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Effects of Camera Arrangement on Perceptual-Motor Performance in Minimally Invasive Surgery

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Minimally invasive surgery (MIS) is performed for a growing number of treatments. Whereas open surgery requires large incisions, MIS relies on small incisions through which instruments are inserted and tissues are visualized with a camera. MIS results in benefits for patients compared with open surgery, but degrades the surgeon's perceptual-motor performance. We used a laparoscopic simulator to measure effects of type (top, front, side) and number (1, 3) of camera views on manual manipulation and manual aiming tasks. These experimental manipulations had implications for perceptual and cognitive processing including frame of reference, movement compatibility, compression, task-information specificity, information integration, attentional demands, and information extraction. Camera views generally degraded performance compared with direct viewing, but learning occurred. Generally, a top view resulted in the best performance, followed by front and side views. Benefits of multiple views depended on practice and the direction of grasper movement. Mappings between movement direction and camera view, the consistency of those mappings, and task difficulty affected performance. The benefits and costs for perceptual and cognitive processing that were introduced by a given camera view were not necessarily weighted equally. Costs and benefits must be considered specifically for each task and for each combination of camera view and movement direction. Surgeons may consider using a top view, using side views only when necessary, and using a consistent view when performing repetitive movements.

Keywords: minimally invasive surgery, perceptual-motor distortion, depth perception, frame of reference, spatial mapping

Minimally invasive surgery (MIS) is performed increasingly and is the procedure of choice for a growing number of treatments (Hanna & Cuschieri, 2001; Khan & Aziz, 2010; Robinson & Stiegmann, 2004). Traditional open surgical procedures with large incisions afford tactile information because surgeons use their hands to palpate and manipulate the surgical structure or organ. One disadvantage of open surgery is limited visibility into the structure as if looking into a cave. In contrast to open surgery, in MIS surgeons insert instruments through small incisions and visualize tissues with a camera. Examples include laparoscopy, arthroscopy, and thoracoscopy (Saleh, 1988; Tendick, Jennings, Tharp, & Stark, 1993). Compared with open surgery, MIS reduces pain, damage to healthy tissues, recovery times, and length of hospitalization stays (Tendick et al., 1993). Despite such benefits of these technologies for patients, there are drawbacks for surgeons (Crosthwaite, Chung, Dunkley, Shimi, & Cuschieri, 1995; Tendick & Cavusoglu, 1997; Tendick et al., 1993). For example, in MIS, surgeons experience impairments in depth perception, in the ability to develop mental models of the anatomical environments, and in perceptual-motor coordination. They also experience greater fatigue (Berguer, 1999).

Despite the promise of emerging technologies, each poses unique problems including costs and the addition of equipment in the already cluttered operating room (Berguer, 1999; Peters, 2000). Moreover, many prior studies aimed at improving the design of image-guided interventions did not report the impact of specific design features on the surgeon's cognitive, perceptual and motor performance such as depth perception and perception-action relationships.

Depth Perception

To avoid unintentional contact between the surgical instruments and healthy tissues, it is critical for surgeons to accurately visualize the surgical tools relative to tissues being treated (Erhart, Ladd, Steiner, Heske, Dumoulin, & Debatin, 1998). This requires effective depth perception. Compared with open surgery, depth perception is degraded in MIS because of several characteristics of the imaging technology. First, the camera image is two dimensional (2D) and lacks the depth cue of binocular disparity (Tendick et al.,

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1993). Disparity is essential for judgments about relative depth (Coren, Ward, & Enns, 1999) and for performance at near distances (Cutting & Vishton, 1995). Although the cameras used in MIS often provide an improved direction of viewing of the surgical structures or organs compared with open surgery, the 2D images put at risk important structures located behind the structure on which the surgeon is operating.

Second, the camera image provides a field-of-view (FOV) that is substantially smaller than the full FOV afforded by open surgery (Tendick et al., 1993). Thus, in MIS, the tissues are viewed through an aperture or "keyhole." Research on night-vision goggles, which also reduce FOV, indicated that reduced FOV is associated with impairments in depth perception; estimates of absolute distance were smaller with night-vision goggles compared with unaided vision (DeLucia & Task, 1995). In the context of MIS, surgeons reported limited FOV as a factor that contributed to constraints and difficulties (MacKenzie & Ibbotson, 2000).

Third, the movement of the camera is limited because it is located in the patient's abdominal wall (Matern, 2004). An assistant aims to keep the camera stationary to prevent the surgeon from experiencing spatial disorientation, fatigue, and nausea (Holden, Flach, & Donchin, 1999; Tendick, Bhoyrul, & Way, 1997). The implication is that the surgeon views a camera image that represents a single viewing perspective, which reduces visual information about depth. In contrast, during open surgery, surgeons can extract information from different perspectives by moving their eyes and heads. Such changes in viewing perspective provide important depth information such as motion parallax and optical expansion that are lost when the environment is viewed from a single viewing perspective (Gibson, 1979; Hochberg, 1978). Limitations in viewing perspective during MIS have been characterized as possible contributors to misperceptions of the surgical environment that result in injuries to the bile duct (Way et al., 2003). Although the selection of the camera's viewing perspective typically is based on the surgeon's preferences, it has been demonstrated that viewing perspective affects different tasks differently (Hanna & Cuschieri, 1999). Studies of aviation displays demonstrated such differential effects and attributed them to specific perceptual and cognitive processes such as line-of-sight ambiguities and mental transformations (Olmos, Wickens, & Chudy, 2000; Wickens, Thomas, & Young, 2000). We discuss such mechanisms in more detail subsequently.

When depth information is impoverished, as it is in MIS, surgeons putatively must "fill in" the missing information by developing mental models of the three-dimensional (3D) space from the 2D images (Chung & Sackier, 1998). They also must perform mental operations on these mental models (e.g., mental rotations) that can contribute to response delays, errors, and cognitive workload (Wickens, 1999). In short, MIS requires different visuospatial skills and potentially greater cognitive processing demands than open surgery (Haluck et al., 2001).

Potential Remedies

At first glance, the obvious approach to improve depth perception in MIS is to restore binocular disparity information with stereoscopic imaging. With this technology, each eye is presented with a slightly different view of the tissues that results in a compelling experience of depth. However, 3D camera systems do not resolve the issue of recovering 3D structures from 2D images (Gallagher, Cowie, Crothers, Jordan-Black, & Satava, 2003) and may not provide accurate depth information (Hanna & Cuschieri, 2001; Mitra, Lee, & Krile, 1990). Indeed, it has been shown that 3D systems may not result in better performance than 2D systems (Chan, Chung, Yim, Lau, Ng, & Li, 1997; Crosthwaite et al., 1995; McDougall, Soble, Wolf, Nakada, Elashry, & Clayman, 1996; Tendick, Bhoyrul, & Way, 1997). For example, the performance of laparoscopic cholecystectomy (removal of gall bladder) did not differ in execution time or errors between 2D and 3D camera systems (Hanna, Shimi, & Cuschieri, 1998). This is not surprising based on studies of visual perception that demonstrated that even people born without effective binocular disparity information may achieve good depth perception (Hochberg, 1978). Similarly, when many monocular depth cues are available in the surgical environment, binocular information may not lead to an advantage over 2D displays (Hanna & Cuschieri, 2001; Hanna, Shimi, & Cuschieri, 1998). The implication is that the increased costs associated with 3D systems may not be justified because comparable performance can be achieved with less expensive 2D systems. Moreover, hospitals that cannot afford 3D systems will continue to rely on less expensive 2D systems. It is important to pursue alternative remedies to degraded depth perception in MIS.

Another way to compensate for the loss of depth information in 2D images is to provide the surgeon with different viewing perspectives with the use of multiple cameras. With such multiple-view displays, the surgeon has access to information about three dimensions. In the field of transrectal ultrasound, it has been reported that 2D images are mentally integrated to yield perception of 3D anatomy (Tong, Downey, Cardinal, & Fenster, 1996). Further, it has been proposed that different perspectives improve anatomical interpretation and laparoscopic performance (Hanna & Cuschieri, 2001). Consistent with this proposal, human-factors studies of teleoperation tasks indicated that a 2D display that represents multiple viewing perspectives can result in superior performance compared with a 3D display (Park & Woldstad, 2000). Moreover, a study of suturing on inanimate torso models suggested that performance can be improved with multiple–camera views with benefits increasing as task complexity increased (Geis, Gillian, & Berry, 1999). However, a systematic comparison among different individual camera viewing perspectives or between an individual camera view and a multiple-view display was not undertaken. In addition, effects of camera perspective and multiple views on specific perceptual and cognitive processes have not been analyzed in MIS. Such analyses have been conducted for aviation displays and inform the present study. We compared perceptual-motor performance with multiple camera perspectives to performance with a single–camera view, and compared performance among three different single-camera views.

Perception-Action Relationships

To avoid unintentional contact between the surgical instruments and healthy tissues, it is critical for surgeons to move the instruments directly to the target location without contacting surrounding tissues. Surgeons control such aiming actions on the basis of their perceptions of the relative positions of the instruments and the target. That is, performance is based on perception-action relationships. In open surgery, perception and action are interde-

pendent. Visual information about the task environment changes as a direct consequence of the surgeon's movements. However, in MIS, this perception-action relationship is degraded in several ways.

First, in many MIS procedures the camera is controlled by an assistant (Haluck et al., 2001; Holden et al., 1999; Tendick & Cavusoglu, 1997). Consequently, changes in the visual information provided by the camera images are not a direct consequence of the surgeon's actions. In addition, the surgeon must communicate navigational directions to the assistant which increases cognitive load and introduces potential communication errors.

The dissociation between perception and action can disrupt perceptual-motor coordination (Flach, 1990). Active viewing occurs when changes in visual information are a direct consequence of the observer's actions (Flach, 1990). Viewing is passive when such changes are not because of the observer's own movements. Active viewing can facilitate visual performance in various tasks (DeLucia, Mather, Griswold, & Mitra, 2006; Gibson, 1962; Harman, Humphrey, & Goodale, 1999; Stappers, 1989). The implication for MIS is that performance may improve when surgeons receive feedback about the camera's movements because of active viewing.

Second, certain camera images in MIS can violate the human-factors principle of compatibility (Wickens & Hollands, 2000). This principle refers to the relationship between the movement of a control device and the resulting display. For example, because of the camera's location, a forward–backward movement of a surgical grasper in the 3D environment may result in leftward–rightward movement of the grasper in the display (Tendick et al., 1993). When compatibility is violated, surgeons must learn new eye–hand mappings (Holden et al., 1999). This involves mental rotations and other mental operations that contribute to response delays, errors, and cognitive workload (Wickens, 1999). In short, violations of compatibility result in degraded performance (Crosthwaite et al., 1995; Wickens & Hollands, 2000) and should be minimized in MIS. We discuss compatibility in more detail subsequently.

Potential Remedies

One way to address perception-action issues is to provide multiple–camera views so that the surgeon can select the view that does not result in compatibility violations. Another is to allow the surgeon to control the camera to provide active viewing (see DeLucia et al., 2006). In the current study, we compared performance between multiple camera perspectives and a single-camera view, and among different mappings between the camera perspective and the direction of grasper movement.

Purpose and Overview of Experiments

The aim of the current study was to examine effects of the type and number of camera views on perceptual-motor performance relevant to MIS. Our manipulations and interpretations of the results are framed in terms of the perceptual and cognitive processes that have been implicated in previous manipulations of aviation displays (e.g., Olmos, Wickens, & Chudy, 1999; Wickens, Liang, Prevett, & Olmos, 1996; Wickens, Thomas, & Young, 2000). First, we describe our manipulations. Then we describe implications for underlying perceptual and cognitive processes.

We used a laparoscopic box simulator to measure manual manipulation and manual aiming under different camera viewing conditions. The experimental set-up and apparatus is shown in Figure 1. In Experiment 1, observers performed a pick-and-place task; they used a surgical grasper to pick up a peg from one location and move it to another location. We manipulated the number of camera views and the viewing perspective provided by each camera. In Experiment 2, observers performed a reciprocal tapping task; the camera manipulations were the same as in Experiment 1. In addition, task difficulty was manipulated by changing the size of the targets and the distances between them. In Experiments 3 and 4, observers aimed pegs through six target holes in a specified sequence. We manipulated the mapping between movement direction and camera view, and the consistency of the mapping. In the consistent mapping condition, a specific movement direction was always paired with a specific camera view (e.g., leftward–rightward movement was always viewed from the side). In the varied mapping condition, all movement directions were performed with all camera views. Learning was assessed in all experiments by comparing performance across two replications of the task.

