Control Design and Task Performance in Endoscopic Teleoperation

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Abstract

Endoscopic surgery, while offering considerable gains for the patient, has created new difficulties for the surgeon. One problem is the fulcrum effect, which causes the movement of a surgical instrument, as seen on the monitor, to be in the opposite direction to the movement of the surgeon's hand. The problem has been shown to impede the acquisition of endoscopic skills. Teleoperated robotic arms may circumvent this problem by allowing different control-response relations. Four alternative control designs of a teleoperated device were compared in a simulated endoscopic task. A rigid teleoperated robotic arm with two degrees of freedom representing a surgical tool was coupled to a joystick in a position control mode. Feedback was provided through a video display. Participants without prior experience in endoscopy performed a target acquisition task, first by pointing the robotic arm at the targets, and later by maneuvering an object. Performance was measured under four different combinations of visual-motor mapping (normal/reversed), and the joystick's orientation (upwards/downwards). Task completion time under normal visual-motor mapping was found to be significantly shorter than under reversed visual-motor mapping, emphasizing the potential advantage of a teleoperated endoscopic system. The joystick's orientation affected the maneuvering of an object under only the reversed visual-motor mapping, implying that the positioning of a surgical tool and the manipulation of tissues or objects with the tool may be differentially affected by the control design.

1 Introduction

Over the last decades, there has been a growing tendency in surgery towards endoscopic, minimally invasive techniques. These techniques offer several advantages for the patient over conventional surgery, such as a shorter recovery time, a decreased risk of infection, and less pain and trauma. Health care organizations also tend to favor these techniques because they decrease hospitalization time and costs (Tendick et al., 1993).

However, the physician who performs endoscopic surgery faces some difficulties that are inherent to this technique. These were described both by surgeons (Treat, 1997) and by the technologists who set out to solve the problems (Tendick et al., 1993). The issues were impaired depth perception, impaired orientation due to changes in perspective, lack of tactile feedback, and constrained movement of the instruments.

A major problem that stems from the nature of the instrument's movement under endoscopic conditions is that of reversed visual-motor mapping. To

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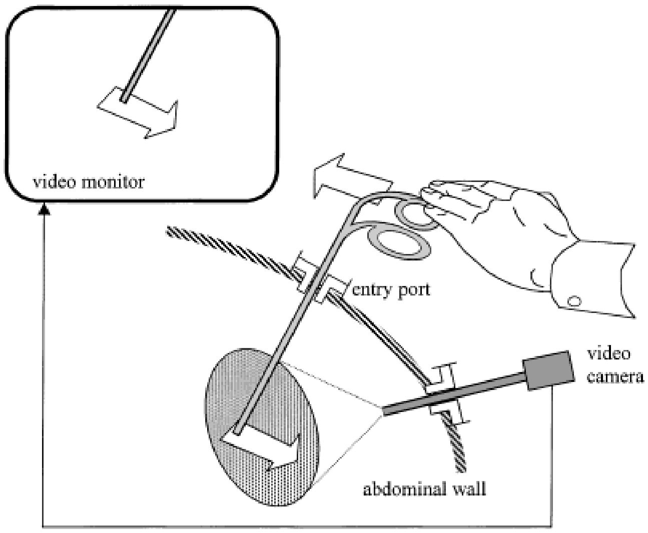

Figure 1. *The movement relations in endoscopic surgery.*

move the instrument's tip inside the body in a chosen direction in the horizontal plain, the surgeon's hand has to move in the opposite direction, due to the fulcrum effect at the entry port in the patient's abdominal wall. Practitioners recommend positioning the camera so that it captures an image that resembles the surgeon's natural view of the surgical site (Faraz, Payandeh, & Nagy, 1995). With this camera placement, the movement on the monitor is in the opposite direction to the movement of the hand, reversing the normal compatibility of motor and visual input (figure 1). This impedes skill acquisition, as demonstrated by Gallagher et al. (1998).

Recently, robotic technologies have been introduced into the operating room. In this environment, robotic systems usually manipulate one or more surgical tools under the surgeon's control in ways that enhance manual performance through canceling tremor or scaling down movement. In Sheridan's (1992) terms, this is a case of *sharing control,* in which the human and the computer control different aspects of the system at the same time. This technology has the potential to eliminate some of the difficulties inherent to endoscopy (Garcia-Ruiz, 1997). We believe that by introducing an interface between the surgeon's hand movements and the actual movement of the instruments inside the patient's body, we can circumvent the reverse-motion effect.

Extending a person's sensing and manipulation capabilities to otherwise inaccessible locations is the essence of teleoperation. The operator's performance in accomplishing a task in a remote environment is strongly affected by the way the task is perceived. In this study, we focus on two factors that affect a person's interaction with a teleoperated system: the compatibility between movements and the user's mental model of the system.

