



Reaction times and the decision-making process in endoscopic surgery

An experimental study

B. Zheng, Z. Janmohamed, C. L. MacKenzie

School of Kinesiology, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada V5A 1S6

Received: 9 September 2002/Accepted: 9 January 2003/Online publication: 19 June 2003

Abstract

Background: There are times during endoscopic procedures when the displayed surgical field does not align with the actual field due to rotation of the camera. The surgeon's performance may deteriorate under this situation. However, the effects of misalignment on the decision-making processes during endoscopic procedures have not been fully explored. The present study addresses this problem and suggests a technique that may be used to alleviate it.

Methods: Two experiments were completed in a mock endoscopic surgical setup where the image of the work plane inside the training box was either projected on a vertical monitor placed at eye level or superimposed over the training box by means of a half-silvered mirror. The work plane consisted of a start plate and four target plates. The experimenter varied the number of choices of target location among one, two, and four target choices. Rotating the camera about its longitudinal axis misaligned the displayed and the actual work plane. There were two experiments that differed in task difficulty. The task in experiment 1 was to touch the target plate, whereas the task in experiment 2 was to reach, grasp, and transport the object from the target to the start plate.

Results: Experiment 1 showed that reaction time increased with the number of the choices for a touch task, in accordance with the Hick-Hyman law. Using a grasp-and-transport task, experiment 2 replicated experiment 1 and extended the results to show that the use of a superimposed image display facilitated the decision-making process, leading to shorter reaction times compared to the vertical image display.

Discussion: During endoscopic procedures, the surgeon needs to translate indirect perceptions to instrument-mediated actions by "mapping" them through sensorimotor integration. The superimposed image alleviates

the mental load of spatial transformations by reducing the difficulty of the required sensorimotor mapping. These findings have important implications for the design of high-quality superimposed display technologies.

Key words: Endoscopic decision making — Sensorimotor integration — Task complexity — Surgical training — Surgical skills — Ergonomics

At times during endoscopic procedures, the surgeon has to operate with the camera rotated about its longitudinal axis, so that the displayed surgical field is not aligned according to the actual field. This situation frequently arises when the camera is controlled by an assistant who is not familiar with the anatomic structure of the surgical field. Camera rotation creates certain difficulties for the primary surgeon because the expected relationship between the movement of the surgeon's hand and the movement of the instrument is altered [6]. The surgeon has to adjust his or her manual movements to ensure that the tip of the instrument is reaching the correct surgical site, which is oriented differently from the image shown on the monitor. Performance under this kind of duress tends to deteriorate, leading to longer execution time and greater action errors [3, 4, 13, 16].

We believe that the decision-making processes of the surgeon are similarly prolonged because misalignment between the displayed and the actual surgical field increases the mental load associated with spatial transformations [5, 14, 17]. It is not unusual for endoscopic surgeons to report heavier fatigue after an endoscopic procedure than after a conventional procedure with the same duration and surgical goal [2]. A major part of this fatigue is due to the mental exertion required for intensive concentration during the laparoscopic procedure, where mental rotations and transformations play a demanding role. The cost of mental fatigue is not trivial;

