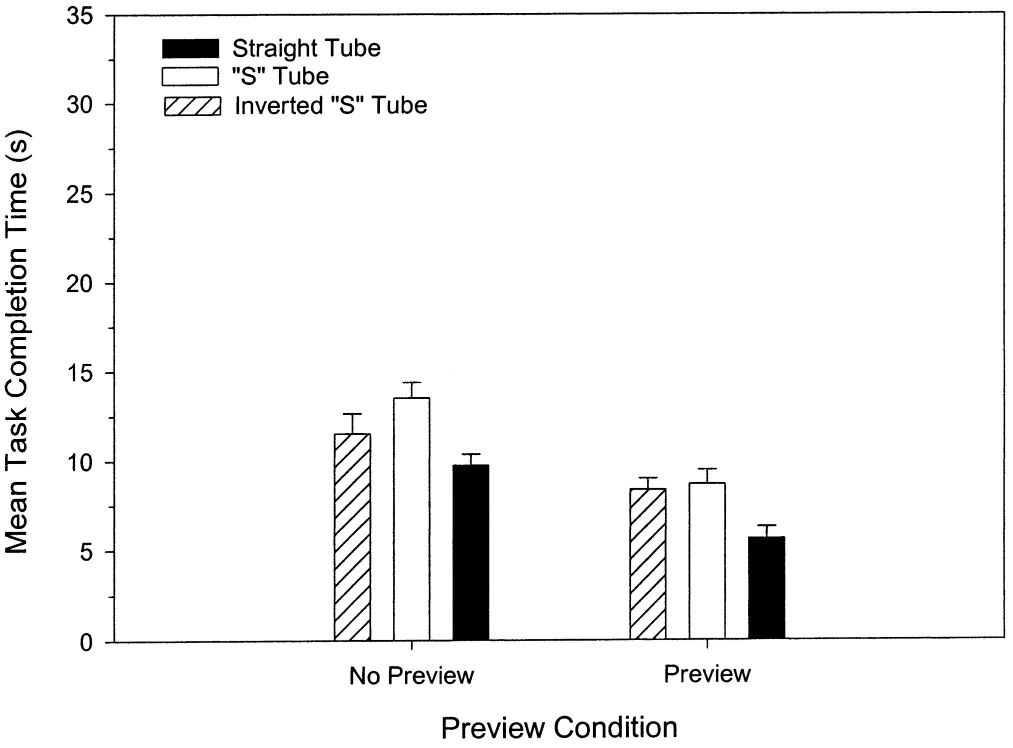


*Figure 4.* Experiment 1. Top panel: Mean percentage accuracy of shape identification as a function of preview condition and shape of tube. Bottom panel: Mean task completion time as a function of preview condition and shape of tube. Error bars indicate ±1 standard error of the mean.

## EXPERIMENT 2

As noted earlier, reduced FOV can result in misperceptions of an object's direction of motion. At first glance, it seems that the obvious approach to reduce performance errors associated with reduced FOV is to increase the FOV. However, there is a trade-off between FOV and image quality. As FOV increases, image resolution decreases (Levy, Chen, Moffitt, Corber, & McComb, 1998; Tendick et al., 1993). More important, an increase in the camera's FOV may not provide a more effective view of the surgical site, because relevant tissues often are blocked from view by other internal structures. It is important to consider other ways to improve visual performance when FOV is limited. One possibility is to vary the shape of the aperture. Prior research indicated that the shape and size of a viewing aperture affected motor performance (Coello & Grealy, 1997) and motion perception (Wallach, 1935, as cited in Shimojo, Silverman, & Nakayama, 1989). For example, when observers reached toward a target, certain types of errors were smaller with orthogonal (square) apertures than with circular apertures (Coello & Grealy, 1997). Thus, the purpose of Experiment 2 was to measure the potential effects of an aperture's shape on motion perception.

### Method

*Participants.* The observers were 320 students with the same characteristics as those in Experiment 1.