1.1 Compatibility

The dynamic components in the local site of a teleoperation setting are the controls, the entities on the display, and the operator's pose. Directional movement relations between these components may vary according to their relative orientation and the control function of the teleoperator system. Directional compatibility exists when the operator's movement results in a movement in the same direction on the display. However, forward and backward movements of the hands that are translated into upward and downward movements on the display are also perceived as compatible. A classic study by Fitts and Deininger (1954) showed that performance was more accurate and faster when targets were directly assigned to control positions than when the assignment was mirrored. Worringham (1989) defined three types of directional compatibility—visual-motor, control-display, and visual-trunk—and compared subjects' performance across eleven alternative combinations of them in a target acquisition task. Performance was found to be superior under conditions of visual-motor compatibility, while other forms of directional compatibility appeared not to be fundamentally related to performance.

Stins and Michaels (1997) claimed that the compatibility phenomena should be interpreted in light of the operator's intentions, rather than through the mere physical description of their actions. Therefore, the same movement may be executed with different goals in mind and be subject to different compatibility effects. This idea was demonstrated in an experiment in which participants were required to turn a steering wheel in the direction of the stimulus (left or right). When the hands were placed on the bottom point of the wheel, a movement to the right could mean "moving my hands to the right" or "turning the wheel to the left." In each case, the action would be strongly coupled to a different stimulus.

Compatibility effects were shown to be a function of the person's intentions, which reflect his or her understanding of the situation. This understanding is grounded in the person's mental model of the system. Consequently, a designer who wishes to utilize the principle of compatibility in the design should consider the mental model that may be held by the user of the system.

1.2 The Mental Model

As the term *teleoperation* implies, the operator is remote from the task, and the connection between the end-effector and the operator's controlling actions is usually invisible to the operator. Michotte (1951) referred to the cases in which not all the elements of the causal chain of a system are manifest to the viewer. In these cases, "there is a break in the perceived chain, and then only by means of hypothesis, or through the application of acquired experience, can the continuity be restored; but this involves a level beyond mere perception" (p. 101). To predict the functioning of a system, the user develops a set of explanations, predictions, beliefs, and naive theories about the system, which is considered to be the *mental model* of the system (Gentner & Stevens, 1983). Mental models are constrained by factors such as the user's technical background, previous experience with similar systems, and the structure of the human information-processing system (Norman, 1983), but they are also determined by the design of the interface, with certain design solutions making certain mental models particularly likely.

For every system and task, the designer may try to predict which mental model is likely to arise. Often it is possible to manipulate the user of a system into using a certain mental model (Wilson & Rutherford, 1989). This may be done explicitly, by instructing the user, or implicitly, by designing the visible features of the system to give the desired impression.

1.3 Design Alternatives of a Hand-Controller for Endoscopic Teleoperation

Our study deals with the performance of endoscopic tasks with a master-slave robotic system. The perception of the task depends on the visual-motor mapping (VMM) that is employed in the system. Endoscopic surgery compels physicians to work under reversed VMM, due to the fulcrum effect. Experienced surgeons may prefer that robotic systems maintain this mapping, with which they are already familiar. On the other hand, a robotic system makes it possible to perform endoscopic tasks with normal VMM, which may lead to an improvement in performance.

When performing conventional surgery, commonly used instruments are handled with a precision grasp, which is similar to gripping a pencil (Tendick et al., 1993). The surgeon holds these instruments relatively close to their point of contact with the tissue. In endoscopic surgery, however, a typical distance of up to 40 cm exists between the surgeon's hand and the instrument's tip. This relative remoteness of the surgeon's grip from the point of action, combined with the reversed motion due to the fulcrum effect, may introduce difficulties in the performance of various surgical activities. A robotic system provides an opportunity to give the surgeon the impression of directly manipulating the tip of the instrument. To create this impression, the hand-controller of the robotic system should bear a mechanical resemblance to the surgical instrument by being top-mounted, with a pivot that is above the point at which it is held. With this design, movements of the hand-controller are parallel to the movements of the surgical instrument's tip on the monitor. On the other hand, most hand-controllers are bottom-mounted, such as the familiar joystick. These considerations emphasize the potentially important role of the hand-controller's orientation.

Our experiment aimed to assess the effects of the VMM (normal or reversed) and the orientation of the hand-controller (upwards or downwards) on the performance of an endoscopic task. This experimental system is composed of an operator's control station and a re-