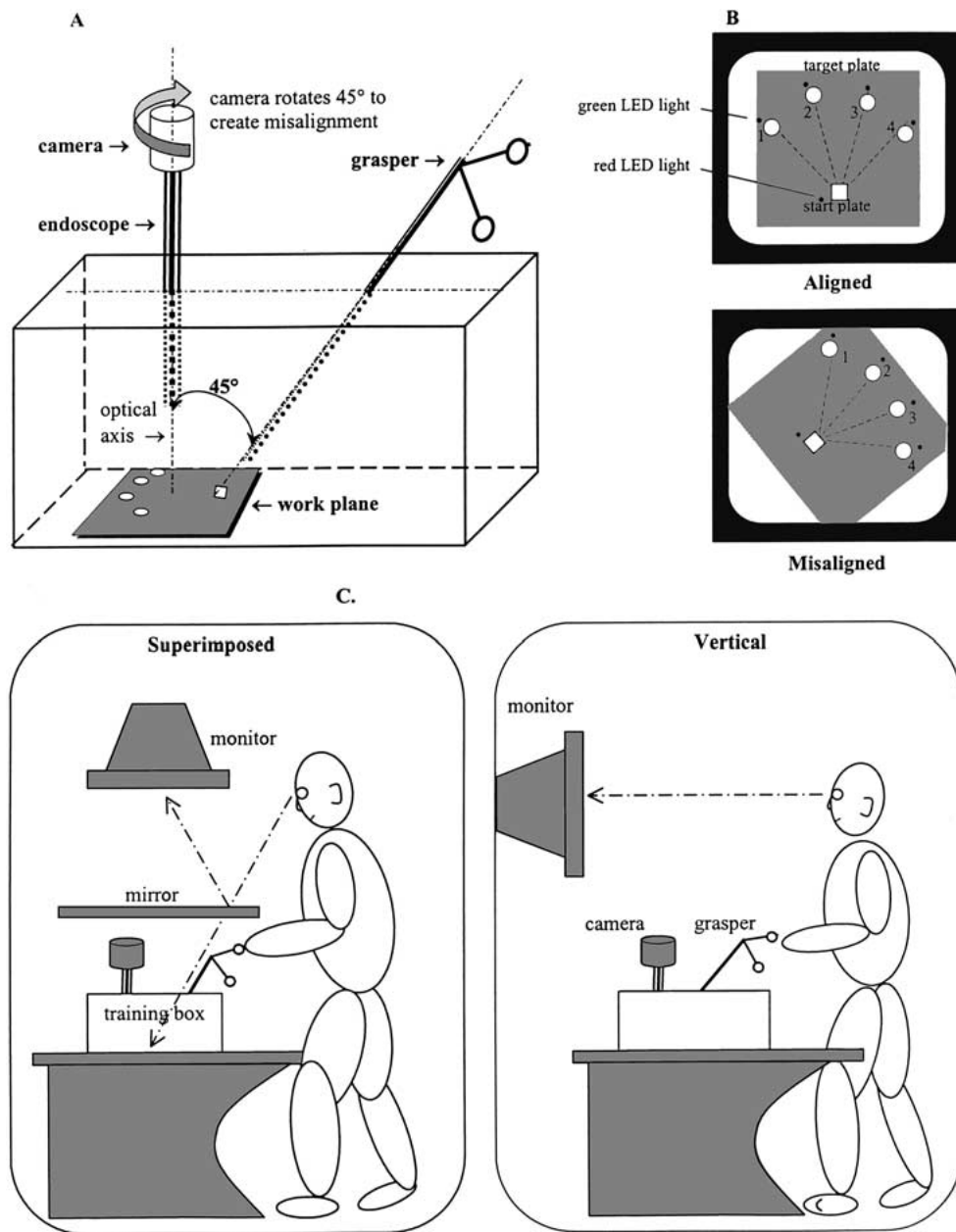


Fig. 1. Setup for experiment 1. **A** The endoscope and grasper entered the training box on the same plane, forming a 45° angle. The optical axis of the endoscope focused on the center of the work plane, which contained one start and four target plates. The start plate was located at the center of a semicircle (radius = 6 cm) on the work plane. Each target plate was located on the arc 30° apart. **B** Alignment conditions. *Top:* Displayed work plane with no camera rotation, *Bottom:* Displayed work plane when the camera rotated 45° clockwise about its longitudinal axis. Note that the actual work plane was stable; camera rotation created spatial misalignment between the displayed and the actual work plane. LED, light-emitting diode. **C** Display methods. *Superimposed (left)* and *vertical (right)* image displays, with a constant viewing distance of 85 cm between the subject's eyes and the work plane.

it can reduce the surgeon's decision-making ability and increase the potential for errors, thus affecting patient outcome [1, 3, 15, 17].

The present study was designed to address the influence of camera rotation on the planning of motor activities by human operators engaged in pseudo-endoscopic tasks. Methods to overcome the problem, such as displaying the surgical image above the patient using a superimposition technique [7, 8, 15], were also investigated.

Materials and methods

We carried out two experiments, which differed from each other in terms of the complexity of the task: a simple touch task in experiment 1 and a reach, grasp, and transport task in experiment 2. In both experiments, we predicted that misalignment between the displayed and

the actual work plane would prolong the reaction time needed to make choices during the planning stage for motor activities. We further predicted that the superimposed display technique would facilitate information processing—i.e., decrease reaction time, as compared to a vertical display.

