1989 IEEE INTERNATIONAL CONFERENCE ON SYSTEMS, MAN, AND CYBERNETICS

CONFERENCE PROCEEDINGS

November 14-17, 1989
Hyatt Regency, Cambridge
Cambridge, Massachusetts

89CH2809-2

VOLUME III OF III

LEARNING EFFECTS IN TELEMANIPULATION WITH MONOSCOPIC VERSUS STEREOSCOPIC REMOTE VIEWING

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Abstract

As part of a larger study to investigate the potential usefulness of stereoscopic display technology for teleoperation, an investigation has been carried out on the effects on skill acquisition of the type of closed circuit video system used. Two experiments were performed, using a mobile explosive ordnance disposal robot, equipped with a switchable monoscopic/stereoscopic video system. Experiment 1 comprised a simple, repetitive approach-and-touch task. Experiment 2 involved a Fitts' Law type of speed accuracy tradeoff task. In both experiments subjects' learning data were recorded. The results are discussed in terms of relative performance of stereoscopic vs. monoscopic viewing, as a function of repetition number and of task difficulty.

Introduction

Remote manipulators are in use around the world, in the nuclear industry, by police and military forces, in space, and undersea. The majority of these manipulators use single or multi-camera monoscopic displays. Since the development of suitably high fidelity, economical stereoscopic video displays, many investigations into the advantages of using stereoscopic versus monoscopic displays for telemanipulation have found that stereoscopic displays can considerably reduce task execution time, improve accuracy, and reduce error rates, depending on the nature of the task investigated [1,2,3]. Some operations which are in fact impossible to carry out with monoscopic displays become possible with stereoscopic displays [4].

Although the parameters affecting the utility of stereoscopic video displays, such as camera separation, convergence angles, magnification, visibility conditions, and task demands, have been investigated for a variety of stereoscopic display formats [8], most studies have examined the behaviour of well trained operators. Very little work has been done to investigate the behaviour of relative novices in remote manipulation tasks, particularly with regards to the effects of the type of video display used. Of the studies which have been carried out, the findings have not been consistent. For instance, whereas one study found that, for a simple target positioning task, the advantages of using a stereoscopic video system were not as great for novices as for experienced operators, implying that relative benefits increase with experience [1], another, using a peg-in-the-hole task, found, in contrast, that the relative benefits of stereoscopic displays decreased with experience [9].

One topic which has apparently not yet been addressed is whether or not the particular visual display mode employed is likely to affect the *rate* at which operators become skilled at a particular telemanipulation task. If it were to be shown, for example, that skill acquisition occurred at a faster rate for tasks employing stereoscopic displays than for those using monoscopic displays, the practical implications for operator training would be obvious. The goal of this research was to investigate whether any such benefit exists, and, if so, under what conditions

In order to accomplish a remote manipulation task, the operator must have a sufficiently sound internal model of the state of the manipulator, and what must be done to accomplish the task. There are three different factors involved in attaining that internal model:

i) integration of current information about the manipulator with respect to the remote environment.
ii) familiarity with the control of the manipulator and the task to be performed,
iii) familiarity with the spatial layout of the remote environment,

It is reasonable to expect learning to play a part in all of these aspects of an operator's internal model. It is also reasonable to assume that the ability to perceive and interpret the distance and depth cues[1] available on the display screen will influence the ability to form an accurate internal model of the remote situation [10], and that stereoscopic displays will enhance that ability. It is not well established, however, to what extent practice is necessary for interpreting the extra depth cues available with stereoscopic displays. Nor is it known, furthermore, whether replacing a monoscopic display with a stereoscopic display can facilitate attaining familiarity with the manipulator, the task, and the remote environment. This study was intended to provide insight into these questions.

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[1] There are many cues in the visual scene used by the brain to estimate the distance to an object. The "monoscopic" depth cues include size, perspective, lighting/shadows, interposition, motion parallax, textural gradient, and accommodation. For remote viewing with a fixed monoscopic (i.e. single camera) display, for example, it is possible to use the location of a known object within the plane of the display screen as a distance cue. The "stereoscopic" depth cues include retinal disparity and, to some extent, binocular convergence [12].

CH2809-2/89/0000-1244 $1.00 © 1989 IEEE

Context of the Work

The research reported here is part of a larger study to investigate the potential use of stereoscopic video displays for Explosive Ordnance Disposal (EOD), conducted for the Canadian Department of National Defence (DND). The remote manipulator used for most DND and police EOD operations in Canada is the Remote Mobile Investigation (RMI) Unit, manufactured by Pedsco (Canada) Ltd. The RMI is a mobile platform with a 3 degree of freedom manipulator arm and an 80 m tether. Using various tools and attachments, the RMI can be used to remotely X-ray, disable, detonate, or transport a suspected explosive device. The RMI is generally equipped with a single camera monoscopic video display system.

The RMI is typically called into action when a suspicious package has been found that is suspected to contain an explosive device. If possible, the RMI is used to dispose of the suspected bomb rather than risk the lives of the EOD experts. The preferred method of disabling a suspected explosive is to use a miniature water cannon loaded with 100 mL of water, referred to as a "disruptor" or "centaur". When the disruptor is fired, the water is forced out through a nozzle at a very high speed, with sufficient force and speed to rip most bombs apart before they can detonate. The optimal separation between the disruptor and the package is between 3 and 7cm. To accurately and safely achieve this separation using a monoscopic video system, an operator will typically attach a loop of tape to the end of the disruptor. Any movement of the tape is a visual signal that the desired distance has been reached.