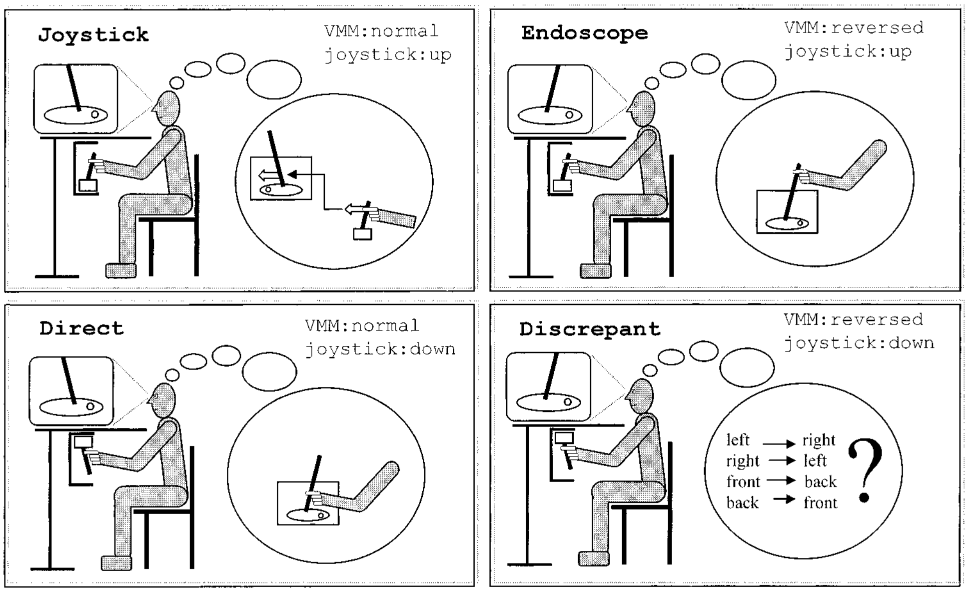

Figure 2. *The four design alternatives of a hand-controller in endoscopic teleoperation and their corresponding mental models.*

mote site accommodating a task board. The operator uses a conventional two-DOF joystick to control a surgical tool, which acts upon the task board, seen on a video monitor. The design alternatives of the hand-controller in this setting are the combinations of different joystick orientations and different VMMs between the movements of the operator's hand and the movements of the tool's tip as seen on the monitor. The joystick may be positioned in a conventional fashion, with its handle facing upwards, or upside down, with the handle facing downwards. The VMM may be normal, so that movements seen on the monitor and the hand's movements are in the same directions, or reversed (with these movements in opposite directions). Each design alternative is likely to give rise to certain conceptualizations of the system (a mental model). The specific descriptions of the four alternatives are detailed below. We named each alternative with a term by which we will refer to it throughout the paper. Figure 2 depicts graphically the four alternatives and the mental models that are likely to arise in each.

1. **Joystick** Here the joystick faces upwards, and the VMM is normal. This combination is normally implemented in the use of joysticks as control devices. The operator is likely to perceive that the movement of the instrument's tip is coupled to the movement of his/her own hand. The mental model involved here is that of a regular joystick control.
2. **Endoscope** Here the joystick faces upwards, and the VMM is reversed. This combination is rather like conventional endoscopy, in which the movements of the hand lead to inverse movements of the tip of the instrument in the patient's body. An operator with experience in endoscopy probably perceives this condition as if he/she actually holds the handle of the endoscopic tool, while seeing the tip on the monitor. The physical similarity between the joystick's handle and the end-effector strengthens this model, while the lack of "feel" (force and tactile feedback) weakens it.
3. **Direct** Here the joystick faces downwards, and the VMM is normal. In this combination, the movements of the end-effector and of the hand-controller are parallel. During an endoscopic maneuver, the operator is aware of the handle's orientation at all times. This positional information is in agreement with the image on the monitor. Thus, the operator may feel that he or she

actually holds the tip of the tool, although his/her hand is not seen on the monitor. The mental model is that of direct manipulation.

4. **Discrepant** Here the joystick faces downwards, and VMM is reversed. For this combination, we could not predict a simple mental model, either based on prior experience (as in Joystick), or based on a physical assumption (as in Endoscope and Direct). The operator might apply a set of semantic rules in this case, such as "to go left, I must move my hand to the right."

Rasmussen (1983) describes the performance of skilled human operators in terms of levels of behavior. **Skill-based behavior** represents sensory-motor performance during activities that are initiated intentionally but proceed in a smooth, automated pattern of behavior. **Rule-based behavior** takes place when the action sequence is governed by a stored rule stemming from the operator's experience, derived through logical induction, or communicated from other persons' know-how. In the absence of relevant rules, control of performance moves to **knowledge-based** behavior, which deals with the formulation of goals. Performance of a given task is governed by the continuous interaction of these levels of behavior, but the level in focus changes according to the familiarity of the situation. The performance of routine tasks is mostly skill based. Newer tasks, for which no skills have been acquired, require rules to be learned and executed consciously. Totally unfamiliar situations need to be considered in the knowledge-based level. Thus, perceiving a situation as familiar may facilitate the efficient use of the operator's skills repertoire, without the need to construct new paradigms. This perception is related to the operator's mental model of the system. The mental models that arise from the design alternatives in question may be classified according to the conceptual level they promote. The Joystick, Endoscope, and Direct designs are perceived as related to the common skills of joystick control or the manipulation of physical objects. The Discrepant design, in contrast, is unlikely to be related to an existing skill, and thus promotes rule-based behavior. We expect this difference to be reflected as markedly slower task performance with the Discrepant design.