There were five viewing conditions. In the direct-view condition, observers viewed the task environment directly without cameras. In three single-camera view conditions, the task environment was viewed from a top, front, or side location. In the multiple-view condition, these camera views were shown concurrently in split view on a single display, as shown in Figure 1.

Implications of Manipulations for Perceptual and Cognitive Processes

The arrangement of the camera(s) determined the information presented in the camera image. This in turn affected the observer's perceptual and cognitive processes during the task and thus task performance and the observer's ability to learn the task. We considered the effects of two aspects of camera arrangement: camera orientation and number of camera views.

Camera Orientation

A camera's orientation with respect to the task environment and with respect to the observer's point of view determines the characteristics of the camera image and the perceptual and cognitive processes used to perform the task. These include frame of reference, movement compatibility, line-of-sight ambiguity or compression, and task-specific information.

Camera frame of reference. The camera's frame of reference refers to the viewpoint from which the camera projects the task environment (Wickens & Hollands, 2000). The degree to which the camera's frame of reference is aligned with the frame of reference of the observer looking at the camera image determines cognitive costs, specifically, the degree to which observers must perform mental transformations (i.e., to translate from one frame of reference to another). Misalignments represent a deviation from the observer's natural viewing perspective and thus lower realism and result in greater cognitive demands because of mental rotations that can contribute to greater response time and errors (Wick-

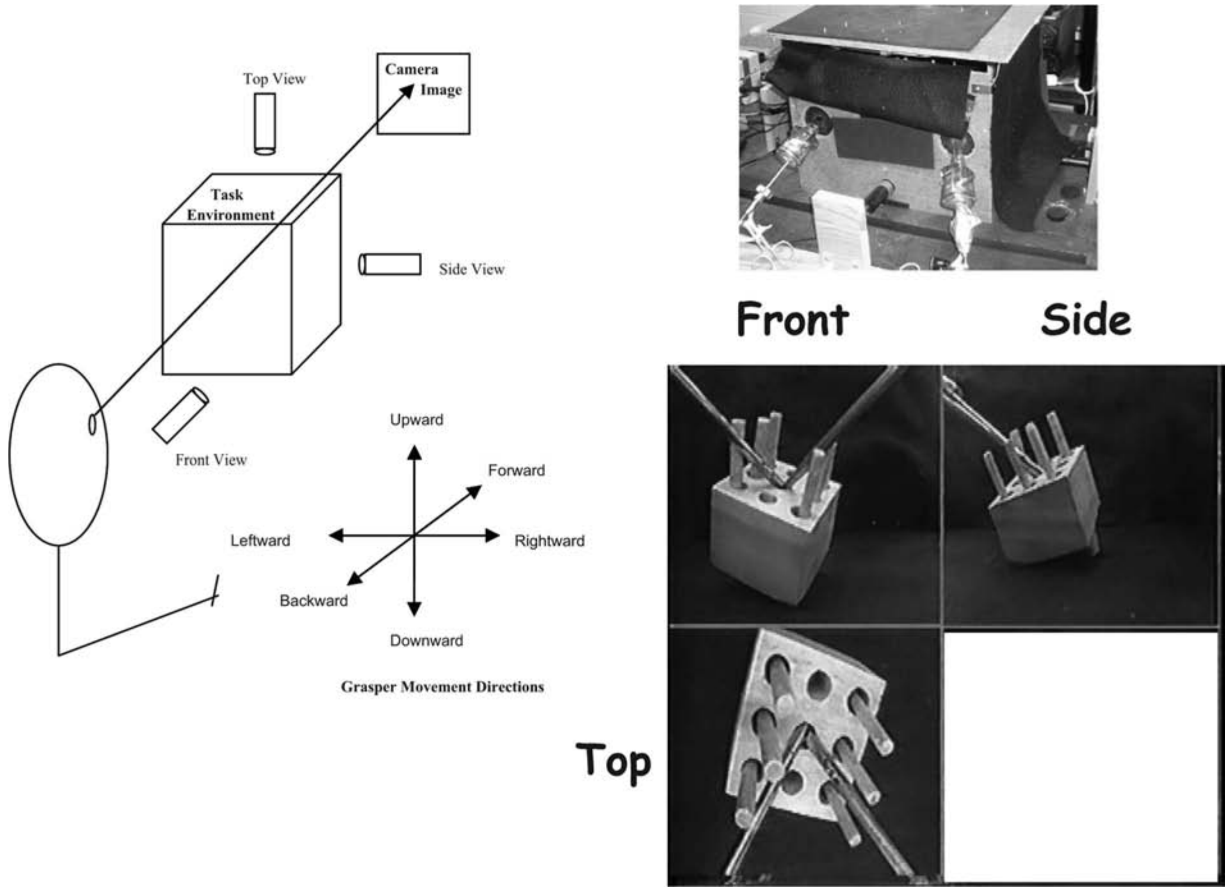

Figure 1. Experimental set-up and apparatus. Left panel: Schematic representation of camera orientations, and grasper movements. Top right panel: External view of laparoscopic simulator box. Bottom right panel: Top-front- and side–camera views of task environment in Experiment 1. (Reproduced with permission from *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting*. Copyright, 2004 by the Human Factors and Ergonomics Society. All rights reserved.)

ens et al., 1996). Using a camera image to display an environment results in a misalignment from the observer's point of view because the camera cannot be located at the same location as the observer's eyes. Thus, any camera view is expected to result in performance decrements compared with a direct view. In the current study, the front view provided the greatest alignment and realism compared with the top and side views.

In studies of aviation displays, effects of frame of reference depended on the task. Displays that provided a 3D or "immersed" field of view (front view in current study) were advantageous for navigation tasks; displays that provided a 2D plan view (top view in current study) were advantageous for accurate judgments about the environment (Olmos, Wickens, & Chudy, 2000; Wickens et al., 1996; Wickens, Thomas, & Young, 2000). In the current study, observers performed manual manipulation and manual aiming that involved navigation of objects through space and consequently a benefit of the front view was expected.

Movement compatibility. When observers move a control device such as a surgical grasper to affect an object viewed on a display they have expectations regarding how the display will change because of their actions. The degree to which the display changes in accordance with the observer's expectations is termed movement compatibility (Wickens & Hollands, 2000). The greater the compatibility between the device's movement direction in 3D space and the 2D image of that movement the lower the cognitive costs; there are lower cognitive demands because of fewer mental transformations (Wickens & Hollands, 2000; Wickens & Keller, 2010). Incompatibility can result in longer response times and slower training (Chan & Hoffmann, 2010).

Compatibility is determined by the relationship between the camera's frame of reference and the movement direction of the control device. In the current study, movement compatibility occurred when observers used top or front camera views while moving the grasper leftward and rightward, upward and downward, or forward and backward (refer to Figure 1). However, incompatibility occurred when observers used a side–camera view while moving the grasper leftward and rightward (displayed as forward–backward movement) or forward and backward (displayed as leftward–rightward movement).

Line-of-sight ambiguity or compression. The nature of information about depth and motion provided by a camera image depends in part on the relationship between the camera's frame of

reference and the movement direction of the control device. When the camera's line-of-sight is parallel to the device's movement direction there is foreshortening or compression of depth and motion in the camera image of the device's movement, known as line-of-sight ambiguity or compression (Wickens et al., 1996; Wickens, Thomas, & Young, 1995). This results in perceptual costs, that is, performance decrements when tasks require precise judgments of depth along the camera's line-of-sight (Wickens et al., 1996). Although a frame of reference that is parallel to the observer's view is more natural or realistic it degrades information about depth and motion when the controlled object is parallel to the camera's line-of-sight (Wickens et al., 1996). In the current study, line-of-sight ambiguity occurred when observers used the top-camera view while moving the grasper upward and downward, used the front view while moving forward and backward, and used the side view while moving leftward and rightward.

Task-information specificity. In addition to the previously described effects of camera orientation on characteristics of the 2D image, it is important to consider the effects of camera orientation on display information that is specific to the task, which also contributes to perceptual costs and benefits. For example, in Experiment 1, the task was to retrieve pegs with a grasper and place them into holes on top of a wooden cube. To complete this task the observer must place the peg above hole and drop it in. The critical information for this task is the location and size of the hole in relation to the peg. When the camera provides a top view (i.e., the line of sight is parallel to the long axis of the peg and perpendicular to the surface of the cube), the information about the hole is highly accessible. When the camera provides a front or side view (the line of sight is parallel to the surface of the cube and perpendicular to the long axis of the peg), it is difficult to see the hole and determine when the peg is above it (to enhance this information the cube was slightly tilted; see Figure 1). Thus, the top view provides information specific to the requirements of the task or task-information specificity. This contrasts with the costs of frame of reference and line-of-sight ambiguity: The top view results in a misalignment between the camera's and observer's frames of reference (putatively requiring mental transformations), and results in compression of depth along the line-of-sight. In Experiments 3 and 4 the task-information specificity provided by a given camera view depended on movement direction. In short, the availability of information specific to the task may offset other costs of a particular frame of reference. Although task-information specificity and line-of-sight ambiguity both have perceptual consequences, we consider task-information specificity separately because it captures the reciprocity between the availability of information provided by a specific camera view and the requirements of a specific task and reflects the results of studies of aviation displays that showed that effects of frame of reference are task-dependent.

Number of Camera Views

Laparoscopic surgery typically uses one camera. Different camera views can be provided by moving the camera but a stable camera is preferred because camera movement can result in spatial disorientation, fatigue, and nausea (Holden, Flach, & Donchin, 1999; Tendick, Bhoyrul, & Way, 1997). To offset limitations of a single view (e.g., line-of-sight ambiguity), multiple views can be provided. However, studies of aviation displays demonstrated that the number of cameras and the manner in which the different camera images are presented to the observer have implications for perceptual and cognitive processing including information integration, and attentional demands. We also consider implications for information extraction. The first two have cognitive consequences; the third has perceptual consequences.

Information integration. Compared with a single–camera view, multiple–camera views of the task environment provide the observer with access to more information about 3D space and access to the information that resolves line-of-sight ambiguities. However, if the task requires observers to mentally integrate different sources of information to reconstruct 3D space, cognitive demands will be higher when multiple–camera views are presented than when a single–camera view is presented (Olmos, Wickens, & Chudy, 1999; Wickens et al., 1996; Wickens, Thomas, & Young, 1995). In the current study, the use of information from multiple–camera views to reconstruct 3D space putatively required mental integration.

Attentional demands. When multiple views are provided, observers must shift their attention from one view to another or may divide their attention among the views, which requires attentional resources (Olmos, Wickens, & Chudy, 2000; Wickens, Thomas, & Young, 1995) and can result in less learning (Sweller, 1993). In the current study, multiple–camera views provided more information about 3D space but putatively imposed more attentional demands compared with a single-camera view.

Information extraction. When multiple–camera views of the task environment are provided on a single display, each image is smaller relative to a single-camera view shown on the same-sized display. With smaller images, information about detail, depth, and motion is more difficult for the observer to extract, which can impose performance costs (Wickens, Kroft, & Yeh, 2000). In the current study, each image in the multiple-view condition contained smaller images than the corresponding image in the single-camera condition. Information extraction refers to manner in which the display characteristics (e.g., display size and resolution) constrain the observer's extraction of information (e.g., details, depth information).

Learning and Consistency of Mapping

With practice, observers can adapt to perceptual-motor misalignments (Harris, 1965; Helmholtz, 1925; Redding, Rossetti, & Wallace, 2005). However, benefits of practice depend on the cognitive demands of a task. Learning degrades when cognitive demands are relatively higher as would occur when a task requires working memory or information integration (Sweller, 1993). In the current study, camera arrangements that resulted in information integration, incompatibility of movement, misaligned frames of reference, and divided attention increased the cognitive demands of the task and putatively degraded learning. Learning also is better when there is a consistent, rather than a varied, relationship between a display and the observer's response (e.g., Rogers, Lee, & Fisk, 1995). Mapping consistency was varied in the current study.

General Hypotheses and Predictions

Studies of aviation displays indicated that each camera arrangement introduced costs and benefits to perceptual and cognitive processing (Wickens et al., 1996). One approach to developing display design recommendations is to use these costs and benefits to generate predictions of spatial-cognitive difficulties (Wickens & Keller, 2010). We used this approach in the present study. We hypothesized that camera arrangements resulting in a relatively greater ratio of benefits to costs would result in relatively better perceptual-motor performance.