*Apparatus and displays.* Computer simulations were created with a Pentium III 550 MHz computer with an Evans & Sutherland Tornado-3000 graphics card and were presented in 640- × 480-pixel resolution at an update rate of 25 frames/s. Displays were rear-projected onto a 1.83 m high × 2.44 m wide screen (6 × 8 feet) with a Sharp XG-NV4SU LCD projector. A computer-generated line that was oriented 45° to the vertical axis moved leftward, rightward, downward, or upward at a constant speed. The black line was drawn against a white background and was located behind a black aperture, which occluded the endpoints of the line and the rest of the display. As shown in Figure 5, the aperture consisted of a circle, rectangle, octagon, and an octagon rotating either clockwise or counterclockwise. Each aperture was shown for 3.76 s. To ensure experimental control, the area bounded by the aperture remained constant as shape varied. As a result, the moving line was visible for either 3.48 s (stationary octagon), 3.56 s (stationary circle and rotating octagons), or 3.76 s (rectangle).

The circular aperture was included to verify that our displays would result in the motion illusion reported in prior studies. It also served as a baseline condition for comparison with the other apertures. The rectangular aperture was included to determine whether improvements would occur in motion perception as they did in motor performance (Coello & Grealy, 1997). We hypothesized that the rectangle would result in a smaller illusion magnitude because it has corners. Consequently, the relative change in the angle between the moving line and the aperture was larger in the rectangle than the circle. We explore this further in the Discussion section. Finally, the octagonal apertures were included to further evaluate our hypothesis.

*Procedure.* Each of five groups of 64 observers viewed a different aperture. Data were collected from 1 to 7 observers simultaneously. The observers were seated 1.22 to 2.74 m (4–9 feet) from the screen and viewed the line's four directions of motion in one of two different orders. Observers reported the apparent direction of the moving line by drawing an arrow on a response sheet. The sheet contained a black-on-white drawing of the line located centrally within an aperture. We measured the angle between the line and the observer's arrow. To determine whether the noncircular apertures reduced the typical illusion magnitude, we computed the absolute value of the difference between this angle and 90°. Larger deviations from 90° reflected a smaller illusion magnitude.

### Results

Results are summarized in Figure 5 and suggest that the motion illusion can be reduced with rectangular or rotating octagonal shapes. As expected, the typical illusion occurred when the circular aperture was stationary. The mean (absolute) difference from 90° was 7.50°. However, results of a one-way ANOVA indicated an effect of the aperture's shape (and rotation) on illusion magnitude, $F(4, 315) = 52.75$, $p < .0001$, $\omega^2 = 39.28\%$. Tukey's HSD tests indicated that the (static) rectangular