1.4 Considerations in the Design of the Experiment

The design alternatives were evaluated using an experimental set-up whose conditions reflect the aforementioned combinations for the design parameters. Our objective was to construct a set-up that both allows well-controlled experimentation and is sufficiently similar to the real surgical environment to provide meaningful results. We assembled a simplified set-up that resembles a situation in which a surgeon manipulates a single tool with the right hand, while viewing a video image of the surgical site that was taken from his or her natural viewing direction. The tool is kept at a fixed depth, and does not revolve around its axis, keeping the system with two degrees of freedom (pitch and roll). In the experimental set-up, the joystick's handle and the end-effector were rigid rods of similar dimensions and profile. The rods represented a surgical tool, inserted halfway into the body, so that the length of the handle is equal to the length of the tool inside the body, and there is no scaling of movement. Feedback was provided through a video channel, and no tactile or force feedback was available.

The experiment required the performance of two tasks—pointing and manipulation. In the first task, the tool had to reach certain points on the task board; in the second task, the tool manipulated an object to reach these points. The tasks represented two components of the surgical task: bringing a surgical tool to a desired position in the surgical site, and handling tissues or surgical aids inside the abdominal cavity.

Because we were interested in the basic principles that govern performance with different control conditions, we used regular participants with no surgical experience. We assume that the same principles will hold also for surgeons, although they may perform the tasks overall better because of their experience.

2 Method

2.1 Participants

Twelve male and twelve female students of engineering and economics (mean age 23.67 years, s.d. 3.14) served as subjects. The participants had no prior

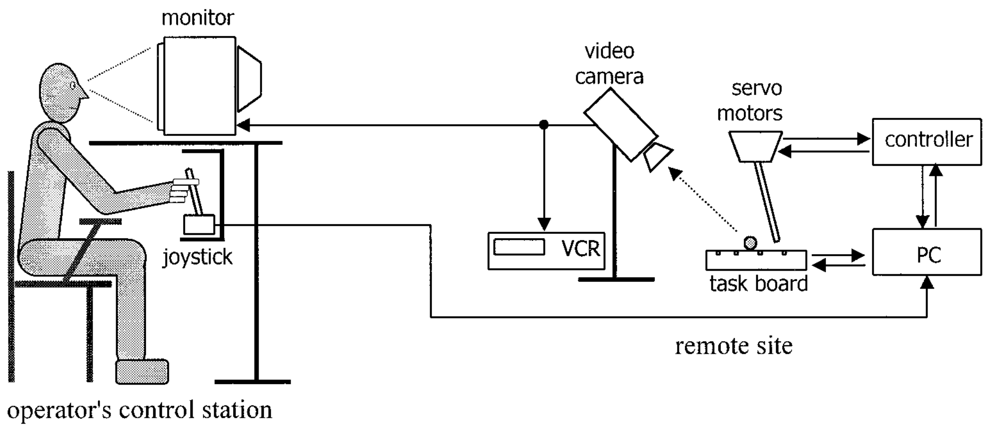

Figure 3. *A schematic depiction of the experimental apparatus.*

experience in endoscopy. We ensured that participants were right dominant, as indicated by their declaration that they used their right hand for writing. Participants were paid 20 NIS (approximately $5) for participation and were promised a bonus of 50 NIS (approximately $12) if they achieved the best performance in their experimental condition. Each participant was randomly assigned to one of the four experimental conditions, with the constraint that in each condition were three male and three female participants.

2.2 Apparatus

The experimental apparatus was divided between the operator's control station and the remote site (which resided in the same room). The task board was located so that it could not be seen from the operator's control station. A schematic depiction of the experimental apparatus is shown in figure 3.

The **operator's station** consisted of a 12 in. monochromatic video monitor that was placed at a distance of 80 cm from the subject's eyes and provided a view of the task board, and a joystick with two degrees of freedom that served as a master. The joystick used was a model 100 by CH products, whose centering springs were removed to create an isotonic joystick. The joystick's orientation (upward or downward) is an independent variable in the experiment. To minimize irrelevant effects of the height of the joystick or its grip, the joystick was placed in a symmetrical construction that compelled the participant to use the same grip and posture regardless of the joystick's orientation (figure 4). The grip area on the joystick's handle stretched from 140 mm to 220 mm from the pivot and was defined by plastic caps at its borders. Because the hand traces a curve and does not stay in the middle plane, subtle differences remain between the two orientations. The handle's rotation was limited to 23 deg. on either side of the vertical axis, and the distance between the point of grip on the handle and the joystick's pivot was 180 mm. This implies a vertical distance of up to 14 mm between the arcs formed by the hand in different joystick's orientations.