Experiment 1

Method

Eight healthy Simon Fraser University students participated in this study, five men and three women, aged 20–36 years (mean, 24). All of the participants provided informed consent and were paid for their time. All subjects were right-handed, with normal or corrected-to-normal vision.

The experimental task was carried out in a black endoscopic training box (length, 35 cm; width, 30 cm; height, 20 cm) placed on a wooden table 72 cm above the floor. Figure 1A shows a dark gray plastic work plane (length, 15 cm; width, 15 cm; height, 0.5 cm), placed

horizontally inside the training box, consisting of one metal start plate (1-cm square) and four metal target plates (0.9-cm-diameter circles). These plates were connected to the OPTOTRAK Data Acquisition Unit (ODAU, Northern Digital, Waterloo, Canada), an A-D converter; contact with a metal endoscopic grasper elicited a change of 5 V.

The work plane also had signal lights near the plates (Fig. 1B). Green light-emitting diodes (LED) were located 0.5 cm above each of the four target plates. A red LED was positioned 0.5 cm down and to the left of the start plate. The red warning signal varied randomly in duration from 100 to 700 msec. When the red signal switched off, a green signal turned on, indicating which target to touch. The green signal stayed on for a constant 1.5 sec. A controller was designed so that the experimenter could turn the green signals on and off and vary the warning time randomly.

The training box had ports of entry for the endoscope and the grasper (Fig. 1A). A 0° endoscope of 10 mm diameter and 33 cm length (A5254; Olympus, Heidelberg, Germany) was inserted into the training box with its objective lens 9 cm from the work plane, providing a $\times 2$ magnification. This positioning is rare in endoscopic surgery; however, it has been used in experimental setups where the optical axis of the endoscope was perpendicular to the work plane [9]. The work plane in this experiment was laid horizontally on the bottom of the training box. Placing the endoscope with its optical axis focusing on the center of the start plate and the target plates ensures that the illumination and magnification effects are identical to each target plate, even when the camera is rotated.

The laparoscopic grasper (Ethicon Endo-Surgery, Cincinnati, Ohio, USA) entered the training box 18 cm in front of the port of entry of the endoscope. The tip of the grasper and the camera's optical axis converged at an angle of 45° inside the training box (Fig. 1A). The system used a Sony color video camera (model DXC-C1; Sony Electronics, Tokyo, Japan) to capture the image of the work plane. The camera was positioned at 0° for the aligned conditions and rotated 45° about its longitudinal axis for the misaligned conditions (Fig. 1B). An ORC Illuminator 6000 xenon light source (Benson Eyecare, Azusa, CA, USA) was used.

The work plane image was displayed on identical Studio Works 995E 19-in color monitors (LG Electronics, Seoul, Korea) (Fig. 1C). In the vertical conditions, a monitor was positioned vertically at eye level, 85 cm in front of the subject. A superimposed image display was obtained by employing an identical monitor (with left/right display reversed) positioned upside down 75 cm above the training box. The image on the monitor was reflected by way of a half-silvered mirror located halfway between the training box and the monitor (at 37.5 cm). The viewing distance from the subject's eyes to the work plane was ~ 85 cm.

The experimenter controlled the image display, the alignment of the displayed work plane relative to the actual work plane, and the number of choices for target locations. The order of the image display (vertical and superimposed) and the alignment conditions (aligned and misaligned) were counterbalanced. For one choice, only the green light for target 2 would turn on; for two choices, the light corresponding to either target two or three would turn on; for four choices, LEDs for targets one, two, three, or four would light up. For each of these conditions, the target locations were randomized, and the subject performed 10 trials for each target. Thus, there were 280 trials for each subject. In all conditions, only data from target two were analyzed.

The experimental task was to reach and touch the specified target plate. Subjects rested the grasper tip on the start plate, reached and touched the target plate when the green signal light turned on, and then returned to the start plate for the next trial. All subjects were read the same instructions and had five familiarization trials.

Voltage data were used to calculate reaction time to the nearest millisecond. Reaction time was defined as the duration from the time when the green signal turned on to the time when the subject broke contact with the start plate.