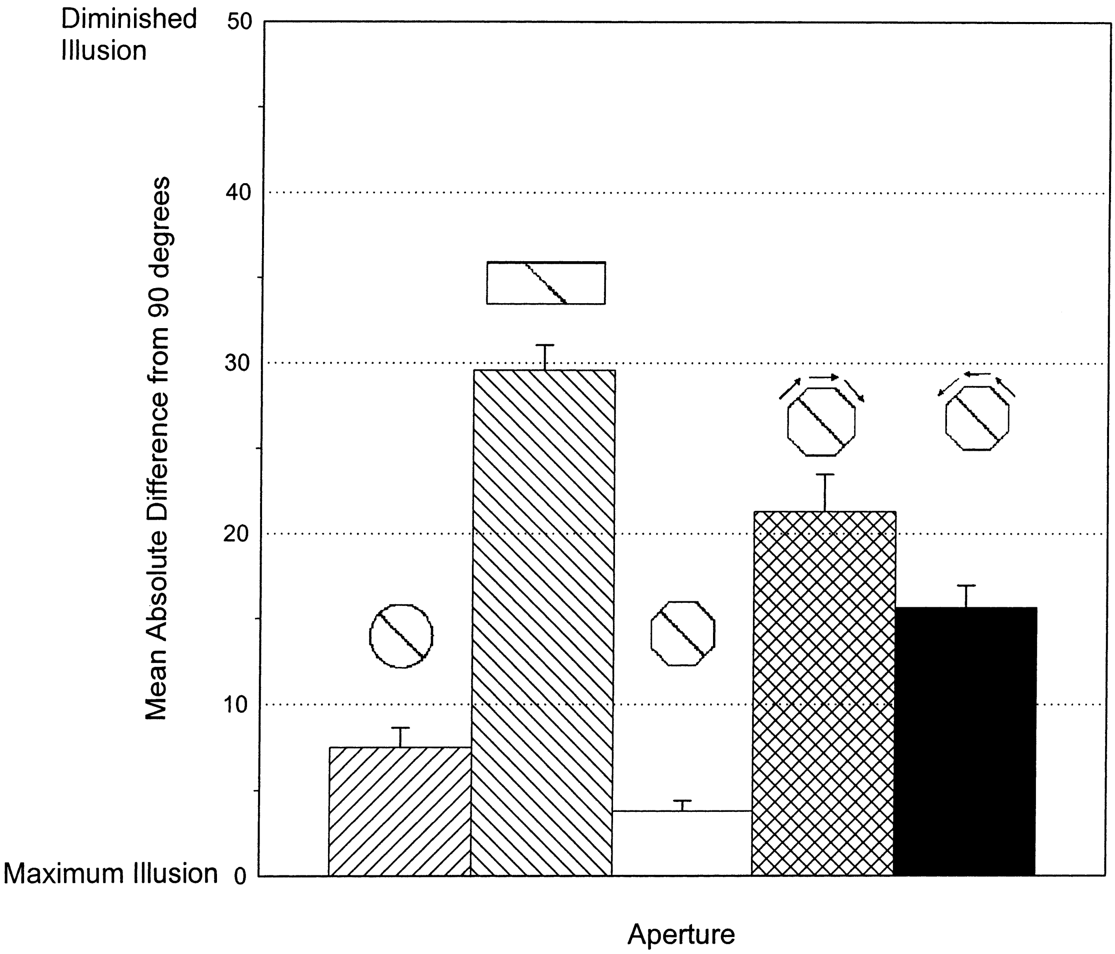


*Figure 5.* Experiment 2. Mean absolute difference between the participant's reported direction of motion and 90° (maximum illusion) as a function of the five apertures. A larger difference indicates a smaller illusion magnitude. Error bars indicate ±1 standard error of the mean.

aperture and the rotating octagonal apertures resulted in a smaller illusion magnitude (larger deviation from 90°) than did the stationary circular or stationary octagonal aperture, $p < .05$.

## EXPERIMENT 3

As noted earlier, passive viewing may disrupt perceptual-motor performance and active viewing may facilitate performance in various tasks. The implication is that MIS would be enhanced when the surgeon controls the camera's movements. Speech-recognition technologies that allow voice-activated control (Digioia, Colgan, & Koerbel, 1998) may reduce performance decrements associated with passive viewing. However, voice commands can interfere with other aspects of a task (Wickens & Liu, 1988). It is important to demonstrate the benefits of active control technologies with objective measurements of performance. Therefore, we compared performance in active and passive viewing conditions.

### Method

*Participants.* These observers were 24 students with the same characteristics as those in Experiment 1.

*Apparatus and displays.* The apparatus and procedures were as described in Experiment 1, except that we used a UXR-FF4015 flexible fiber-optic borescope with a 60° FOV and a 24-W internal light source. The scope's two-way articulating tip was rendered inoperational so that the camera maintained a 0° direction angle. The length of the cable was 1500 mm, and the diameter was 4 mm. The image was displayed on a video monitor with a digital CCD color video camera with 450 lines of horizontal resolution. As shown in Figure 2, the image was displayed within a circular aperture (approximately 17.5 cm in diameter).

*Procedure.* While "active" observers fed the scope through the tube, they viewed the images on a monitor from approximately 1.22 m (4 feet). These images were videotaped. Each of the observers in the "passive" group viewed the videotape of an active observer. They stood in the same location as did the active observers so that the monitor was the same distance away. Thus, active and passive observers viewed the same images or their displays were "yoked" (Harman et al., 1999). Because of the fragile nature of the scope, active observers were not instructed to perform the task as rapidly as possible, as they were in Experiment 1.