Another deviation from symmetry is due to the handle's weight, which tends to move it towards the center when the joystick faces downwards, and away from the center when the joystick faces upwards. Due to the nature of the experimental task, a tendency towards the center may give an advantage to the downward orientation. This problem was solved by using a lightweight tube 8 mm in diameter as a handle whose weight could not outplay the force of friction.

Participants may be affected by seeing the motion of their hand and of the joystick's handle in the peripheral field of vision, or they may be tempted to look at their hands during performance. To avoid this, a screen blocked direct view of the hand and joystick.

The **remote site** consisted of a task board which presented the experimental stimuli. The task board held a set of nine LEDs, eight of which were arranged around the periphery of a circle and the ninth at its center (fig-

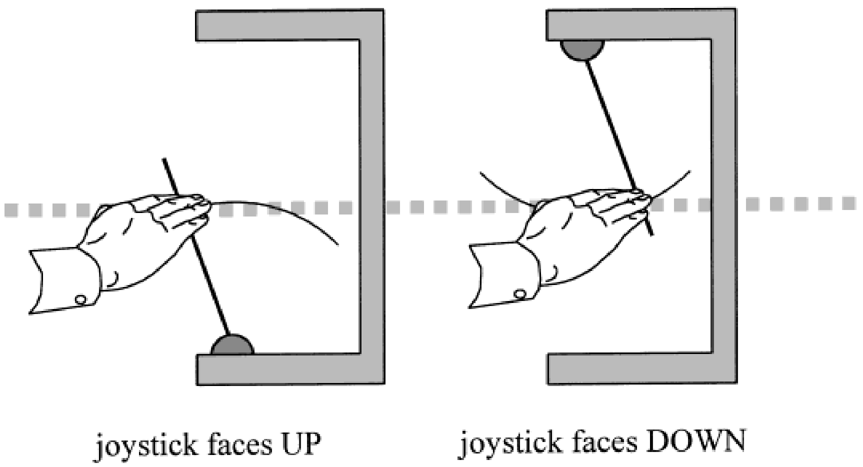

Figure 4. *A schematic depiction of the construction that holds the joystick. It ensures a similar grip in both the upward and the downward orientations of the joystick.*

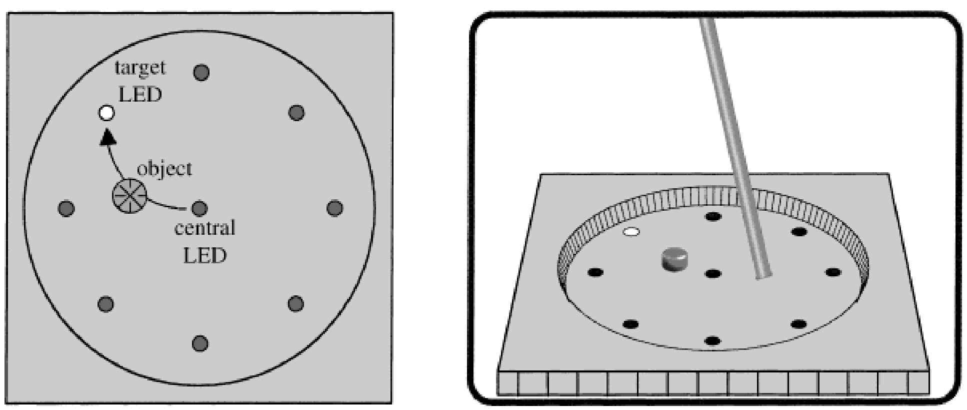

Figure 5. *The task board (left) and its approximate view on the monitor.*

ure 5). This arrangement is similar to the stimulus set used by Fitts and Deininger (1954). A light-sensing resistor (LSR) was coupled to each LED, so it could sense the presence of a light-reflecting object above the LED (figure 6). All components were fitted into 5 mm holes beneath the flat surface of the task board. The PC controlled the task board, lighting up one LED at a time as a target, and switching to another LED when the target was reached. The system recognized that a target was reached when the rod pointed at the target in the pointing task, and through the presence of an object above the target LED in the manipulation task.

A spherical plastic object, 23 mm in diameter and 24 mm high, was used in the manipulation task. The shape was chosen for its stability and maneuverability. A metal disc measuring 19 mm in diameter (of which 16 mm were a highly reflective surface) was used as the object's base and allowed smooth movement and easy recognition by the photoelectric components of the task board.