Tables 1 and 2 show the costs and benefits in perceptual and cognitive processing associated with each combination of camera viewing condition (top, front, side, and multiple views) and grasper movement direction (leftward–rightward, upward–downward, forward–backward) used in the current study. For example, when a front camera view is used while performing upward–downward movements, there are benefits of realism and movement compatibility and there are no costs (at least for the way we conceptualized the task here; for costs associated with forward-looking views more generally, see Olmos, Wickens, & Chudy, 2000). In contrast, when a top view is used, there are benefits of movement compatibility and task-information specificity and also costs of compression and misaligned frame of reference. Thus, the front view should result in better performance than the top view. The multiple-view condition provides all the benefits and costs of the three single-camera views but also introduces three additional costs of information integration, divided attention, and putatively less effective information extraction because of smaller images.

If one adds the benefits and costs for all grasper movement directions and computes benefit-cost ratios, an ordinal ranking of performance for the different camera arrangements can be generated: Overall, from best performance to worst performance, the order should be the front view, top view, multiple view, and side view. In addition, learning should be degraded in those conditions with relatively higher cognitive demands (misaligned frame of reference, movement incompatibility, information integration, and divided attention) resulting in less cognitive resources available for learning (Sweller, 1993; Wickens & Hollands, 2000). Finally, in all experiments we expected performance to be best with the direct view.

Experiment 1

The purpose of Experiment 1 was to determine whether and how the number and type of camera views affect manual manipulation. We measured performance on a pick-and-place task when observers viewed the task environment with three cameras concurrently to performance when observers viewed the environment with only one of the camera views. We also compared performance among the three single-camera views and compared all camera viewing conditions to a direct view.

The task required moving the grasper in all three dimensions of space. According to the costs and benefits shown in Table 1, we expected the order of conditions from best performance to worst performance to be the front view, top view, multiple views, and side view. Because learning decreases when cognitive demands increase, we expected learning to be best with the front view which

Table 1
Benefits and Costs Associated With Each Combination of Camera Viewing Condition and Grasper Movement in Experiments 1 and 2

	Camera condition											
	Single-top view			Single-front view			Single-side view			Concurrent multiple views (top + front + side)		
Grasper movement direction[a]	L/R	U/D	F/B	L/R	U/D	F/B	L/R	U/D	F/B	L/R	U/D	F/B
Benefits (B)												
Realism	—	—	—	B	B	B	—	—	—	B	B	B
Movement Compatibility	B	B	B	B	B	B	—	B	—	B	B	B
Task-information Specificity	B	B	B	—	—	—	—	—	—	B	B	B
Costs (C)[b]												
Frame of reference	C	C	C	—	—	—	C	C	C	C	C	C
Movement Incompatibility	—	—	—	—	—	—	C	—	C	C	—	C
Compression	—	C	—	—	—	C	C	—	—	C	C	C
Information Integration	—	—	—	—	—	—	—	—	—	C	C	C
Divided Attention	—	—	—	—	—	—	—	—	—	C	C	C
Information Extraction	—	—	—	—	—	—	—	—	—	C	C	C
Benefit/cost ratio	2/1	2/2	2/1	2/0	2/0	2/1	0/3	1/1	0/2	3/6	3/5	3/6
Totals for each view	Top: 6/4			Front: 6/1			Side: 1/6			Multiple: 9/17		

[a] L/R denotes leftward—rightward, U/D denotes upward—downward, F/B denotes forward—backward. [b] Compression and information extraction represent perceptual costs; the other costs are cognitive.

Table 2
Benefits and Costs Associated With Each Combination of Camera Viewing Condition and Grasper Movement in Experiments 3 and 4

	Camera condition											
	Single-top view			Single-front view			Single-side view			Concurrent multiple views (top + front + side)		
Grasper movement direction[a]	L/R	U/D	F/B	L/R	U/D	F/B	L/R	U/D	F/B	L/R	U/D	F/B
Benefits (B)												
Realism	—	—	—	V, Ex4	V	V, Ex3	—	—	—	B	B	B
Movement Compatibility	V	V, Ex3	V, Ex4	V, Ex4	V	V, Ex3	—	V, Ex4	—	B	B	B
Task-information Specificity	—	V, Ex3	—	—	—	V, Ex3	V, Ex3	—	—	B	B	B
Costs (C)[b]												
Frame of reference	V	V, Ex3	V, Ex4	—	—	—	V, Ex3	V, Ex4	V	C	C	C
Movement Incompatibility	—	—	—	—	—	—	V, Ex3	—	V	C	—	C
Compression	—	V, Ex3	—	—	—	V, Ex3	V, Ex3	—	—	C	C	C
Information Integration	—	—	—	—	—	—	—	—	—	C	C	C
Divided Attention	—	—	—	—	—	—	—	—	—	C	C	C
Information Extraction	—	—	—	—	—	—	—	—	—	C	C	C
Benefit/cost ratio												
Varied mapping Experiments 3 and 4	1/1	2/2	1/1	2/0	2/0	3/1	1/3	1/1	0/2	3/6	3/5	3/6
Consistent mapping Experiment 3	na	2/2	—	—	na	3/1	1/3	—	na	—	—	—
Experiment 4	na	—	1/1	2/0	na	—	—	1/1	na	3/6	3/5	3/6

Note. The benefits and costs specific to the consistent mapping conditions are denoted by "Ex3" and "Ex4." The benefits and costs in the varied mapping condition are denoted by V. Benefits and costs in the multiple-view condition are the same for both consistent and varied mapping.
[a] L/R denotes leftward–rightward, U/D denotes upward–downward, F/B denotes forward–backward. [b] Compression and information extraction represent perceptual costs; the other costs are cognitive.

imposed the fewest cognitive costs, followed by the top, side, and multiple views; the latter imposed the greatest cognitive costs.

Method

Participants. Twelve undergraduates (6 males, 6 females) at Texas Tech University participated for course credit. All participants reported being right-handed and having normal or corrected visual acuity. We selected undergraduates so that we could achieve a sample size that would allow experimental control and adequate statistical power to detect differences among experimental conditions. The availability of expert surgeons for experimentation is limited and makes adequate sample sizes difficult to achieve (Tuggy, 1998). In addition, the education that surgical trainees receive outside of the operating room allows them to develop habits to overcome deficiencies of imaging devices. Undergraduates allowed us to measure performance unfettered by the strategies and habits of experienced surgeons and were less likely to exhibit negative transfer because of prior knowledge and experience (Perkins, Starkes, Lee, & Hutchison, 2002). The generalizability of the results from undergraduates to surgeons is considered in the General Discussion section.

Apparatus. As represented in Figure 1, we used a wooden box, bullet cameras, and surgical graspers to simulate a perceptual-motor task relevant to laparoscopic surgery (DeLucia, Hoskins, & Griswold, 2004). The task environment (inside the box) contained a block of wood with nine holes. The block of wood was approximately 5.1 × 5.2 × 3.4 cm. Each of the nine holes was .9 cm in diameter and separated by .7 cm. Wooden pegs were located in six of the holes. Each peg was about 5.5 cm tall. Three of the pegs were thin and three of the pegs were thick, measuring .4 and .6 cm in diameter, respectively. Color CCD bullet cameras were mounted on the top, front, and right side of the box. The viewing perspective of each camera was orthogonal to that of the other cameras. Hanna and Cuschieri reported that the performance of an aiming task (inserting a probe into holes on a target plate) was faster, more accurate, and achieved with less force when the viewing axis of an endoscope was 90 degrees to the target plane compared with 45, 60, and 75 degrees.

The camera images were fed through a 30 frames/s real-time color quad-splitter and were displayed on a 13" color video monitor. The quad-splitter permitted the camera images to be displayed on the monitor either one at a time or concurrently in split view. A fourth camera was directed at the participant to record direction of gaze and the number of times each image was fixated. The image of the participant was occluded from the participant's view with cardboard. The task environment was illuminated by lining the

interior of the box with clear rope lights and adjusting the lighting with a dimmer. Finally, to provide a direct view of the task environment, the top of the box opened with a hinge.

Procedure. Two identical stainless steel surgical graspers were inserted through plastic trocars into openings in the box through neoprene rubber. The graspers were held and operated similar to scissors. When observers raised their hands upward the end-effector (tip) of the grasper moved downward and vice versa; when they moved their hands leftward the tip of the grasper moved rightward. This is known as the fulcrum effect (Gallagher et al., 2003).

Participants were instructed to reverse the locations of the thin and thick wooden pegs with the graspers. Accuracy (i.e., not dropping pegs) was emphasized rather than speed. After familiarizing themselves with the operation and feel of the graspers, participants practiced the task with the direct view until they could move at least two thick pegs and two thin pegs successfully. During this practice, the locations of the thick and thin pegs were reversed from the locations used in the experimental trials. Participants then performed the task with the direct view followed by the multiple–camera views. In the latter condition, the top, front, and side–camera views were shown concurrently in a split view in the lower left, upper left, and upper right quadrants of the display, respectively, as shown in Figure 1. After completing the multiple-view condition, the top, front, and side views were presented alone in an order that was completely counterbalanced across participants. Finally, a second replication of each of the viewing conditions was completed in the reverse order, ending with the direct view. After each trial participants reported which camera view they looked at most frequently and least frequently.

At the start of each trial, participants positioned the tips of both graspers on top of the center hole in the wooden block (see Figure 1) and the experimenter verbally signaled the start of the task. We measured task completion time as the time between the experimenter's verbal signal to begin the task and the time at which the last peg dropped into the hole. Task completion time is a critical measure of eye–hand coordination tasks (Payandeh, Lomax, Dill, Mackenzie, & Cao, 2002). A portable karaoke machine was used to tape the experimenter's verbal signals onto the videotape. Pick-and-place performance and eye movements were recorded on videotape and measured off-line.

Results and Discussion

A 2 × 5 (replication × viewing condition) within-subjects ANOVA was used to analyze task completion time. The *p* values in all experiments reflect Greenhouse-Geisser corrections. The five viewing conditions consisted of the direct view, three single views (top, front, and side), and multiple concurrent views. Because the participants could move the grasper in any direction and movements were not constrained by the experimenter, we did not analyze the movement directions separately; this was done in Experiments 3 and 4.

Results are summarized in Figure 2 and indicated that viewing condition and replication affected performance. A partial analysis of the results from Experiment 1 was reported at the 48th meeting of the Human Factors and Ergonomics Society and was published in the conference proceedings (DeLucia, Hoskins, & Griswold, 2004).

Task completion time. There was a main effect of viewing condition, $F(4, 44) = 23.79$, $p < .001$, $w^2 = 45.58\%$. Tukey's HSD analyses indicated that mean task completion time was significantly faster for the direct view compared with the front and side views, and the side view resulted in the slowest completion time compared with all other views, $p < .05$. The difference between the direct view and the top view was not significant $p > .10$; neither was the difference between the direct view and multiple views, $p > .08$. The implication is that the top view and multiple-view conditions can result in performance as good as the direct view. However, this result should be viewed in the context of our relatively conservative statistical approach (i.e., Tukey's HSD post hoc comparisons rather than a priori comparisons). Task completion time was significantly faster for the second replication than the first, indicating that learning occurred, $F(1, 11) = 20.37$, $p < .001$, $w^2 = 4.54\%$. The interaction between viewing condition and replication was not significant.

Performance in the multiple-view condition was not significantly different from the front or top views and resulted in a performance benefit only when compared with the side view. We considered the possibility that participants did not utilize all three views in the multiple-view condition. Indeed, all except two participants reported looking at the top-camera view most frequently and the side view least frequently, $p < .001$ (using binomial probabilities based on the null hypothesis that one third of the participants would report the top view, one third would report the front view, and one third would report the side view). Consistent with participants' subjective reports, analyses of gaze direction indicated that 10 of the 12 participants looked at the top-camera view 100% of the time, $p < .001$. Thus, it is possible that the results of the multiple-view condition occurred because participants mostly looked at the top view. The benefits and costs of multiple views listed in Table 1 were not realized. Finally, the statistical equivalence of the top and front views implies that the benefit of task-information specificity outweighed the benefits of realism and the combined benefits of movement compatibility and task-information specificity offset the costs of compression and misaligned frame of reference. Learning occurred in all conditions, suggesting that differences in cognitive demands among the viewing conditions did not affect learning.