### Results

Results are summarized in Figure 6 and suggest that active viewing can improve certain aspects of a navigation task as compared with passive viewing. Results were analyzed with a 2 × 3 × 6 (Active vs. Passive Viewing × Tube Shape × Order) mixed ANOVA. We focus our discussion on differences between the active and passive conditions. The mean percentage accuracy of the reported number of turns in the tube was greater (and mean absolute error was smaller) for active observers than for passive observers, $F(1, 12) = 5.76$, $p < .034$, $\omega^2 = 3.64\%$. This difference was not significant for mean percentage accuracy of shape identification, although the mean for active observers was nearly twice that for passive observers (31% vs. 18%). Furthermore, percentage accuracy of shape identification in the active viewing condition was lower than expected. The mean was significantly above chance probability for only the straight tube ($p < .004$), and even in this case it was only 50%. Accuracy was not significantly above chance for the curved tubes in either the active or the passive condition. Thus, performance benefits from active viewing seem to be limited.

As in Experiment 1, tube shape affected the mean percentage accuracy of shape identification, $F(2, 24) = 6.04$, $p < .011$, $\omega^2 = 11.97\%$. The overall means were 41.7%, 16.7%, and 14.6% for the straight, inverted S shape, and S shape, respectively. The effect of shape on percentage accuracy in reported number of turns (or on mean absolute error) was not significant.

## DISCUSSION

### Summary of Results and Implications for Patient Safety

The objectives of the present study were to measure the impact of specific features of imaging devices on tasks relevant to MIS and to investigate cognitive and perceptual factors in such tasks. We focused on three questions. First, does a mental model of 3-D space affect navigation performance when FOV is limited? Second, when a moving target is viewed through an aperture, does the shape of the aperture influence the apparent direction of the target's movement? Third, does active control during navigation result in better judgments of 3-D space than does passive viewing? We consider each in turn.

In Experiment 1, mean percentage accuracy in shape identification was greater when a preview of the tube was provided than when it was not provided. The answer to our first question is that a mental model of 3-D space enhances navigation performance when FOV is limited. Our findings are consistent with previous proposals that mental models are important in MIS (Cao & Milgram, 2000). The tube's shape also affected performance. Mean percentage accuracy in shape identification was greater for the straight tube than for the curved tubes. We hypothesize that to perform the tasks quickly and accurately, observers must identify the relationship between the properties of the 2-D optic flow pattern that occurs during navigation and the tube's 3-D shape. Generally, navigation through a straight tube results in symmetrical optical expansion, whereas navigation through a curved tube results in asymmetrical expansion. The present results suggest that observers recognized the optic flow pattern of the straight tube better than that of the curved tubes. The absence of an interaction between preview and shape suggests further that the 5-s preview did not enhance this ability.

However, our results also suggest that the benefits of a preview are limited. For example, shape-identification judgments, but not judgments of the number of turns, benefited from the preview.