A two-DOF servomechanism, serving as a slave, was mounted above the task board with a rigid rod (length 22 cm, diameter 6 mm) as an arm. When the rod was in a vertical position, its tip was 0.5 mm above the central LED of the task board. A PC was used to activate the

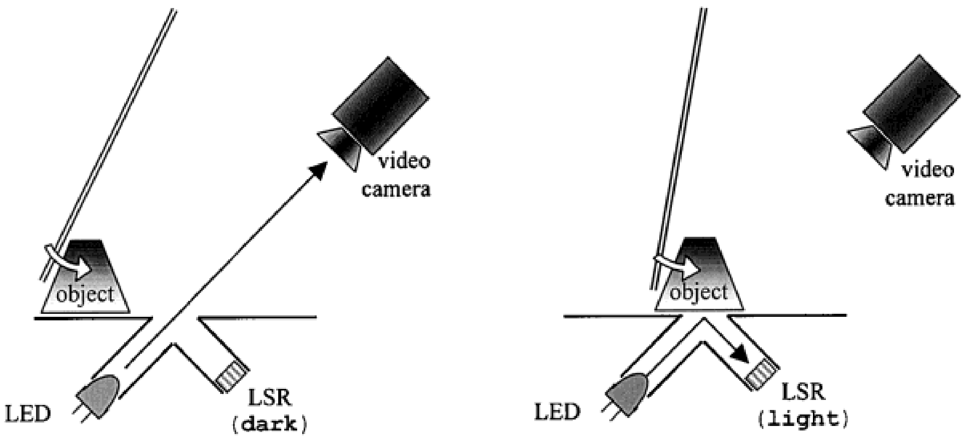

Figure 6. *The object-detection mechanism that was implemented in the task board.*

task board, to make time measurements, and to control the servomechanism via a DMC 1000 controller card by Galil Motion Control, Inc., and a power supply. A Panasonic Digital 5000 video camera, equipped with an 80 mm zoom lens, was aimed at the task board from a distance of 100 cm, at an angle of 45 deg. The image from the camera was transmitted to a VCR, which recorded the video and audio channels from the camera.

2.3 Procedure

The experimental conditions were the four combinations of the VMM (normal or reversed) and the joystick's orientation (upwards or downwards). Participants were randomly assigned to one of the four conditions, and the apparatus was set up accordingly prior to the arrival of the participant. Upon arrival to the laboratory, the participant was seated and given printed instructions. The instructions stated that the experiment consisted of two tasks and explained that a bonus would be given to the participant with the best performance in a group of six participants.

The instructions emphasized that the task should be done as fast as possible. The task began after the participant indicated that he or she had read and understood the instructions.

Each trial in the pointing task began when one of the peripheral LEDs lit up to serve as a target. The participant had to point the rod's tip at the target. The system then turned off the target LED and turned on the central LED, again waiting for the participant to point the rod at the light. A trial was completed when the rod pointed at the central LED, causing it to turn off, and immediately another randomly chosen peripheral LED lit up as the next target. This sequence was repeated 64 times. The time measurement (referred to as *trial time*) began when a peripheral LED lit up and ended when the next peripheral LED lit up.

Each task consisted of eight groups of eight successive trials. The eight peripheral targets were randomly mapped to the eight trials in each group, so that in each group of trials every target occurred once. Two successive groups formed a set.

The instructions for the manipulation task were similar to those for the pointing task, except that, instead of pointing the rod's tip at the targets, the participant was instructed to use the rod's tip to maneuver an object until it covered the target LED. The instructions stated that this task might be more difficult than the former one, and therefore it was divided into four parts that were separated by breaks. The participants had control over the duration of the breaks. To terminate a break, the participant was required to maneuver the object until it covered the central LED. The participants were told that time measurement halted during the breaks, so that their performance was not affected by the duration of the break.

The instructions also stated that only the best result among the four parts of this task would be taken into account as a criterion for receiving the bonus. To begin the manipulation task, the experimenter placed the object on the center LED of the task board. As in the pointing task, a peripheral LED lit up as a target, and the participant had to move the object with the teleoperated rod until it covered that LED. Then the central LED lit up, and the object had to be moved until it covered the central LED again. This completed a trial, and immediately the next trial began. The manipulation task used a trial arrangement identical to that of the pointing task.

After completion of the manipulation task, the experimenter interviewed the participant, inquiring about prior experience in using a joystick or in remote control, the use of rules or strategies during the experiment, whether the tasks reminded the participant of something else, and whether the participant used any kind of similarity or an analogy to something familiar to perform the task. Participants were also asked about their subjective feeling of difficulty and how they thought they performed the task.

3 Results and Discussion

The results for the pointing task and the manipulation task were analyzed with separate three-way analyses of variance (ANOVA) with the trial time as the dependent variable and the VMM (normal/reversed), the joystick's orientation (upwards/downwards), and the experimental set (1–4) as independent variables. The VMM and the joystick's orientation were between-subjects variables, and the experimental set was a within-subjects variable. An additional ANOVA was conducted on the duration of the breaks in the manipulation task, with the VMM and the joystick's orientation as independent variables.