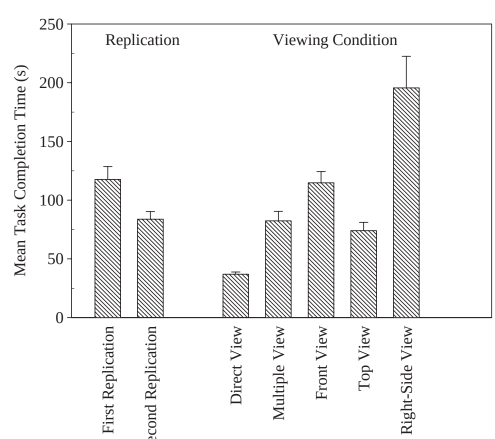

Figure 2. Experiment 1. Main effects of replication and viewing condition on mean task completion time. Error bars indicate ± 1 *SEM*.

Experiment 2

The purpose of Experiment 2 was to determine whether the number and type of camera views affect aiming performance using a reciprocal tapping task similar to that described by Fitts (1954). Participants moved a surgical grasper primarily leftward and rightward to tap two disks in alternation while they viewed the task environment on a video monitor (see also Tendick & Cavusoglu, 1997). As noted earlier, in a study of suturing, the performance benefits with multiple-camera views increased as task complexity increased (Geis, Gillian, & Berry, 1999). To evaluate effects of task difficulty, four combinations of disk sizes and distances were included. The task difficulty as measured by Fitts' index of difficulty ranged from 1.44 to 3.56. The index of difficulty is defined as *logbase2 (2D/W*), where D = movement distance, and W = target width (Fitts & Peterson, 1964). This manipulation allowed us to determine whether the effect of task difficulty on performance varied with camera arrangement.

We expected the direct view to result in better performance than all camera views. On the basis of the costs and benefits for leftward–rightward movement shown in Table 1, we expected the ordinal ranking for the different camera arrangements, from best performance to worst performance, to be the front view, top view, multiple views, and side view. In addition, we expected accuracy to decrease and mean movement time to increase as task difficulty increased. We also expected learning to be best in the front view, followed by top, side, and multiple views, based on the relative number of cognitive costs among these conditions.

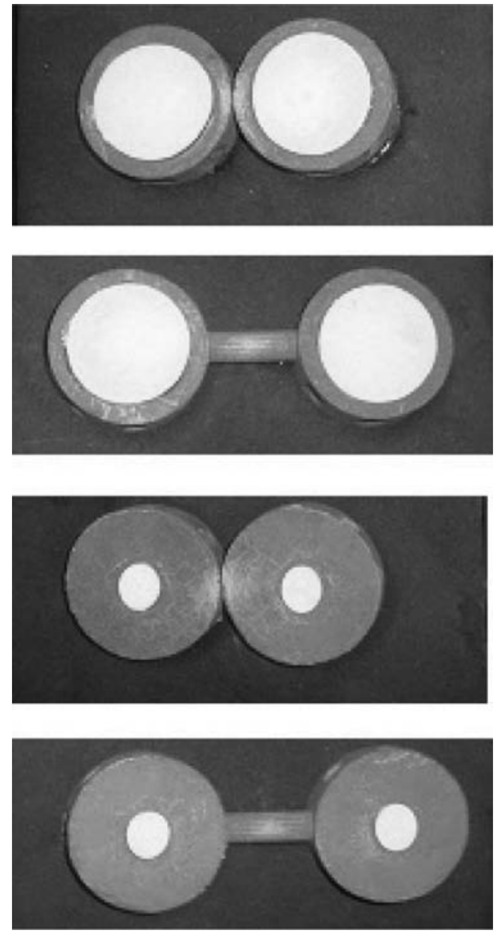

Figure 3. Digital image of task environments used for the alternate tapping task in Experiment 2. Top panel: Large, near. Second panel: Large far. Third panel: Small near. Bottom panel: Small far. Respective indices of difficulty were 1.44, 2.07, 2.93, and 3.56.

Method

Participants. Twenty-four different participants (12 male, 12 female) had the same characteristics as in Experiment 1.

Apparatus. The apparatus was as described in Experiment 1 except that the position of the side view and top views were reversed to determine whether poor performance with the side view was because of its location on the monitor. Thus, the front, top, and side views were shown in the upper left, upper right, and lower left quadrants, respectively.

As shown in Figure 3, the task environment consisted of four wooden disks glued onto a black rectangular board. Two small yellow disks were glued onto larger blue surrounding disks, about 4.1 cm in diameter (the yellow disks appeared white on the monitor). The distance between the centers of the disks was either about 4.2 or 6.5 cm and the diameter of the yellow disks was either 1.1 or 3.1 cm. This led to four disk configurations of large near disks, large far disks, small near disks, and small far disks. Each represented a different level of task difficulty. Respective indices of difficulty were 1.44, 2.07, 2.93, and 3.56.

After familiarizing themselves with the operation and feel of the grasper, participants were given four practice trials. The first set of experimental trials was completed with the direct view. In the second set of trials, participants viewed the environment with multiple-camera views. In the next three sets of trials the participants viewed the environment with a single-camera view consisting of the front, top, or side view, with order completely counterbalanced across participants. The remaining trials were a repeat of the five viewing conditions in the reverse order, ending with the direct view.

Procedure. Participants were instructed to strike the yellow disks alternately with the tip of the grasper and to score as many such hits as they could within 15 s. Participants were informed that hitting the outer blue disks was scored as an error. Accuracy was emphasized over speed. At the beginning of each trial participants placed their fingers in the grasper handle and put the tip of the grasper midway between the two disks. The experimenter provided a verbal signal to start and stop the task. There were four replications of each camera-view condition, one for each of the four levels of task difficulty. Each of the 24 orders of the disk configurations was presented to a different participant. In short, there were two trials for each combination of task difficulty and camera view with the second trial presented in the reverse order for a total of 40 trials. Tapping performance and gaze direction were videotaped and measured off-line. Accuracy was defined as the number of hits within the 15-s period. Mean movement time was computed by dividing 15 s by the number of hits. After each multiple-view trial participants were asked to report which camera view they looked at most frequently, and least frequently.

Results and Discussion

Accuracy and movement time were analyzed separately. Movement times were averaged across replication because in some trials there were zero hits which resulted in an undefined value of mean movement time and in missing cells; such trials were not included in the analyses.

Accuracy. A 2 × 4 × 5 (replication × task difficulty × viewing condition) within-subjects ANOVA was used to analyze accuracy. Viewing conditions consisted of the direct view, multiple views, top, front, and side views. Generally, there were fewer hits with the side view compared with the other views, more hits for the second replication than the first, and a decrease in accuracy as task difficulty increased.

Specifically, there were main effects of viewing condition, $F(4, 92) = 196.03$, $p < .001$, $w^2 = 32.69\%$, replication, $F(1, 23) = 29.56$, $p < .001$, $w^2 = 1.33\%$, and task difficulty, $F(3, 69) = 128.88$, $p < .001$, $w^2 = 26.63\%$. There also were two-way interactions between viewing condition and replication, $F(4, 92) = 4.24$, $p < .007$, $w^2 = .22\%$, and between viewing condition and task difficulty, $F(12, 276) = 3.15$, $p < .007$, $w^2 = .25\%$, shown in Figure 4. Statistical results of the analyses of simple main effects are shown in Appendix 1.

The effect of viewing condition was significant for both replications. In the first replication, the mean number of hits was greatest for the direct view, followed by the top, multiple, front, and side views, with all pairwise comparisons significant, $p < .05$. On the second replication, mean hits were greater for the direct view than all other views. In addition, mean hits was greater for the multiple views and top view (not different from each other) compared with the front and side views, and the side view resulted in the lowest hits compared with all other views, $p < .05$. The mean number of hits was greater for the second replication than the first for all camera views except the top view, possibly indicating a ceiling effect.

The finding that the multiple-view and top-view conditions were comparable (on second replication) suggests that participants looked at the top view in the multiple-view condition. Indeed, in the multiple-view condition, all except one participant reported looking at the top view most frequently, and the side view least frequently, $p < .001$. Consistent with subjective reports, analyses of gaze direction indicated that participants looked at the top view most frequently. Such analyses indicated that 71.19% of the fixations recorded were on the top view, followed by 27.88% on the front view, and .92% on the side view (the latter was contributed by one participant). The total number of fixations for all participants, conditions and trials was 434.

On the basis of Table 1, the finding that accuracy was greater with the top view than the front view suggests task-information specificity in the top view (in this case being able to see the entire target disk without angular distortion) outweighed the benefits of realism in the front view and the combined benefits of task-information specificity and movement compatibility offset the costs of misaligned frame of reference in the top view.

The effect of viewing condition was significant for all levels of task difficulty, and vice versa. For all levels of task difficulty, the mean number of hits for the direct view was greater than for all other views; the means for the multiple-view and top-view conditions were greater than the front and side views, and the side view resulted in the fewest mean hits than all other views, $p < .05$. The mean number of hits decreased as task difficulty increased. For all viewing conditions except one, all pairwise comparisons of task difficulty were significant, $p < .05$. For the side view, the difference between the 2.93 and 3.56 indices of difficulty was not significant. In short, none of the camera viewing conditions eliminated effects of task difficulty.

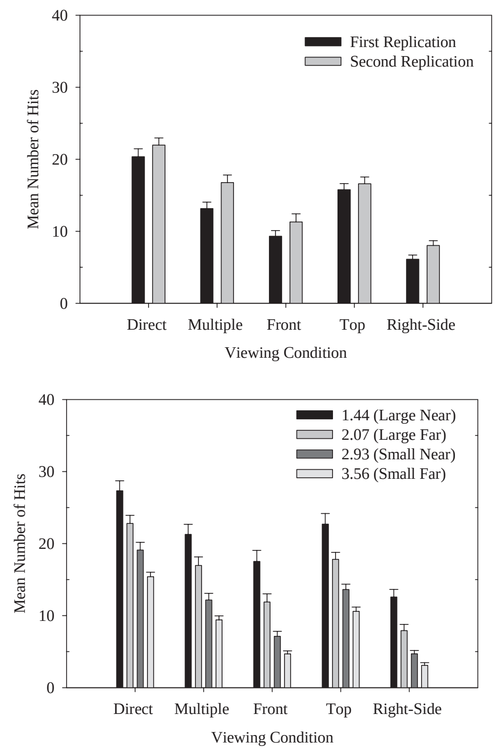

Figure 4. Experiment 2. Top panel: Mean number of hits for two-way interaction between replication and viewing condition. Bottom panel: Mean number of hits for two-way interaction between task difficulty (the number indicates the index of task difficulty) and viewing condition. Error bars indicate ± 1 *SEM*.

Movement time. A 4 × 5 (task difficulty × viewing condition) within-subjects ANOVA was used to analyze movement time. There were main effects of viewing condition, $F(4, 92) = 83.16$, $p < .001$, $w^2 = 32.37\%$, and task difficulty, $F(3, 69) = 53.13$, $p < .001$, $w^2 = 14.01\%$, and an interaction between viewing condition and task difficulty, $F(12, 276) = 12.43$, $p < .001$, $w^2 = 9.66\%$, shown in Figure 5.

The effect of viewing condition on mean movement time was significant for all levels of task difficulty, $p < .004$. In all cases, mean movement time was slower in the side view compared with all other views, $p < .05$. The front view resulted in longer movement times compared with the multiple, top, and direct views, $p < .05$, except when task difficulty was lowest (1.44); in the latter case differences among direct, front, top, and multiple views were not significant. There were no differences among the direct, multiple views, and top view in any task difficulty conditions. This again suggests that observers looked primarily at the top view in the multiple-view condition and did not realize the costs of that condition.

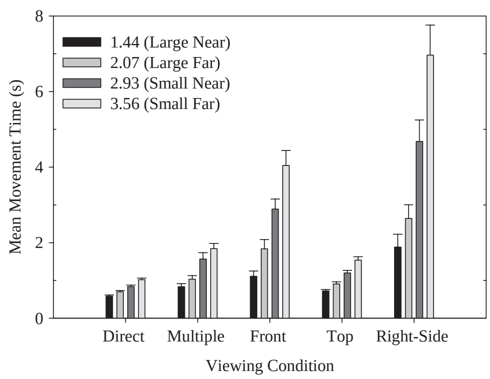

Figure 5. Experiment 2. Mean movement time for two-way interaction between task difficulty (the number indicates the index of task difficulty) and viewing condition. Error bars indicate ± 1 *SEM*.

The effect of task difficulty was significant only for multiple views, front view, and side view, $p < .019$. Generally, mean movement time increased as task difficulty increased but some pairwise comparisons were not significant (e.g., 1.44 vs. 2.07) possibly because the change in task difficulty was not sufficient.