A 2 (display: vertical, superimposed) \times 2 (alignment: aligned, misaligned) \times 3 (target choices: one, two, four) repeated-measures analysis of variance (ANOVA) was performed using the median values for reaction time. A priori, α was set to 0.05.

Results

Reaction time increased as the number of choices of target locations increased ($F_{1,1, 7.5} = 6.030, p = 0.040$; the Greenhouse-Geisser F

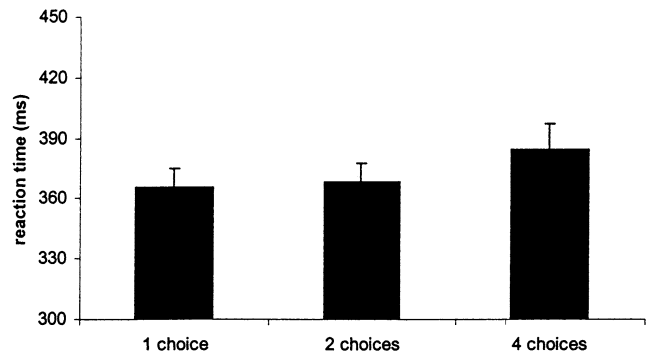


Fig. 2. Experiment 1. Reaction time (msec) increased as the number of choices was doubled. Means and SE are based on the individual subjects' median reaction times.

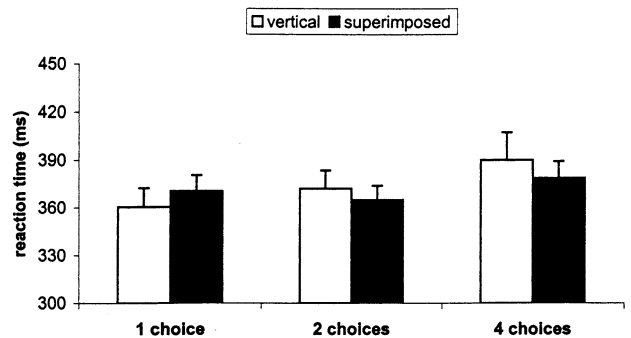


Fig. 3. Experiment 1. In the vertical image display, reaction time lengthened as the number of choices increased. Note that reaction time was shorter with the superimposed image display than with the vertical display.

value is reported since sphericity assumptions were not met). Specifically, as the number of target choices increased from one to two to four, the mean reaction time increased from 365 to 368 to 384 msec, respectively (Fig. 2). Neither image display nor alignment of the displayed work field relative to the actual field resulted in significant effects on reaction time.

Comments

The results of experiment are in accord with the Hick-Hyman law, which states that reaction time increases as the number of target choices increases [11]. In other words, the uncertainty caused a longer time in the decision-making process. Reaction time was not affected significantly by alignment conditions; therefore, our hypothesis was not supported. Although the results were not significant, image display did show an interesting trend (Fig. 3). In the vertical image display condition, reaction time increased as the number of choices doubled; however, in the superimposed image display condition, reaction time did not follow the same pattern. In the two- and four-choice conditions, reaction time was shorter in the superimposed image display than in the vertical display.

This trend suggests that the benefit of superimposed image displays on reaction time may interact with task difficulty. More specifically, the superimposed image display may not be advantageous when the endoscopic task is simple, but it may confer advantages as task difficulty increases. One might expect that if we were to increase the complexity of the task, we would obtain different results—for example, if we changed from a touch task to a prehension task that had reach, grasp, and transport components.

Experiment 2

The results from experiment 1 indicated that reaction time increases as the number of target choices increases, in accordance with the Hick-