3.1 Pointing Task

The results of the pointing task showed a significant main effect of the VMM: $F(1, 20) = 51.06$, $p < 0.0001$. Normal VMM led to faster pointing (1.46 sec.) than reversed VMM (2.96 sec.). This is in line with the visual-motor directional compatibility phenomenon (Worringham, 1989). In the context of endoscopic surgery, this finding demonstrates the difficulty that is caused by the fulcrum effect. Even in a very simple pointing task, such as the one here, normal VMM had a continuing advantage over reversed VMM.

The effect of the experimental set was found to be significant: $F(3, 60) = 6.98$, $p < 0.0001$. The mean trial time for the first set (2.50 sec.) was significantly longer than the trial time in the other sets (2.20 sec., 2.06 sec., and 2.08 sec., respectively), indicating that some learning may have occurred in this task, but the improvement was not very pronounced.

The joystick's orientation had no effect on performance, and the experimental set did not interact with the VMM or the joystick's orientation, indicating that learning was similar in all conditions. Thus, none of the conditions in this task seemed to have been particularly difficult or required significant coping activity.

Table 1. *Summary table for the results of the three-way ANOVA for the manipulation task*

Effect	df	MS error	F	p-level
Orientation (O)	1, 20	28.02	7.89	0.011
VMM (V)	1, 20	28.02	106.64	0.0001
Set (S)	3, 60	4.73	20.78	0.0001
O × V	1, 20	28.02	12.91	0.002
O × S	3, 60	4.73	7.20	0.001
V × S	3, 60	4.73	14.87	0.0001
O × V × S	3, 60	4.73	5.72	0.002

3.2 Manipulation Task

The pattern of results for the manipulation task was more complex (table 1). Here, all main effects and interactions were significant. The three-way interaction of the joystick's orientation, the VMM, and the experimental set is shown in figure 7. To gain a better understanding of these results, the two VMMs were analyzed separately with two-way ANOVAs with the trial time as the dependent variable and the joystick's orientation

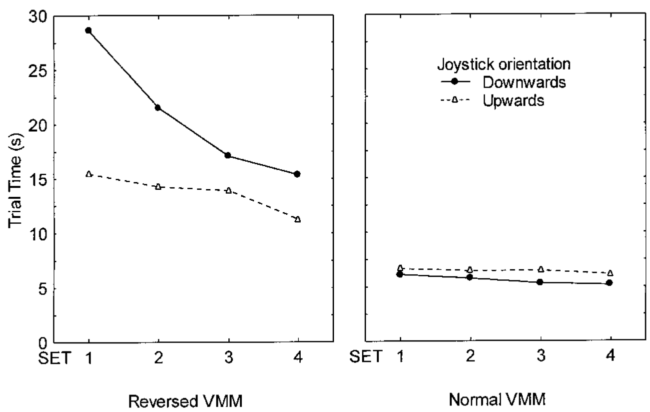

Figure 7. *Trial time for the manipulation task as a function of the visual-motor mapping (VMM), the orientation of the joystick, and the experimental set.*

Table 2. *Results of the separate ANOVAs for the two VMMs in the manipulation task*

Effect	df	Normal VMM (F values)	Reversed VMM (F values)
Orientation (O)	1, 10	1.08	11.95**
Set (S)	3, 30	3.55*	18.35***
O × S	3, 30	.69	6.67**

*$p < 0.05$.

**$p < 0.01$.

***$p < 0.001$.

(upwards/downwards) and the experimental set (1–4) as independent variables. The joystick's orientation was a between-subjects variable, and the experimental set was a within-subjects variable. The effects are summarized in table 2.

With normal VMM, only the experimental set had a significant effect. A weak learning curve is evident in this condition: The mean trial time for the first set (6.40 sec.) is similar to that of the second set (6.12 sec.), but is significantly longer than the trial time for the third (5.91 sec.) or fourth (5.66 sec.) set. This implies that performance under normal VMM improves somewhat with training. This improvement is not very large and is not significantly affected by the joystick's orientation.

With reversed VMM, the joystick's orientation, the experimental set, and their interaction had significant effects on task performance. As can be seen in the left panel of figure 7, when the joystick points downward, task performance begins with a very slow trial time in the first set (28.59 sec.), which dramatically improves over the second (21.52 sec.) and the third (17.08 sec.) sets. The fourth set, although not significantly different from the third, shows the shortest trial time of 15.35 sec. Altogether, the time to accomplish a single move was reduced by 46.3% over the course of the experimental task.

When the joystick is oriented upwards, task performance begins with a trial time of 15.45 sec., and gradually improves to 11.26 sec. in the fourth set. The second (14.26 sec.) and third (13.90 sec.) sets do not differ significantly from the other results. The total improvement in this condition is 27.1%. The performance with a downward-oriented joystick is 85% slower than the performance with an upward-oriented joystick in the first quarter of the task, but this difference shrinks to about 36% in the last quarter.

One should keep in mind that the joystick's orientation has only a perceptual effect on the task. The same visual stimuli are viewed, and the same motor responses are required, regardless of the joystick's orientation. The results are in line with our prediction that, under reversed VMM, the skill-based behavior that arises when the joystick faces upwards (Endoscope condition) will bring about better performance than the rule-based behavior that is required when the joystick faces downwards (Discrepant condition).