Experiment 3

The results of Experiments 1 and 2 suggest that when a single camera is used, the camera's viewing perspective can affect manual manipulation and manual aiming performance. However, several parameters of the display necessarily changed when the camera view varied, including the availability of task-specific information. For example, in Experiment 1, the surfaces of the wooden block that were visible changed with each camera view. In addition, the relationship between the actual grasper movement and the displayed grasper movement differed with each camera view. For example, when the grasper moved leftward and rightward in 3D space, it appeared to move leftward and rightward in the top view but appeared to move backward and forward in the side view. This violation of the compatibility principle may account for slower performance in the side view obtained in Experiments 1 and 2. The purpose of Experiments 3 and 4 was to determine whether effects of camera view depended on the direction in which the grasper moved and whether the consistency of this mapping affected performance.

In Experiments 3 and 4, observers moved a peg (that was attached to a wooden ball) through a target hole and contacted a target surface located beyond the hole. Movement was leftward–rightward, upward–downward, and forward–backward and each of these movements was aimed at a different target hole. This task required observers to align the peg with the hole and move it through the hole far enough so that it contacted the target surface (such contact presumably could be discerned partly via haptic feedback). As in Experiment 1, the critical information for this task is the location and size of the hole in relation to the peg. The camera view that provided this task-specific information varied with the direction of movement (see Figure 6). When the movement was leftward–rightward a side view provided the best view of the target holes. When the movement was upward–downward a top view provided the best view of the target holes. When the movement was forward–backward a front view provided the best view of the target holes (note that in all cases the wooden ball and pegs occluded the view of one of the holes in each pair of targets for a given movement direction). However, the pairing between movement direction and camera view also determined other costs and benefits (e.g., movement compatibility).

Table 2 shows the costs and benefits in Experiments 3 and 4. Based on the benefit/cost ratios for consistent-mapping conditions, we expected the single-camera view conditions to result in better performance than the multiple-view condition except when leftward–rightward movement was paired with the side view. We also expected performance for a given movement direction to depend on the camera view. For example, the benefit/cost ratios suggest that leftward–rightward movement would be better with a front view than a side view. Comparisons of different camera views for a given movement direction requires contrasts between results of Experiments 3 and 4; these analyses are presented after the results of Experiment 4 are discussed. Finally, we expected learning to depend on cognitive demands in each viewing condition. We anticipated that learning would be greatest with the front view and lowest with the multiple views, and would be better with consistent compared with varied mapping.

Method

Participants. Twenty-four participants (12 Male, 12 female) had the same characteristics as in Experiment 1.

Apparatus. The apparatus was as described in Experiment 1.

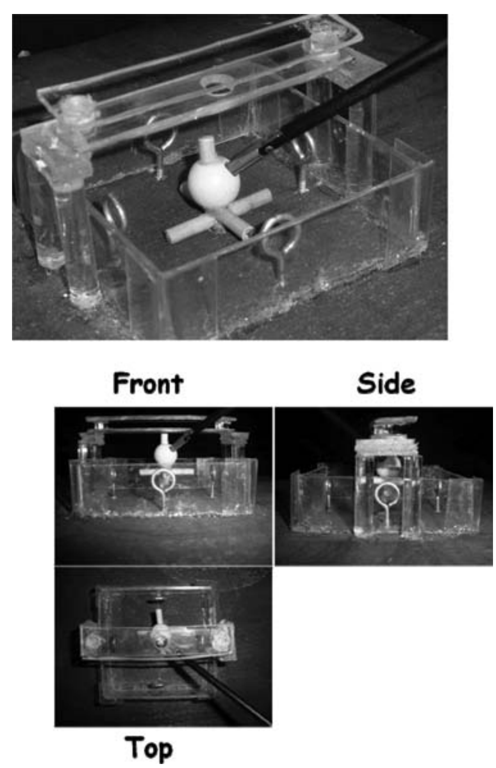

Figure 6. Digital image of task environment in Experiments 3 and 4. Top panel: Close up view of targets and pegs. Bottom panel: Approximation of top, front, and side-camera views.

Procedure. The task environment is represented in Figure 6. There were six target holes. Four of the holes consisted of metal rings each .9 cm in diameter. About .7 cm beyond each ring was a rectangular strip of clear plastic that served as the target wall. These target holes and walls were used for the leftward–rightward and forward–backward movements. The fifth target hole and target wall were created with plastic strips located above the rings. The sixth target hole and wall were located in the wooden floor. The latter two holes were used for the upward–downward movements. The tip of a surgical grasper was attached to a wooden ball by closing the tip of the grasper and inserting it tightly into a drilled hole in the ball. The latter was 1.5 cm in diameter. An orthogonal configuration of wooden pegs, each .4 cm in diameter, were attached to the ball as shown in Figure 6. Each tip of the pegs was inserted into a different target hole during the six movement directions.

Participants began each trial by placing their fingers in the grasper and positioning one of the ball's pegs into a target hole in the wooden base of the task environment. They were instructed to insert each of the wooden pegs through an assigned target hole (i.e., insert the left, right, top, bottom, front, and back pegs through the left, right, top, bottom, front, and back target holes, respectively) until the wooden peg struck the target wall. Doing so constituted a hit. Not moving the peg through the hole far enough to strike the wall was scored as an error. Participants were instructed to move the grasper forward–backward, up–down, and left–right to hit the respective targets, with order of movement directions completely counterbalanced across participants. They repeated this sequence of movements for 45 s and were told to score as many hits as they could; accuracy was emphasized over speed. The experimenter verbally signaled the participant to start and stop. Perceptual-motor performance and direction of gaze were videotaped and scored off-line. After each multiple-view trial participants were asked to report which camera view they looked at most frequently and least frequently.

After familiarizing themselves with the operation and feel of the grasper, participants practiced the task three times or as many times as needed to do the task without error. The first experimental trial was completed with the direct view. This was followed by the multiple-view condition. The location of the top, front, and side-camera views in the upper left quadrant, upper right quadrant, and lower left quadrant of the multiple-view display was completely counterbalanced across participants to eliminate the possibility that the poor performance with the side view in Experiments 1 and 2 was because of the location of the side view on the monitor. To aid participants while using the side view, a white vertical mark was painted on the side of the top target wall so that participants could see the horizontal position of the hole. The lower right quadrant contained the camera view of the participant and was covered with cardboard.

After the direct and multiple-view conditions were completed, the third through fifth trials consisted of either consistent or varied mapping; the third trial was provided for practice and was not analyzed. In the consistent mapping condition, participants performed only one movement direction for a given camera view for 15 s before the view changed. When the camera view changed the assigned direction of movement also changed so that each camera view was paired with a specific movement: With the front view, participants moved the grasper forward and backward. With the top view, participants moved the grasper upward and downward. With the side view participants moved the grasper leftward and rightward. Thus, task-specific information (the target holes were highly visible) was available for each movement direction. The order of the camera views and movement directions was counterbalanced across observers.

In the varied mapping condition, participants performed all three grasper movement directions for a given camera view for 15 s before the camera view changed. For example, when the camera showed a front view of the task environment, the participant moved the grasper forward and backward, then upward and downward, then leftward and rightward. They repeated this sequence of movements for 15 s with each of the three camera views for a total of 45 s. The sequence and duration of each camera view was achieved with settings on the quad splitter. For a given camera view, task-specific information was available for only one of the movement directions because the camera view did not change.

The final two trials consisted of the multiple-camera view and direct view, respectively. The order of camera views and grasper movements was completely counterbalanced across participants. Mapping consistency was a between-groups factor with half of the participants completing one of the conditions.

Results and Discussion

A 2 × 2 × 3 (replication × mapping consistency × viewing condition) mixed ANOVA with mapping consistency as the between-subjects variable was used to analyze the number of hits. Each pairing of camera view (top, front, side) with each grasper movement direction (leftward–rightward, upward–downward, and forward–backward movement) was analyzed separately so that mappings with different benefits and costs could be compared. The three viewing conditions consisted of the direct view, multiple-camera views, and one of the camera views (the one that was mapped to the movement direction in the consistent mapping condition; the subheadings of the results section indicate this mapping). In other words, we compared results for a particular movement direction (e.g., leftward–rightward) when performed in the single-view condition (e.g., side view) to the results of that same movement direction when performed in the direct and multiple-view conditions. We also compared results for a particular movement direction between the consistent and varied mapping conditions. Statistical results of the analyses of simple main effects are shown in Appendix 1.

As in Experiments 1 and 2, in the multiple-view condition a significant number of participants in Experiment 3 reported looking at the top view most frequently, and at the side view least frequently, $p < .001$. Consistent with subjective reports, analyses of gaze direction indicated that participants indeed looked most frequently at the top view (56.91%) followed by the front view (33.15%) and the side view (9.90%). The total number of fixations for all participants, conditions and trials was 181. We interpret the results with these findings in mind.

Left–right movement with side-camera view. There were main effects of replication, $F(1, 22) = 65.86$, $p < .001$, $w^2 =$ 1.70% and viewing condition, $F(2, 44) = 256.63$, $p < .001$, $w^2 =$ 81.68%. There also was an interaction between viewing condition and replication, $F(2, 44) = 32.83$, $p < .001$, $w^2 = 1.50\%$, shown in Figure 7.

For both replications, the mean number of hits was greater for the direct view than the multiple-view and side-view conditions, $p < .01$. In addition, mean hits were greater for multiple views than the side view, $p < .01$. The effect of replication was significant for the direct and multiple views but not for the side view; mean hits was greater for the second replication compared with the first.

The implication is that the benefits of movement compatibility and realism provided by the multiple-view condition outweighed the costs of compression, frame of reference, and incompatibility introduced by the side view. This assumes that observers took advantage of the top and front views available in the multiple-view condition. Analyses of gaze direction indeed indicated that observers looked at the top and front views. It also appears that costs associated with degraded information extraction because of smaller images of the multiple views were not enough to degrade performance compared with the side view. The absence of learning with the side view indicates that it was difficult to perform the task with the side view potentially because of cognitive demands. Finally, the effect of mapping consistency (whether the side view was paired with one movement or all movements) was not significant, suggesting that the cognitive load in the side view impeded learning.

Up–down movement with top-camera view. There were main effects of replication, $F(1, 22) = 49.61$, $p < .001$, $w^2 = 1.77\%$, and viewing condition, $F(2, 44) = 156.90$, $p < .001$, $w^2 = 61.74\%$. There also were interactions between viewing condition and replication, $F(2, 44) = 13.75$, $p < .001$, $w^2 = .98\%$, and between viewing condition and mapping consistency, $F(2, 44) = 24.03$, $p < .001$, $w^2 = 9.12\%$, shown in Figure 8. There was a significant effect of viewing condition at both replications. On both replications the mean number of hits was greater for the direct view than the multiple-view and top-view conditions, $p < .01$. However, on the second replication the multiple views resulted in more hits than the top view, $p < .01$. The implication (based on costs and benefits in Table 2) is that with learning, observers benefited from the multiple views by using the front view which provided realism in contrast to the misaligned frame of reference in the top and side views. The effect of replication was significant for only the direct and multiple-camera views, with the second replication resulting in more hits in both cases. These results

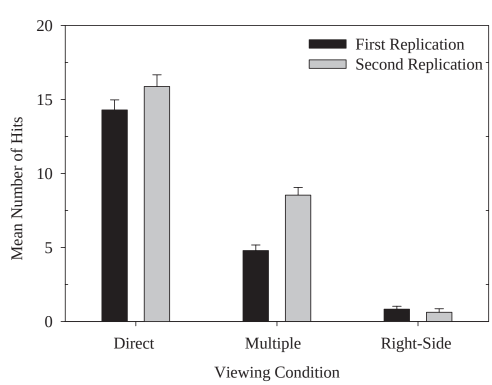

Figure 7. Experiment 3: Left–right grasper movement with side view. Mean number of hits for the two-way interaction between replication and viewing condition. Error bars indicate ± 1 *SEM*.