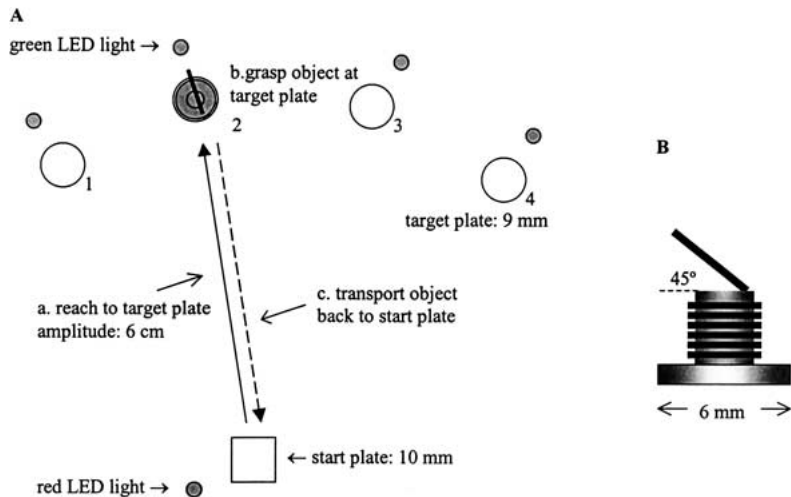


Fig. 4. Experiment 2 setup. **A** Top view of the work plane. The task was to (a) reach and (b) grasp a selected object placed on one of the target plates, and (c) transport it back to the start plate. **B** Side view of the object that was grasped by the small copper handle. LED, light-emitting diode.

Hyman law. We suggested that the results might be different if a more complex task were performed. Hence, in experiment 2, we investigated whether the reaction time would increase when the task is more difficult. The new task was to reach, grasp, and transport an object from a target location using an endoscopic grasper and then place it on the start plate. We predicted that a superimposed image display would facilitate information processing—i.e., decrease reaction time, as compared to a vertical display of the workspace image.

Method

Eight healthy Simon Fraser University students participated in this study, four men and four women who ranged in age from 17 to 32 years (mean, 23). Subject participation and apparatus was the same as for experiment 1.

To make the task more difficult, we made an object for the subjects to grasp, transport, and place (Fig. 4A). The object was a screw 0.6 cm in diameter at the base; its 0.2-cm stem was coiled with 1-mm-diameter solid copper wire in a green wrap (Fig. 4B). A handle, made with unwrapped copper wire, extended from the screw at an angle $\sim 45^\circ$ from the horizontal. The small object looked similar to the rock used in the sport of curling but with the handle jutting out. To minimize stimulus-response (S-R) ensemble compatibility, target plates not used in each choice condition were covered with black paper.

The objects were placed on each of the four target plates. The handle was oriented so that its tip pointed to the green light located above the target location. This condition was intended to add difficulty to the task by forcing the subject to grasp each target object at a specified angle. Using an endoscopic grasper, at the “go” signal, subjects reached, grasped the handle of the object, and then transported the object from the target plate to the start plate.

As in experiment 1, we report only reaction times. Reaction time was defined as the duration from the time when the green signal turned on to the time when the subject broke contact with the start plate. A 2 (display: vertical, superimposed) \times 2 (alignment: aligned, misaligned) \times 3 (target choices: one, two, four) repeated-measures ANOVA was performed using the values for each subject’s median reaction time.

Results

As in experiment 1 and following Hick-Hyman’s law, reaction time increased (from 367 to 387 to 402 msec, respectively) as the number of choices of target locations increased from one to two to four ($F_{2,14} = 8.267, p = 0.004$). The reaction time analysis yielded main effects for display ($F_{1,7} = 6.42, p = 0.039$). Reaction time was shorter when the display was superimposed (374 ± 13 msec) over the work field than when the image was displayed vertically (397 ± 19 msec) (Fig. 5). Therefore, our hypothesis that reaction time would decrease when a superimposed image was displayed over the work plane was supported in experiment 2, in which the task was more complex.

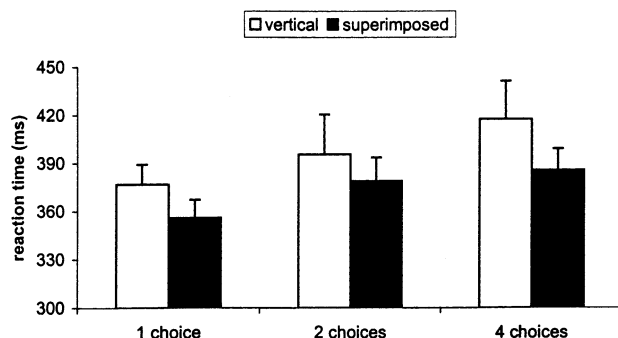


Fig. 5. Experiment 2. Reaction time (msec) was shorter with a superimposed image display compared to a vertical image display across three levels of choice. Means and SE are collected over the subjects’ median reaction times.