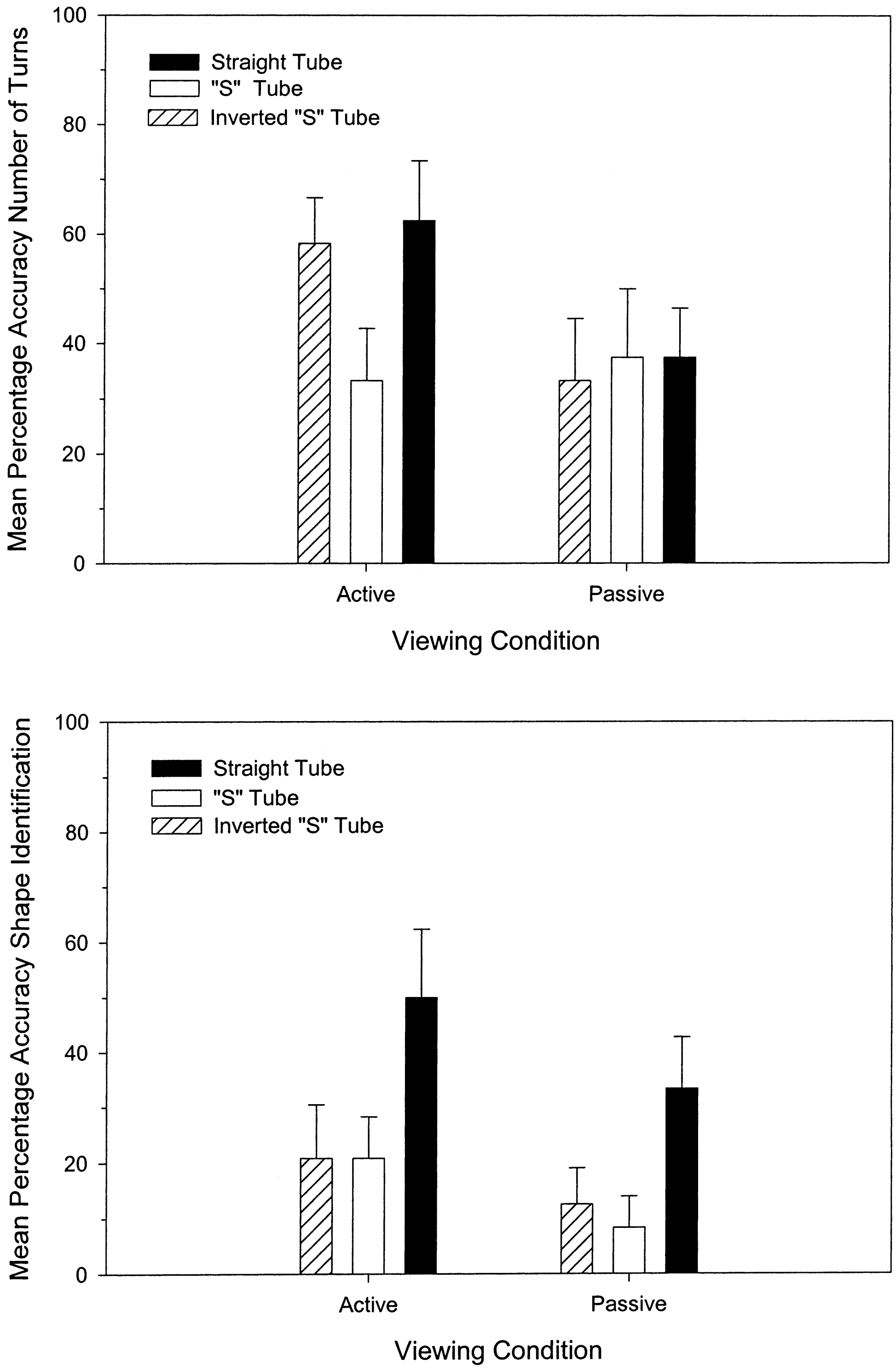


*Figure 6.* Experiment 3. Top panel: Mean percentage accuracy of the reported number of turns as a function of viewing condition (active or passive) and shape of tube. Bottom panel: Mean percentage accuracy of shape identification as a function of viewing condition (active or passive) and shape of tube. Error bars indicate ±1 standard error of the mean.

We hypothesize that a 5-s preview allowed observers to extract global or world-referenced information (Cao, 2001) about the tube (shape) that was sufficient to recognize it from a set of drawings. In contrast, the preview was not sufficient for observers to extract local or ego-referenced information (number of turns). Judgments of local information are facilitated by landmarks (Cao, 2001), which were not provided. Furthermore, percentage accuracy of shape-identification judgments in the preview condition was lower than expected. The mean was 75% for the straight tube and less than 42% for the other tubes. Accuracy did not reach 100% even though observers viewed the tube's exterior prior to each trial. This may indicate that 5 s was not adequate for observers to develop an effective mental model of the tube, or, alternatively, that 5 s was adequate to develop a model but the delay between preview and navigation resulted in memory decay. Future studies should examine longer preview times and shorter delays. The implication is that the benefits of a mental model for navigation may be limited.

Moreover, such limits may be greater in surgical environments than in the laboratory environments studied here. For example, observers in the preview condition of Experiment 1 viewed the tube directly for 5 s prior to navigation. This preview provided an accurate physical model from which an accurate mental model could be formed. In contrast, laparoscopic surgeons do not directly view the surgical site prior to surgery (which would defeat the purpose of MIS). Rather, they review 2-D images of the patient's anatomy, such as computed topography, X rays, ultrasound, and magnetic resonance images (Eyal & Tendick, 2001). It is reasonable to expect that such images are less effective in the development of a mental model than are direct views of the anatomy. Similarly, in Experiment 1, the preview was completed immediately before navigation. In surgery, a much greater delay (on average, 3–7 days) occurs between the surgeon's reviews and the start of surgery. The implication is that memory decay may limit the benefits of mental models based on anatomical reviews undertaken prior to surgery. It is important to develop visual aids that facilitate the development of a surgeon's mental model, and such aids should be available throughout a surgical procedure.