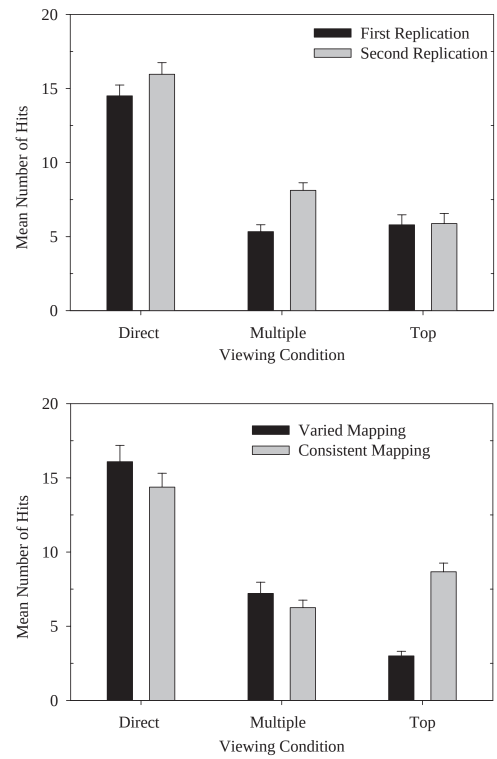

Figure 8. Experiment 3: Upward–downward grasper movement with top view. Top panel: Mean number of hits for the two-way interaction between replication and viewing condition. Bottom panel: Mean number of hits for the two-way interaction between mapping consistency and viewing condition. Error bars indicate ± 1 *SEM*.

suggest that participants extracted beneficial information from multiple concurrent camera views beyond that from looking only at the top view but only after some degree of learning occurred.

Analysis of the interaction between viewing condition and mapping consistency indicated an effect of viewing condition in both the varied and consistent mapping conditions. In the varied mapping condition, the mean number of hits was greater for the direct view than multiple views and top view, and was greater for the multiple views than the top view, $p < .01$. The latter finding again suggests that participants extracted beneficial information from multiple concurrent camera views beyond that which would occur from looking only at the top view. However, in the consistent mapping condition, the top view resulted in more hits than the multiple-view condition, $p < .05$. Similarly, the beneficial effect of mapping consistency was significant only in the top-view condition. One possible reason is that with lower cognitive load of consistent mapping, participants weighed the benefits of the top view more compared with the costs. That is, participants were better able to use the benefits to offset the costs when cognitive demands were relatively lower.

Forward–backward movement with front-camera view. There were main effects of replication, $F(1, 22) = 41.01$, $p < .001$, $w^2 = 1.64\%$, and viewing condition, $F(2, 44) = 241.92$, $p < .001$, $w^2 = 75.92\%$. There also were interactions between viewing condition and replication, $F(2, 44) = 18.11$, $p < .001$, $w^2 = .72\%$, and between viewing condition and mapping consistency, F(2,

44) = 11.86, $p < .001$, $w^2 = 3.42\%$, shown in Figure 9. On both replications, the mean number of hits was greater for the direct view than the multiple-view and front-view conditions, $p < .01$. On the second replication the multiple-view condition resulted in more hits than the front view, $p < .01$. The effect of replication was significant for only the direct and multiple-view conditions, with the second replication resulting in more hits in both cases. These results suggest that participants extracted beneficial information from multiple concurrent camera views beyond that from looking only at the front view but only after some degree of learning occurred. The implication is that the performance benefits of the multiple-view condition reflected the use of either the top or side views. Given that participants looked mostly at the top view and secondarily at the front view, we surmise that learning in the multiple-view condition involved extracting information from the top view, possibly trading off the cost of compression (in the front view) for the cost of misaligned frame of reference (in the top view). The latter may have been less detrimental to performance compared with compression when performing forward–backward movements.

Analysis of the interaction between viewing condition and mapping consistency indicated an effect of viewing condition in both the varied and consistent mapping conditions. In the varied mapping condition the mean number of hits was greater for the direct view than the multiple-view and front-view conditions, and was greater for the multiple-view condition than the front view, $p < .01$. In the consistent mapping condition, the direct view resulted in more hits than the multiple-view and front-view conditions, $p < .01$. The benefit of the multiple-view condition compared with the front view was not observed, and the beneficial effect of mapping consistency was significant only in the front-view condition. Further study is warranted.

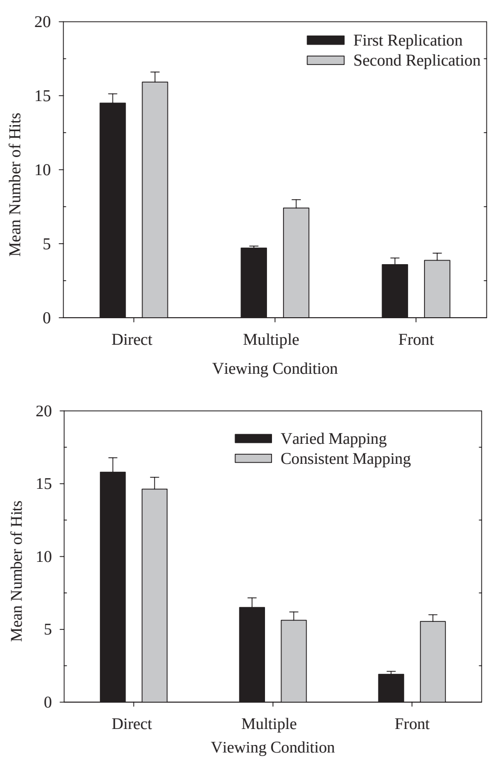

Figure 9. Experiment 3: Forward–backward grasper movement with front view. Top panel: Mean number of hits for the two-way interaction between replication and viewing condition. Bottom panel: Mean number of hits for the two-way interaction between mapping consistency and viewing condition. Error bars indicate ± 1 *SEM*.

Experiment 4

The purpose of Experiment 4 was to measure performance with different mappings between camera view and direction of grasper movement. By comparing the results of Experiments 3 and 4, we could determine whether a specific direction of movement benefited from a specific camera view. Notably, the camera-movement mappings in Experiment 4 resulted in the absence of the depth compression and task-information specificity that characterized the mappings in Experiment 3. In addition, leftward–rightward movement resulted in control-display compatibility because it was mapped to the front camera view. In contrast, in Experiment 3 leftward–rightward movement was mapped to the side view and introduced a compatibility violation. These characteristics led to different costs and benefits in Experiments 3 and 4.

As in Experiments 1–3, in the multiple-view condition, a significant number of participants in Experiment 4 reported looking at the top view most frequently, and at the side view least frequently, $p < .002$. Consistent with subjective reports, analyses of gaze direction indicated that participants indeed looked most frequently at the top view (56.07%) followed by the front view (36.92%) and the side view (7.00%). The total number of fixations for all participants, conditions and trials was 214. We interpret the results with these findings in mind.

Method

Twenty-four different participants (12 male, 12 female) had the same characteristics as in Experiment 1. The apparatus and procedure were identical to Experiment 3 except that in the consistent mapping condition participants moved the grasper leftward and rightward exclusively with the front-camera view, forward and backward exclusively with the top-camera view, and upward and downward exclusively with the side-camera view.

Results and Discussion

A 2 × 2 × 3 (replication × mapping consistency × viewing condition) mixed ANOVA with mapping consistency as the between-subjects variable was conducted on the number of hits. Each pairing of camera view and grasper movement direction was analyzed separately so that mappings with different benefits and costs could be compared. Statistical results of the analyses of simple main effects are shown in Appendix 1.

Left–right movement with front-camera view. There were main effects of replication, $F(1, 22) = 12.83$, $p < .002$, $w^2 = 1.05\%$, viewing condition, $F(2, 44) = 189.28$, $p < .001$, $w^2 = 62.64\%$, and mapping consistency, $F(1, 22) = 7.25$, $p < .013$, $w^2 = 4.40\%$. There also were two-way interactions between viewing condition and replication, $F(2, 44) = 8.37$, $p < .002$, $w^2 = .70\%$, and between viewing condition and mapping consistency,

$F(2, 44) = 5.79$, $p < .006$, $w^2 = 1.59\%$. There was a three-way interaction among replication, viewing condition and mapping consistency, $F(2, 44) = 4.16$, $p < .028$, $w^2 = .30\%$, shown in Figure 10.

When only varied mapping was considered, the effect of viewing condition was significant for both replications. In both cases, the mean number of hits was greatest for the direct view, followed by the multiple-view and front-view conditions, with all pairwise comparisons significant, $p < .05$. Mean hits was greater for the second replication than the first but only for the direct-view and multiple-view conditions; learning did not take place with the front view.

When only consistent mapping was considered, the effect of viewing condition was significant for both replications. In the first replication, the mean number of hits was greater in the direct view than the multiple-view and front-view conditions, $p < .05$. On the second replication, the mean number of hits was greatest for the direct view, followed by the multiple-view and front-view conditions, with all pairwise comparisons significant, $p < .05$. Mean hits was greater for the second replication than the first, but only for the multiple-view condition. These findings suggests that participants extracted beneficial information from multiple concurrent camera views beyond that from looking only at the front view but only after some degree of learning occurred. Given that there were no costs introduced by the front view and the cost of misaligned frame of reference was introduced by the top view in the multiple-view condition, we consider the possibility that the top view (to which participants most frequently glanced) provided a benefit that we have not yet identified and which participants learned to use during the multiple-view presentation. Alternatively, participants learned to benefit from the task-information specificity in the side view despite its relatively greater costs. The performance advantage with multiple views compared with the front view suggests that observers extracted information from the different views without mentally integrating them to reconstruct 3D space. Doing so would have imposed additional cognitive demands (information integration, attentional demands) and a lower benefit/cost ratio, which we assume would have resulted in less effective performance in the multiple-view condition.

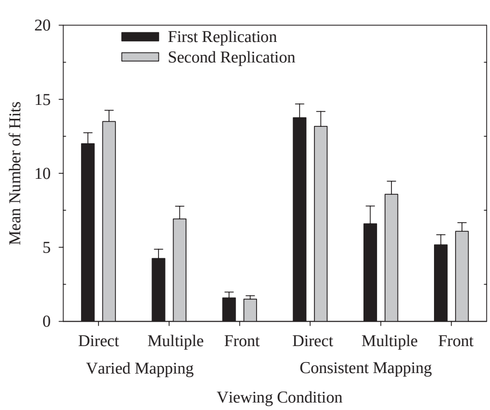

Figure 10. Experiment 4: Left–right grasper movement with front- camera view. Mean number of hits for the three-way interaction among replication, mapping consistency, and viewing condition. Error bars indicate ± 1 *SEM*.

The two-way interaction between viewing condition and mapping consistency was significant for only the second replication. There were more hits for the direct view followed by the multiple-view and front-view conditions, with all pairwise comparisons significant, $p < .05$, and this occurred for consistent and varied mapping conditions. The beneficial effect of mapping consistency was significant only with the front view. Further study is needed to explain this result. Because the front view did not introduce any costs, results could not have occurred because the lower cognitive load of consistent mapping led participants to weigh the benefits of the front view more than the costs (an explanation we applied to prior results).

The two-way interaction between mapping consistency and replication was significant with only the direct view. Because the direct view did not consist of camera views, the effect of replication may reflect group differences between consistency conditions.

Up–down movement with side-camera view. Results are shown in Figure 11. There were main effects of replication, $F(1, 22) = 5.89$, $p < .024$, $w^2 = .53\%$, viewing condition, $F(2, 44) = 216.12$, $p < .001$, $w^2 = 72.36\%$, and mapping consistency, $F(1, 22) = 8.57$, $p < .008$, $w^2 = 2.54\%$. The mean number of hits was greatest for the direct view followed by the multiple-view and side view conditions, with all pairwise comparisons significant, $p < .05$. The implication is that the advantage of the multiple views over the side view occurred because participants looked primarily at the top and front views that provided additional benefits of task-information specificity and realism, respectively (all views resulted in movement compatibility). These benefits may have offset the costs of compression and misaligned frame of reference introduced by the top view. Finally, mean hits were greatest for the second replication than the first replication and was greater for the consistent mapping compared with the varied mapping.

Forward–backward movement with top-camera view. There were main effects of replication, $F(1, 22) = 8.31$, $p < .009$, $w^2 = .80\%$, viewing condition, $F(2, 44) = 200.87$, $p < .001$, $w^2 = 59.82\%$, and mapping consistency, $F(1, 22) = 9.68$, $p < .005$, $w^2 = 5.08\%$. There also were interactions between viewing condition and replication, $F(2, 44) = 5.86$, $p < .01$, $w^2 = 1.08\%$, and between viewing condition and mapping consistency, $F(2, 44) = 13.91$, $p < .001$, $w^2 = 3.86\%$, show in Figure 12.

In the first replication, the mean number of hits was greater in the direct view than the multiple-view and top-view conditions, $p < .05$. On the second replication, the mean was greatest for the direct view, followed by the multiple-view and top-view conditions, with all pairwise comparisons significant, $p < .05$. There was a greater mean number of hits for the second replication than the first, but only for the multiple-view condition. Consistent with earlier results, participants putatively extracted beneficial information from multiple concurrent camera views beyond that from looking only at the top view but only after some degree of learning occurred. We suspect that participants learned to use the front view in addition to the top view when presented with multiple views; the front view provided additional benefits of realism and task-information specificity that may have offset the cost of compression.