Discussion

The benefits of placing a superimposed image over the work plane on task performance have been documented in both virtual and endoscopic task environments [7, 8, 16]. Experiment 2 extended these benefits to motor planning, which takes place even before the actual movement is initiated.

Motor planning for endoscopic tasks is a process of selecting the appropriate manual action after the constraints of the surgical tasks have been perceived. In endoscopic surgery, visual information is no longer transmitted directly from the natural source to the human eye. Instead, it is transmitted through an endoscope and a camera and cable system before being displayed on a monitor situated in a location other than that of the actual work plane. In addition, the haptic information transmitted via the instrument does not completely represent the real-time situation at its tip. Furthermore, the production of the end effector movement is mediated by the surgical instrument rather than by the hand itself. Tactile sensation of the surgical field is absent. In such a complicated remote-manipulation system, sensorimotor integration becomes more challenging.

Normally, the surgeon who is performing the endoscopic procedure must mentally process and integrate

the information from the external sources with movements of the eyes, head, neck, arms, hands, and ultimately the instrument held in the hands. In perceiving information about the surgical field, the perspective angle of the endoscope, the orientation of the camera, and the location of the monitor with respect to surgeon's body position are crucial for this spatial transformation. In a laboratory setup, a change in the direction of view of the endoscope had no significant effect on a pseudo-endoscopic knotting task [9]. However, in many surgical scenarios (e.g., when operating over the inguinal canal) where a 30° or 45° endoscope is required, spatial transformation is more difficult for the surgeon. Hanna et al. [10] showed that the surgeon's performance was degraded when the image was displayed in a place that required the surgeon to rotate his or her head. The best location for the image display was directly in the front of the surgeon, at hand level and close to the work plane.

Displaying a superimposed image above the work plane is a means of returning the view of the surgical field to its natural site; it reduces the difficulty of transforming information from perception into appropriate action [14]. Previous studies have found that superimposed displays are an ideal way to facilitate performance in remote environments [3, 7, 8, 16]. The results of experiment 2 indicate that the superimposed viewing condition also facilitates motor planning, shortening the decision-making process.

Camera rotation, on the other hand, introduces misalignment between the displayed and actual work planes, adding more complexity to the perception of task constraints. Although not significant, there was a tendency for this misalignment to lengthen reaction time in both simple (touching) and difficult (reaching and grasping) tasks. We believe that if we continued to increase the demands of spatial transformations by introducing more complicated surgical tasks, alignment might have an effect on reaction time.

A comparison of the simple and the complex manual tasks in experiment 1 and experiment 2 provides some insights. Touch tasks require the transport of the end effector of the limb to the target location. There is one movement component—i.e., the transport task—in experiment 1. The prehensile movements in experiment 2 add a grasp component to the hand transport task. It is known that coordination of these two movement components in a single movement goal intensifies information processing in the motor planning stage [12]. We plan to conduct follow-up research to examine bimanual coordination when two tools are used in a knot-tying task, a task of greater complexity that is more representative of an actual surgical task. We believe that the effect of camera rotation will be revealed, and it is possible that the effects of camera rotation on motor planning will interact with display methods.

It is interesting to note that for the simple touch task in experiment 1 there were no significant main effects of display and spatial alignment on reaction time, but in experiment 2 (the reach, grasp, and transport task), there was a significant main effect of display on reaction time. These results lend support to the idea that human subjects can compensate for the remote environment

when the task is relatively simple. However, when task requirements increase, compensation is more of a challenge. Compensation essentially requires mental processing by the surgeon; high-intensity compensation potentially uses more information transformation capacity, eventually causing mental fatigue. An ideal surgical layout for endoscopic procedures should provide a comfortable environment so that the mental activity of the surgeon is at a moderate level, leaving enough mental resources for the surgeon to deal with an emergency, should one arise during the surgical procedure. The convergent evidence presented here suggests that the display of a superimposed image helps to alleviate the mental stress experienced by surgeons during endoscopic procedures and can also facilitate decision-making processes when task demands are high.