In Experiment 2, the (static) rectangular aperture and the rotating octagonal apertures resulted in a smaller motion illusion, as compared with the stationary circular and stationary octagonal apertures. The answer to our second question is that when a moving target is viewed through an aperture, the shape of the aperture can influence the apparent direction of the target's movement. The implication is that illusions that result from reduced FOV can be decreased by controlling the shape of the aperture that bounds the laparoscopic image (e.g., with video overlays or redesign of the camera). Future research should measure the effects of a greater variety of apertures on a wider range of tasks to determine the design that enhances MIS performance.

We hypothesized that the rectangle would result in a smaller illusion magnitude than would the circle because the relative change in the angle between the line and the aperture was larger in the rectangle. In the noncircular apertures, we measured the angle between the line and the aperture where the line intersected the aperture (there were four such angles; we focused on the angle that resulted in the largest change). In the circular aperture, we measured the angle between the line and a tangent to the aperture. The angle was measured on 10 different frames, including those at the beginning and end of the display. The change in the angle was expressed as a percentage of the angle's magnitude on the first frame of the display. The result was approximately 87% for the circle and 200% for the rectangle. Consistent with our hypothesis, the rectangle resulted in a smaller illusion magnitude. Similarly, the relative change in angle for the rotating octagons (89%) was greater than that for the stationary octagon (50%), and the rotating octagons resulted in a smaller illusion magnitude. Unexpectedly, the relative change for the rotating octagons was not greater than that for the circle, even though the octagons resulted in a smaller illusion. However, the pattern of change differed for the rotating octagons. In the latter, the angle increased and decreased several times as the line moved behind the aperture. Such changes in direction did not occur with the other apertures.

In short, the illusion magnitude was smaller when the relative change in the angle was relatively large or when the change in angle varied in sign. The implication is that the rectangle and rotating octagons may have stimulated a relatively greater number of differently tuned motion detectors, thereby reducing the illusion magnitude. This is consistent with previous proposals that the aperture problem is attributable to the limited receptive fields of local motion detectors and that the perception of global motion is determined by the integration of the responses of such detectors (Bruce et al., 1996; Sekuler et al., 2002).

In Experiment 3, mean percentage accuracy in reported number of turns in the tube was greater for active observers than for passive observers. The answer to our third question is that certain aspects of navigation performance can benefit from active viewing. The implication is that image-guided technologies should allow the surgeon to control the camera rather than rely on an assistant. However, our results also suggest that the benefits of active viewing are limited. Mean percentage accuracy in shape identification was only 50% when active observers viewed a straight tube, and accuracy was not above chance for the curved tubes in either the active or the passive condition. Future research should identify the conditions under which surgical performance is better with active viewing than with passive viewing.

Our results have important implications for patient safety. We identified three possible avenues to pursue toward the improvement of navigation in MIS. Improvements in navigation imply less contact between the surgical tools and healthy tissues and thereby lower risk of complications. This is important because the rate of complications is higher in MIS than in open surgery (Gallagher, Richie, McClure, & McGuigan, 2001). The results of Experiment 1 suggest that tools that permit the surgeon to develop and maintain a mental model of the surgical environment can improve navigation performance. A mental model putatively allows the surgeon to anticipate when and how to change the direction of the instruments and thereby to avoid contacting healthy tissues with the surgical tools. The results of Experiment 2 suggest that the properties of the aperture that frames the laparoscopic image can be designed to reduce motion illusions associated with reduced FOV. Enhanced motion perception putatively allows surgeons to move the instruments through the patient's body more effectively. The results of Experiment 3 suggest that active viewing can improve certain aspects of a navigation task as compared with passive viewing. The implication is that unintentional contact between the surgical tools and healthy tissues can be minimized by allowing surgeons (rather than assistants) to control the camera.