In the varied mapping condition, the mean number of hits was greatest for the direct view, followed by the multiple-view and top-view conditions, with all pairwise comparisons significant, $p < .05$. In the consistent mapping, the mean number of hits was greater in the direct view than the multiple-view and top-view conditions, $p < .05$. The difference between the latter two condi-

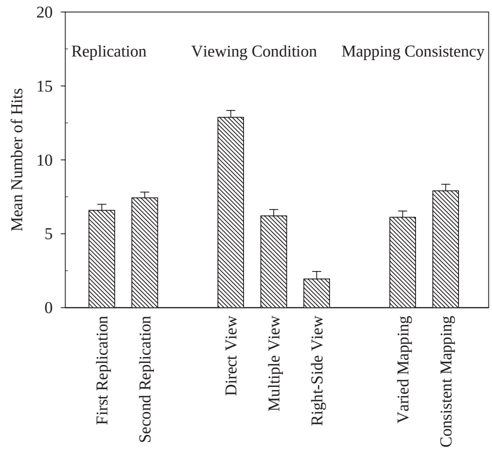

Figure 11. Experiment 4: Upward–downward grasper movement with side-camera view. Main effects of replication, mapping consistency, and viewing condition on mean number of hits. Error bars indicate ± 1 *SEM*.

tions was not significant, possibly because participants focused on the top view in the multiple-view condition. The beneficial effect of mapping consistency was significant only with the top view, which is what one would expect if the lower cognitive load of consistent mapping led participants to weigh the benefits of the top view more than the costs.

Comparison of Two Different Camera Views for One Direction of Movement

To further determine how the mapping between movement direction and camera view affected performance, the results of each camera view condition in Experiments 3 and 4 were compared for a single movement direction with a 2 × 2 × 2 (replication × mapping consistency × experiment) mixed ANOVA with experiment and mapping consistency as between-subjects variables. The leftward–rightward, upward–downward, and forward–backward grasper movements were analyzed separately so that mappings with different benefits and costs could be compared. We discuss only significant effects that involve experiment. Statistical results of the analyses of simple main effects are shown in Appendix 1.

Comparison of front and side views for left–right movement. This analysis determined whether leftward and rightward movements were more accurate when the target was viewed from the side (Experiment 3) or the front (Experiment 4). Results of ANOVA indicated a main effect of experiment, $F(1, 44) = 56.39$, $p < .001$, $w^2 = 32.43\%$, and a two-way interaction between mapping consistency and experiment, $F(1, 44) = 19.71$, $p < .001$, $w^2 = 10.96\%$, represented in Figure 13. The effect of experiment was significant at both levels of mapping consistency. Mean number of hits was greater for the front than the side view. The effect of mapping consistency was significant only in the front view; mean number of hits was greater for consistent mapping.

Results are consistent with the relative costs and benefits of the two views: The front view provided benefits of realism and movement compatibility, and no costs. The side view resulted in benefits of task-information specificity, and in costs of compression, misaligned frame of reference and incompatibility of movement. The implication is that the combined benefits of movement compatibility and realism in the front view outweighed the benefit of task-information specificity in the side view which may have been negated by costs introduced by the side view. In addition, the benefit of mapping consistency was evident in the front view but not in the side view, suggesting that the latter introduced cognitive demands offsetting benefits of consistent mapping.

Comparison of top and side–camera views for up–down movement. This analysis determined whether upward and downward movements were more accurate when the target was viewed from the top (Experiment 3) or the side (Experiment 4). Results of ANOVA indicated a main effect of experiment, $F(1, 44) = 52.02$, $p < .001$, $w^2 = 34.70\%$, and a two-way interaction between mapping consistency and experiment, $F(1, 44) = 7.08$, $p < .011$, $w^2 = 3.50\%$, represented in Figure 13. The effect of experiment was significant at both levels of mapping consistency. The mean number of hits was greater for the top view than the side view.

The costs and benefits shown in Table 2 indicate that both the top and side views introduced a benefit of movement compatibility and a cost of misaligned frame of reference. However, the top view provided an additional benefit of task-information specificity and an additional cost of compression. The implication is that task-information specificity offset compression to result in better performance in the top view. In addition, the misaligned frame of reference in the side view may have imparted greater costs than the misaligned

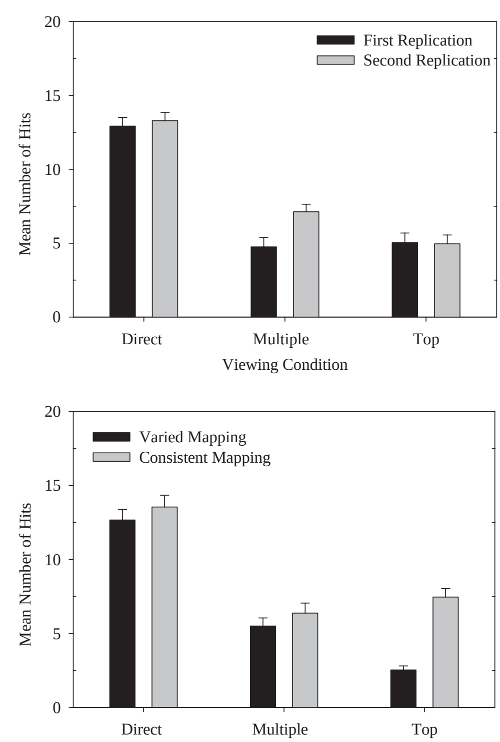

Figure 12. Experiment 4: Forward–backward grasper movement with top-camera view. Top panel: Mean number of hits for the two-way interaction between replication and viewing condition. Bottom panel: Mean number of hits for the two-way interaction between mapping consistency and viewing condition. Error bars indicate ± 1 *SEM*

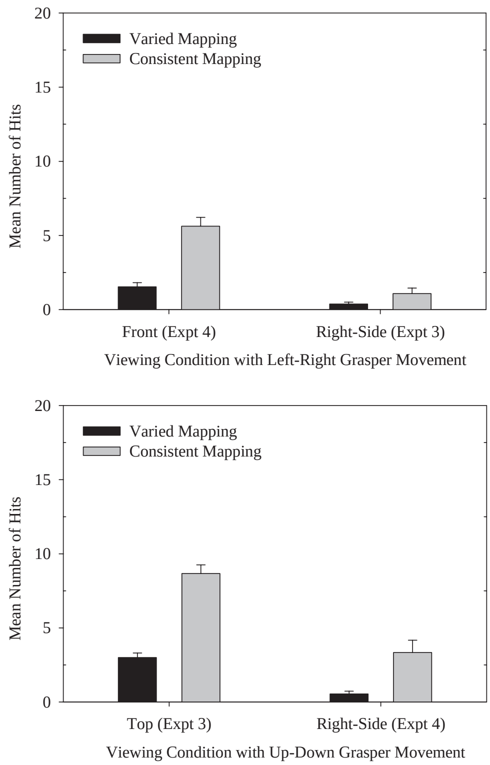

Figure 13. Comparison of results in Experiments 3 and 4. Top panel: Leftward–rightward grasper movement. Mean number of hits for the two-way interaction between mapping consistency and experiment (viewing condition). Bottom panel: Upward–downward grasper movement. Mean number of hits for the two-way interaction between mapping consistency and experiment (viewing condition). Error bars indicate ± 1 *SEM*.

frame of reference in the top view. It may have been easier to mentally rotate from a top view than a side view. This would be consistent with prior studies suggesting that it is easier to perform transformations from a front frame of reference to a top frame of reference than it is to transform from the front to the side, possibly because of the preservation of left–right mappings when translating to a top view (Franklin & Tversky, 1990; Wickens & Keller, 2010).

In both the top view and the side view, the mean number of hits was greater for the consistent mapping compared with the varied mapping. This suggests that the costs of misaligned frame of reference and compression were not great enough to eliminate the benefits of mapping consistency.

Comparison of top and front views for forward–backward movement. This analysis determined whether forward and backward movements were more accurate when the target was viewed from the front (Experiment 3) or the top (Experiment 4). Results of ANOVA indicated a main effect of experiment, $F(1, 44) = 9.73$, $p < .003$, $w^2 = 4.92\%$. The mean number of hits was greater for the top view than the front view which was unexpected based on the relative costs and benefits in Table 2 given equal weighting of costs and benefits.

Both the top and front views introduced benefits of movement compatibility. However, the front view provided additional benefits of task-information specificity and realism. In addition, the costs of the two views differed; the top view introduced a misaligned frame of reference whereas the front view introduced compression. The implication is that the benefits of movement compatibility offset the costs of misaligned frame of reference in the top view (which were small for mapping from the front to the top). In contrast, compression negated benefits of movement compatibility, task-information specificity, and realism in the front view. In addition, compression in the front view may have imparted greater costs than misaligned frame of reference in the top view.

Summary and Implications

Summary of Results and Theoretical Implications

Our results reflected the benefits and costs for perceptual and cognitive processes which differed across camera viewing conditions. Generally, performance was best with the direct view compared with any camera view. We focus our discussion on comparisons among the camera views.

Experiment 1. On the basis of the costs and benefits in Table 1, we expected that task completion time would be fastest with the front view, followed by the top, multiple, and side views. Results were not completely consistent with our expectations. Although mean task completion time was slowest with the side view, differences among the front, top and multiple-view conditions were not significant. Results of the multiple views can be explained by analyses of gaze direction: Participants mostly frequently looked at the top view. Results also suggest that the benefits of task-information specificity outweighed the benefits of realism and combined benefits of movement compatibility and task-information specificity offset the costs of compression and misaligned frame of reference.

Experiment 2. On the basis of Table 1, we expected that accuracy would be greatest and movement time would be fastest with the front view, followed by the top, multiple views, and side view. As expected, the side view resulted in slowest and least accurate performance. Unexpectedly, accuracy was greatest for the top and multiple views (which did not differ from each other), and the front view resulted in fewer hits than the top view. The implication is that task-information specificity in the top view outweighed the benefits of realism in the front view and the combined benefits of task-information specificity and movement compatibility offset the costs of misaligned frame of reference in the top view. Results again suggested participants mostly looked at the top view when presented with the multiple-view condition. Generally, task difficulty affected accuracy and movement time. The slope of the relationship between index of task difficulty and mean movement time was .20, .38, .50, 1.36, and 2.39, for the direct view, top view, multiple views, front view, and side view, respectively. The implication is that the magnitude of the effect of task difficulty on movement time varied with viewing condition but more study is needed.

Experiments 3 and 4. In the manual aiming task of Experiments 3 and 4, performance varied with the specific mapping between camera view and movement direction. For leftward–rightward movement, performance was better with a front view than a side view consistent with relative costs and benefits. The front view provided benefits of realism and movement compati-

bility; the side view provided benefits of task-information specificity and costs of compression, misaligned frame of reference, and incompatibility. For upward–downward movement, performance was better with a top view than a side view. Results suggest that task-information specificity offset compression to result in better performance in the top view, and that it was easier to transform a front frame of reference to a top frame of reference than to transform from front to the side, consistent with prior studies (Franklin & Tversky, 1990; Wickens & Keller, 2010).

For forward–backward movement, performance was better with a top view than a front view. Results suggest that the benefits of movement compatibility offset the costs of misaligned frame of reference in the top view and that compression negated benefits of movement compatibility, task-information specificity, and realism in the front view. In addition, costs of compression in the front view may have been greater than costs of misaligned frame of reference in the top view.

Benefits of the multiple-view condition depended on practice and on the direction of grasper movement. When observers moved the grasper upward and downward or forward and backward they extracted beneficial information from multiple views beyond that from looking only at a single top view, but only after some degree of learning occurred. A similar pattern occurred when results of a single front view were compared with multiple views during forward–backward and leftward–rightward movements. It appears that participants learned to develop strategies in which they could reap the benefits of specific views. However, benefits of multiple views over a single–camera view occurred on both replications (was not dependent on learning) when the latter consisted of a side view and observers performed leftward–rightward or upward–downward movements. When presented with multiple views, participants may have looked at the top or front views on both replications.

Finally, consistent mapping mostly resulted in better performance than varied mapping, but this benefit occurred mostly with single-camera views and not with multiple views. The lower cognitive load of consistent mapping may have permitted participants to give greater weight to the benefits than the costs in the single-view conditions. The effect of consistency did not occur when left–right movement was performed using a side view, suggesting that the cognitive demands imposed by the side view outweighed the cognitive benefits introduced by consistency.