Conclusion

The results presented here can be used to make several inferences about the field of endoscopic surgery. Since actual surgical tasks are far more complex and certainly require more spatial transformations than our simulated experimental tasks, using a superimposed image display instead of a vertical image display could improve the surgeon's performance by reducing the time needed for information processing. Endoscopic surgeons have a strong ability to compensate for the indirect nature of sensory information by means of mental transformations, but this process adds to the mental burden of the surgeon, causing increased fatigue. A clear and strong message from this study is that these compensations have a limited range. Prolonged time in this working environment will lead to mental fatigue, possibly to the detriment of the patient. Improving the design of surgical theaters by providing better representations of the surgical field, such as superimposed high-quality image displays, can alleviate the mental stress of surgeons so that they can concentrate their energies on achieving better surgical outcomes for their patients.

References

1. Berguer R, Forkey DL, Smith WD (1999) Ergonomic problems associated with laparoscopic surgery. *Surg Endosc* 13: 466–468
2. Berguer R, Smith WD, Chung YH (2001) Performing laparoscopic surgery is significantly more stressful for the surgeon than open surgery. *Surg Endosc* 15: 1204–1207
3. Breedveld P, Wentink M (2001) Eye-hand coordination in laparoscopy: an overview of experiments and supporting aids. *Min Invas Ther All Technol* 10: 155–162
4. Cresswell AB, Macmillan AIM, Hanna GB, Cuschieri A (1999) Methods for improving performance under reverse alignment conditions during endoscopic surgery. *Surg Endosc* 13: 591–594
5. Cuschieri A (1995) Visual displays and visual perception in minimal access surgery. *Semin Laparosc Surg* 2: 209–214
6. Gallagher AC, McClure N, McGuigan J (1998) An ergonomic analysis of the "fulcrum effect" in endoscopic skill acquisition. *Endoscopy* 30: 617–620
7. Graham ED, MacKenzie CL (1995) Pointing on a computer display. In: *Proceedings of the Conference on Human Factors in Computing Systems CHI 295*. ACM Press, Addison-Wesley, 95. New York, pp 314–315

8. Graham ED, MacKenzie CL (1996) Physical versus virtual pointing. In: Proceedings of the Conference on Human Factors in Computing Systems CHI 96. ACM Press, Addison-Wesley, New York, pp 292–299
9. Hanna GB, Shimi S, Cuschieri A (1997) Influence of direction of view, target-to-endoscope distance and manipulation angle on endoscopic knot tying. *Br J Surg* 84: 1406–1464
10. Hanna GB, Shimi S, Cuschieri A (1998) Task performance in endoscopic surgery is influenced by location of the image display. *Ann Surg* 227: 481–484
11. Hick WD (1952) On the rate of gain of information. *Q J Exp Psychol* 4: 11–26
12. Jeannerod M, Decety J (1990) The accuracy of visuomotor transformation: an investigation into the mechanisms of visual recognition of objects. In: Goodale M (ed) *Vision and action: the control of grasping*. Ablex Publishing Corp., Norwood, NJ, pp 33–48
13. Kim W, Tendick F, Stark L (1987) Visual enhancement in pick-and-place task: human operators controlling a simulated cylindrical manipulation. *IEEE J Robot Automat* 3: 418–425
14. Lynos J, Elliott D, Ricker KL, Weeks DJ, Chua R (1999) Action-centred attention in virtual environments. *Can J Exp Psychol* 53: 176–178
15. MacKenzie CL, Ibboston JA, Cao CGL, Lomax AJ (1998) Intelligent tools for minimally invasive surgery: safety and error issues. In: *Proceeding of Enhancing Patient Safety and Reducing Errors in Health Care*. Chicago: National Safety Foundation, pp 226–229
16. Mandryk RL, MacKenzie CL (1999) Superimposing display space on workspace in the context of endoscopic surgery. In: *Proceedings of the Conference on Human Factors and Computing Systems, CHI 99*, ACM Press, Addison-Wesley, New York, pp 284–285
17. Jennings RW, Tharp G, Stark L (1993) Sensing and manipulation problems in endoscopic surgery: experiment, analysis, and observation. *Presence* 2: 66–81