## Generalizability

Further investigation is required to determine the generalizability of our results to expert surgeons because our participants were undergraduates (see also Cao, 2001; Eyal & Tendick, 2001; Holden et al., 1999). We selected this population so that we could achieve a sample size appropriate for statistical analyses. We used an experimental design to measure the impact of specific features of imaging devices on tasks relevant to MIS and to investigate cognitive and perceptual factors in such tasks. Such design requires experimental control and a sample large enough to allow detection of statistically significant differences among experimental conditions.

The availability of expert surgeons for experimentation is limited and makes adequate sample sizes difficult to achieve (Tuggy, 1998). However, it seems reasonable to assume that novices and experts rely on at least some of the same cognitive and perceptual processes in our tasks. For example, our navigation tasks required participants to make judgments about a 3-D environment on the basis of 2-D images with reduced FOV. Such judgments rely on spatial abilities, which are a core component of MIS (Tendick et al., 2000). Previous research demonstrated that measures of such fundamental abilities generalize from novices to experts but that novices and expert surgeons may use different strategies in relatively complex tasks (Tendick et al., 2000). For example, visual-spatial ability in novices, but not in experts, correlated with performance on surgical tasks (Eyal & Tendick, 2001; Wanzel et al., 2003). Furthermore, prior results indicated that perceptual-motor tasks performed on a laparoscopic simulator did not differ between surgical trainees and nonsurgeons (Taffinder, Sutton, Fishwock, McManus, & Darzi, 1998). The implication is that the results of our undergraduates may generalize, at least, to surgical trainees. Finally, it is important to note that the education that surgical trainees receive outside of the operating room allows them to develop habits to compensate for deficiencies of imaging devices. Studying participants who are not trained in medicine allows measures of performance and evaluations of imaging devices that are not influenced by such compensatory strategies.

Further investigation also is required to determine the generalizability of our results to MIS because we used a simulator to measure performance on relatively simple perceptual-motor tasks (see also Cao, 2001; Eyal & Tendick, 2001; Holden et al., 1999). We selected such tasks so that we could measure performance objectively and achieve the experimental control needed to identify factors that affect performance. These aims are not possible to achieve in live surgery (Taffinder et al., 1998; Tendick et al., 2000). However, it seems reasonable to assume that our tasks rely on at least some of the same underlying skills as those used in MIS (see also Holden et al., 1999) because our task and displays shared several key features with MIS.

As noted earlier, our navigation tasks required participants to make judgments about a 3-D environment on the basis of 2-D images with reduced FOV. More important, the properties of the optic flow field produced by our camera during navigation through the tube were the same as those produced by a camera during navigation through a patient's body. Furthermore, previous research has demonstrated that novices and experts can be discriminated on the basis of performance with simple virtual reality simulators (Gallagher, Lederman, McGlade, Satava, & Smith, 2004; Gallagher et al., 2001). For example, the ability to recover 3-D information from 2-D displays predicted performance on a laparoscopic cutting task (Gallagher et al., 2003). Moreover, training on a virtual reality surgical simulator transferred to performance in the operating room (Seymour et al, 2002). Such findings suggest that relatively simple perceptual-motor tasks can tap into the same processes as do more complex surgical tasks or that they have *psychological fidelity* (Kantowitz, 1992). *Physical fidelity* is not necessary for training to transfer (Holden et al., 1999; Kantowitz, 1992). One potentially important difference between our study and MIS is that our plastic tubes were rigid. The implication is that our results may generalize to surgery on rigid structures (arthroscopy) but not to surgery on soft tissues (colonoscopy). In any case, simulators are used increasingly to train and assess surgical skills because, compared with live surgery, they are inexpensive, are always available for training, and cannot result in harm to patients (Tendick et al., 2000).

In conclusion, our results suggest several avenues to pursue toward the improvement of image-guided interventions and the enhancement of patient safety. Navigation performance in MIS may be enhanced when surgeons develop a mental model of the surgical environment, when surgeons (rather than assistants) control the camera, and when the shape of the image is designed to reduce visual illusions. Further studies of this kind are warranted to determine how to configure image-guided interventions so that surgical procedures can be optimized.

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