Learning. We expected learning to occur and results generally were consistent with this prediction. We also expected less learning to occur when cognitive demands were relatively greater; generally, this was not consistent with our results. In Experiment 1, the interaction between replication and viewing condition was not significant; learning occurred in all camera conditions even though they differed in cognitive costs. In Experiment 2, the beneficial effects of repetition on accuracy occurred for all camera views except the top view which imposed fewer cognitive costs than the side view and multiple views. This may have been because of ceiling effects in the top view. Based on results of Experiments 1 and 2 it does not appear that differences in cognitive load among the camera views affected learning.

In Experiments 3 and 4, generally there were no interactions between consistency and replication suggesting equally effective learning with both types of mapping. Further study is needed to understand this finding; the cognitive demands introduced by varied mapping may have been insufficient. One exception was that beneficial effects of consistency occurred only on the second replication when the front view was used to perform left–right movement. It is unclear why this occurred; there are no costs to overcome in this condition. Finally, the beneficial effect of repetition was significant mostly for the multiple-view conditions. The occurrence of learning when the side–camera view was paired with upward–downward movement, suggests that the benefit of movement compatibility offset the costs of misaligned frame of reference but (based on results of Experiments 1 and 2) not necessarily by lowering cognitive load.

Conclusions

The results lead to several conclusions regarding effects of camera arrangement on perceptual-motor performance. First, camera viewing mostly resulted in degraded performance compared with direct viewing. Second, participants exhibited learning (i.e., performance improvements) with camera viewing. Third, even when presented with multiple-camera views, participants did not look at all views equally often and may not have necessarily mentally integrated the views to reconstruct 3D space. However, with practice they could learn to use the multiple views to improve performance beyond that achieved with a single view. Fourth, task difficulty as indexed by target sizes and distances affected performance with camera viewing and the magnitude of the effect seemed to vary with viewing condition. Fifth, consistency of mapping between movement direction and camera view generally resulted in better performance than varied mapping.

Finally, the costs and benefits introduced by the camera views were not necessarily weighted equally. For example, in Experiments 3 and 4, forward–backward movements resulted in more hits when viewed from the top than the front even though the ratio of benefits to costs was smaller in the top view than the front view. This suggests that the benefits and costs were weighted differently in the top and front views. Similarly, upward–downward movements resulted in more hits when viewed from the top view than the side even though both views had the same benefit cost/ratio. The implication is that two different views that introduce the same ratio of benefits and costs may not necessarily lead to the same performance. Costs and benefits must be considered specifically for each task and for each combination of camera view and movement direction.

Implications for MIS

The implication for MIS is that surgeons may benefit by selecting the top view, and using side views only when necessary, when performing manual manipulation or aiming tasks. When a single movement direction must be performed repetitively, a camera view that results in consistent mappings (one view for each direction of movement) may be more beneficial than camera views that result in varied mappings. However, the pattern of results obtained in our laboratory setting should be replicated in more realistic settings.

If only one camera is used in surgery, the top view may be most beneficial. Specifically, use of a single camera provides a two dimensional view of 3D structures that are intimately connected or “stacked” on other vital structures that are literally only a cell layer away. Traditionally, view of the gall bladder, as an example, is

from the underside of the liver looking caudad (feet) to cephalad (head) direction (i.e., assuming the patient is lying supine, this is analogous to the side view in the present study). With this view the cystic duct (the main tube draining into the gall bladder), the cystic artery (the main artery to the gall bladder), and the hepatic arteries (the main blood flow to the liver), are stacked next to each other separated only by a cell layer. With the top view, looking "down" on the gall bladder anterior to posterior (from the abdominal wall toward the back) (i.e., a top view in the context of the present study), these structures would orient so that none are "hidden" by the structures in front.

Future Directions

The present study advances the understanding of the effects of camera viewing perspective on manual manipulation and manual aiming which are critical skills in MIS. However, there are more questions to answer and further studies to conduct to achieve a more complete understanding of how to improve performance.

Limitations of current study. The results of our study may be limited in generalizability because of the use of undergraduates rather than surgeons, a training simulator rather than live surgery, and only three camera angles. Further investigation is required to determine whether our results generalize from undergraduates to expert surgeons (see also Cao, 2001; Eyal & Tendick, 2001; Holden et al., 1999). Surgeons may use different information or integrate multiple sources of information differently than undergraduates. Experienced surgeons may not need a minimal degree of learning to benefit from multiple views as did undergraduates in the current study.

Nevertheless, it is reasonable to assume that at least some of the same cognitive and perceptual processes in our tasks are common to novices and experts. For example, our manual manipulation and manual aiming tasks required judgments about 3D space from 2D images. Such judgments rely on spatial abilities that are a fundamental aspect of MIS and measures of such fundamental abilities generalize from novices to experts, although strategical differences may occur in relatively complex tasks (Tendick et al., 2000). In addition, differences between surgical trainees and nonsurgeons did not occur with perceptual-motor tasks performed on a laparoscopic simulator (Taffinder, 1998). The implication is that results of our undergraduates may, at least, generalize to surgical trainees.

Further investigation also is required to determine whether our results generalize from a laparoscopic simulator and relatively simple perceptual-motor skills to live surgery (see also Cao, 2001; Holden et al., 1999; Eyal & Tendick, 2001). We selected such tasks so that we could achieve experimental control which is not possible in live surgery (Taffinder, 1998; Tendick et al., 2000). Despite the many differences between live surgery and surgical simulators, novices and experts can be discriminated on the basis of performance with simple virtual reality simulators (Gallagher, Lederman, McGlade, Satava, & Smith, 2004; Gallagher, Richie, McClure, & McGuigan, 2001). For example, the ability to recover 3D information from 2D 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).

Monitor location. The current study focused on the effects of the type and number of camera views on perceptual-motor performance relevant to MIS. However, the location of the displayed camera images also is important and warrants study. For example, in gallbladder surgery, if the camera is inserted through the umbilicus and is directed toward the head while the display monitor is placed at the foot of the operating table, the surgeon must look back over his or her shoulder to view the monitor. Operating toward the head while looking back at the feet requires the surgeon to make a 180-degree adjustment and results in disorientation. Notably the monitor's location is constrained by the amount of space available in the room. The anesthesiologist occupies the position at the head of the bed, eliminating this location for the monitor. When using a single view, the preferred position for the monitor is at the apex of the direction in which the anatomical site of the surgery is located. For example, in gallbladder surgery, if the surgeon stands on the patient's left side and directs his or her body toward the patient's right shoulder, the preferred monitor position is directly over the patient's right shoulder. Generally, the preferred monitor location is as close to the direction a surgeon would look if he or she was looking directly at the anatomical structure on which the surgeon is operating.

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Appendix 1

Significant Interactive and Simple Main Effects in Experiments 2–4

Effect	*F*	*df*	*p*
Experiment 2			
Mean number of hits			
Viewing condition × replication			
Effect of viewing condition at first replication	144.63	4,155.60	.0001
Effect of viewing condition at second replication	137.52	4,155.60	.0001
Effect of replication at direct view	8.04	1,90.29	.0057
Effect of replication at multiple views	39.76	1,90.29	.0001
Effect of replication at front	12.05	1,90.29	.0008
Effect of replication at side view	11.06	1,90.29	.0013
Viewing condition × task difficulty			
Effect of viewing condition at ID of 1.44	121.57	4,225.20	.0001
Effect of viewing condition at ID of 2.07	129.10	4,225.20	.0001
Effect of viewing condition at ID of 2.93	125.95	4,225.20	.0001
Effect of viewing condition at ID of 3.56	94.88	4,225.20	.0001
Effect of task difficulty at direct view	84.13	3,153.80	.0001
Effect of task difficulty at multiple views	88.57	3,153.80	.0001
Effect of task difficulty at front view	103.54	3,153.80	.0001
Effect of task difficulty at top view	89.16	3,153.80	.0001
Effect of task difficulty at side view	56.38	3,153.80	.0001
Mean movement time			
Viewing condition × task difficulty			
Effect of viewing condition at ID of 1.44	3.95	4,359.10	.0038
Effect of viewing condition at ID of 2.07	9.62	4,359.10	.0001
Effect of viewing condition at ID of 2.93	36.58	4,359.10	.0001
Effect of viewing condition at ID of 3.56	89.54	4,359.10	.0001
Effect of task difficulty at multiple views	3.35	3,341.40	.0192
Effect of task difficulty at front view	25.27	3,341.40	.0001
Effect of task difficulty at side view	80.15	3,341.40	.0001
Experiment 3			
Left–right movement with side-camera view			
Viewing condition × replication			
Effect of viewing condition at first replication	205.64	2,56.71	.0001
Effect of viewing condition at second replication	250.04	2,56.71	.0001
Effect of replication at direct view	20.20	1,65.83	.0001
Effect of replication at multiple-view	113.31	1,65.83	.0001
Up–down movement with top-camera view			
Viewing condition × replication			
Effect of viewing condition at first replication	130.31	2,60.50	.0001
Effect of viewing condition at second replication	136.85	2,60.50	.0001
Effect of replication at direct view	16.24	1,65.96	.0001
Effect of replication at multiple-view	59.49	1,65.96	.0001
Viewing condition × mapping consistency			
Effect of viewing condition at varied	130.15	2,88.00	.0001
Effect of viewing condition at consistent	50.79	2,88.00	.0001
Effect of mapping consistency at top view	28.47	1,50.47	.0001
Forward–backward movement with front camera view			
Viewing condition × replication			
Effect of viewing condition at first replication	209.18	2,55.47	.0001
Effect of viewing condition at second replication	222.22	2,55.47	.0001
Effect of replication at direct view	18.81	1,59.02	.0001
Effect of replication at multiple-view	68.75	1,59.02	.0001
Viewing condition × mapping consistency			
Effect of viewing condition at varied	164.22	2,88.00	.0001
Effect of viewing condition at consistent	89.55	2,88.00	.0001
Effect of mapping consistency at front view	14.83	1,55.17	.0003

(*Appendix continues*)

Appendix 1 (*continued*)

Effect	*F*	*df*	*p*
Experiment 4			
Left–right movement with front-camera view			
Viewing condition × replication × mapping consistency			
Viewing condition × replication at varied	6.65	2,88.00	.002
Effect of viewing condition at first replication	72.00	2,52.74	.0001
Effect of viewing condition at second replication	88.80	2,52.74	.0001
Effect of replication at direct view	5.55	1,66.00	.0215
Effect of replication at multiple-view	17.54	1,66.00	.0001
Viewing condition × replication at consistent mapping	5.88	2,88.00	.004
Effect of viewing condition at first replication	25.87	2,40.38	.0001
Effect of viewing condition at second replication	15.76	2,40.38	.0001
Effect of replication at multiple-view	12.02	1,66.00	.0009
Viewing condition × mapping consistency at second replication	9.49	2,67.26	.0002
Effect of viewing condition at varied	115.64	2,88.00	.0001
Effect of viewing condition at consistent	41.31	2,88.00	.0001
Effect of mapping consistency at front view	18.07	1,46.21	.0001
Replication × mapping consistency at direct view	5.88	1,59.97	.0184
Effect of replication at varied	6.19	1,44.00	.0167
Forward–backward movement with top-camera view			
Viewing condition × replication			
Effect of viewing condition at first replication	125.76	2,86.15	.0001
Effect of viewing condition at second replication	109.52	2,86.15	.0001
Effect of replication at multiple-view	19.49	1,65.99	.0001
Viewing condition × mapping consistency			
Effect of Viewing Condition At Varied	138.52	2,88.00	.0001
Effect of viewing condition at consistent	76.27	2,88.00	.0001
Effect of mapping consistency at top view	31.34	1,44.44	.0001
Comparison of Experiments 3 and 4			
Comparison of front and side views for left–right movement			
Mapping consistency × experiment			
Effect of experiment at varied	4.71	1,88.00	.0327
Effect of experiment at consistent	71.40	1,88.00	.0001
Effect of mapping consistency at Experiment 4 (front)	57.71	1,88.00	.0001
Comparison of top- and side-camera views for up–down movement			
Mapping consistency × experiment			
Effect of experiment at varied mapping	10.36	1,88.00	.0018
Effect of experiment at consistent mapping	48.74	1,88.00	.0001
Effect of mapping consistency at Experiment 3 (top)	55.03	1,88.00	.0001
Effect of mapping consistency at Experiment 4 (side)	13.35	1,88.00	.0004

Note. ID denotes index of difficulty.

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