Even though the reversed VMM with an upward-oriented joystick led to better performance than with the downward-oriented joystick and to much less learning, the mean trial time in this condition was at least twice as long as the trial time in the direct VMM condition. This is additional evidence for the detrimental effect of the fulcrum effect on performance.

The participants controlled the duration of the breaks between the four sets in the manipulation task. Thus, the duration of the breaks can serve as an indication for the participants' own feeling of fatigue during the task. The data were analyzed using a two-way ANOVA with the duration of the breaks as the dependent variable and the VMM and the joystick's orientation as independent variables. The results showed a marginal effect of the joystick's orientation: $F(1, 20) = 4.06$; $p < 0.06$. Mean break time was longer for a joystick facing downward (29.7 sec.) than for a joystick facing upward (18.6 sec.). The VMM had a significant effect over the mean break time: $F(1, 20) = 15.17$; $p < 0.001$. For normal VMM, the break time was 13.5 sec., while for reversed VMM it was 2.58 times longer and equaled 34.8 sec. The interaction between the two variables was not significant ($p < 0.61$). We cannot tell whether the need for a longer break indicated physical or mental fatigue. The mean trial time of the manipulation task under reversed VMM is 17.2 sec., 2.85 times longer than the trial time under normal VMM (6 sec.). Considering that the ratio between the mean break times under these conditions is 2.58, it may be that fatigue is caused by the mere duration of the task, and that a longer task requires a break of proportional duration, with no relation to the mental requirements of the task.

4 Conclusions

Our study deals with the performance of two tasks under various control conditions. The manipulation and the pointing tasks are essentially different. The introduction of an object on the task board that has to be brought to the targets clearly complicates the task. The participant must now consider physical factors such as inertia, friction, and repulse. Consequently, the mean time to complete the manipulation task (742 sec.) is more than five times longer than the mean time to complete the pointing task (142 sec.).

The joystick's orientation has a prominent effect on the performance of the manipulation task under reversed VMM. Changing the joystick's orientation from upward to downward increases the mean trial time by more than 50% and renders a steeper learning curve. In contrast, the joystick's orientation has no effect at all on the pointing task. In the discussion of the design alternatives, the mental model concept and Rassmusen's description of behavioral levels were used to make a prediction about the Discrepant condition (reversed VMM, joystick faces downwards). We claimed that it would yield exceptionally low performance because its design parameters do not support a familiar mental model, which would promote skill-based behavior. It remains to be explained why the performance in the pointing task under this condition is similar to the performance under the Endoscope condition (reversed VMM, joystick faces upwards). In any case, it is clear that the pointing task cannot be used as a simple approximation for the more complex manipulation task. Thus, our study has important methodological implications in the sense that one has to be extremely careful in deciding what simplified tasks to use in order to study more-complex tasks. Every controlled research requires some simplification to control the complexities of actual task performance. However, it is crucial to avoid simplifications that make the study irrelevant for predicting actual performance.

The pointing task was chosen to represent actual tasks consisting of aiming the surgical tool at specific targets, such as the operation of a laser-endoscope, where no contact is made with the tissue. These tasks are common in surgery, and yet they cannot serve for a complete evaluation of the interface design. However, the results of the pointing task resemble only partly those of the manipulation task. In the latter, the VMM had a much stronger effect that interacted with the orientation of the joystick. Apparently the mental model became much more relevant for the manipulation than for the pointing task. A study that would have dealt with the pointing task alone may have led us to assume that the orientation (and the mental model) had no effect on performance.

The results of this experiment demonstrate that the inversion of the normal visual-motor mapping considerably degrades performance of both manipulation and pointing tasks executed in an endoscopic environment. While the experiment simulated a teleoperated endoscopic task, it encountered the problem of reverse movement reported in the study of manual endoscopic tasks (Gallagher et al., 1998).

Our results indicate clearly that reversed VMM has detrimental effects on performance of tasks of various levels of complexity. This shows that a robotic system may have definite advantages because it eliminates the need for reversed VMM during surgery. However, it is obviously necessary to conduct further research before one can define the optimal design of an interface for endoscopic surgery. Future studies should employ robotic systems that have more than two degrees of freedom and that provide force feedback. Additionally, tasks in future experiments should include the use of a functional surgical tool (such as one that is capable of cutting or grasping) and should be performed in a realistic scene that imitates human anatomy. We believe that it is important to include endoscopic surgeons in various degrees of training as participants in these experiments.

The learning effects witnessed in this experiment were all results of a relatively short learning period, repeating the basic step of each task no more than 64 times, and lasting no more than thirty minutes. Real endoscopy requires a much longer period of training, and it would be of interest to repeat this experiment over longer periods of training and observe the resulting learning effect.

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