Whenever feasibile, X-ray photographs are taken of the package before the disruptor is deployed. The X-ray device consists of two parts: a large X-ray photographic plate which swings freely on the end of the RMI's arm, and an X-ray projector aimed directly at the X-ray screen. The plate is lowered behind the suspicious package and is brought as close to it as possible, in order to ensure a clear image. It is critical that the parcel not be disturbed, lest it be motion sensitive. In fact, with the monoscopic display in current use, it is often expedient for operators to set up the X-ray plate manually, thereby putting themselves at risk and essentially defeating the purpose of the RMI.

In order to achieve the skills necessary for EOD teleoperation, operators must undergo an extensive training programme, and practice regularly thereafter. During interviews conducted as part of the present study, operators reported that without this constant practice their skills quickly deteriorate, particularly their ability to use the depth and distance information provided by the monoscopic display.

Most DND operators are assigned only part-time to the EOD unit, because (fortunately) many months can pass before they might be called upon to perform an actual EOD mission. One can therefore envisage a scenario in which an operator who has been away from EOD operations for a long time is summoned back into active service and must re-acquaint him/herself with the display system. Any loss of skill could conceivably jeopardise the success of the mission. The obvious expensive solution to this problem is to enforce strict regular practice requirements. A better solution would be to reduce the amount of re-learning necessary in these circumstances.

Experiments

Objectives

Two experiments were designed, to investigate the following questions related to the manner in which operators develop the different aspects of their internal model of a telemanipulation task, as discussed earlier:

1) Is there a difference in the rates at which operators learn how to interpret monoscopic versus stereoscopic display cues?
2) Do stereoscopic displays facilitate learning of the control actions and planning needed to accomplish a remote manipulation task?
3) Is performance under different levels of task demand affected by the type of display used?

The first experiment was designed to examine the first question. In order to examine how subjects learn to interpret depth information for the two different video systems (i), the other internal model acquisition factors mentioned above were controlled. Learning of the task control actions (ii) was minimised by using an extremely simple task, and by training the operators prior to the experiment using direct viewing. Learning of the remote environment (iii) was controlled by limiting the number of relevant visual elements of the remote view, by keeping the view as static as possible, and by training with direct viewing. Any residual effects of either of these classes of learning were eliminated by means of a balanced experimental design.

The second experiment was designed to investigate the second internal model acquisition factor, the learning of the control actions necessary to accomplish the task (ii). The effects of learning how to interpret the display (i) were controlled with training. The effects of learning the remote environment (iii) were controlled by training under direct view, and by training remotely. Any residual effects were balanced by means of experimental design.

Video Display Systems

An alternating field stereoscopic display with active liquid crystal shuttering spectacles was used for this study [13]. This system has the advantage of using standard camera and television equipment for the creation, recording, and display of the stereoscopic image. Two Hitachi VK-C150 colour cameras with 8 mm lenses were used. For the monoscopic condition one camera was used, pointed directly at the pointer attached to the manipulator arm. For the stereoscopic condition, the cameras were separated by 12 cm, and converged on the pointer, approximately 80 cm from the cameras.

Experimental Design

When comparing the effects of different treatments on experimental subjects, the experimental design must control for relevant existing differences between people. For this study, each subject can be expected to enter the experiment with a different innate proficiency at teleoperation tasks. This can be controlled either by using a very large number of subjects under each treatment condition, thereby averaging out the effect of innate variability, or by blocking the subjects so that each is examined under all conditions. A pilot study revealed the intra-subject variability to be fairly large, which would have made the first method prohibitively expensive. Consequently, a subject blocking design was used.

Unfortunately, this type of experimental design threatens the validity of any conclusions about learning trends, because when subjects perform under their second treatment condition, they are obviously more experienced with the task than under the first condition, and presumably demonstrate different learning trends. In order to minimise this problem, the number of experimental runs for each condition was limited to a relatively small number, and the orders of presentation of experimental treatments were balanced among subjects. Therefore, while no valid conclusions about the absolute performance data can be made from the resulting learning curves, it is still possible to draw conclusions about differences between the learning curves.

The first experiment had no failure condition; that is, every run continued until completion. This was not the case with the second experiment. In order to control the difficulty level of different conditions within the experiment, a Fitts' Law paradigm was used [14]. Including runs where the operators made errors would interfere with this control of difficulty, however. The operators were therefore required to continue performing the task until the required number of successful runs was completed. An excessive number of error runs could interfere with the observation of the learning trends, however.

Experiment One: Approach and Touch

In order to examine fairly the different rates at which operators learn how to integrate the information on the display, it is important to select a task which can be accomplished reasonably well using only monoscopic cues. This was done using a fixed view of an unchanging environment, which provided many highly salient monoscopic depth cues, particularly shadows and absolute location of the object image on the display monitor.

Method. In order to provide an elementary task for which monoscopic depth cues were sufficient, while still providing a link with real EOD operations, the experiment was set up as a simple simulated bomb disposal task. A mock "disruptor" was mounted onto the RMI arm. At the end of the disruptor was a spring loaded loop of paper, the movement of which was a visible sign that the disruptor was close to the target.

The subjects (eight university students and one defence scientist) were instructed to drive the RMI from a fixed starting position, as quickly as possible, to a target 3m away, until they saw the paper move, indicating that they were 7 cm from the target. For each run, lateral target position was varied randomly. The arm of the manipulator was fixed at the correct orientation, so the subjects had only to drive the robot into position using a two degree of freedom joystick for locomotion control. The environment in which the task was performed was designed to contain many monoscopic depth cues. The target was a brightly coloured 10 cm square glued onto the side of a small box on a table with a highly reflective surface, in a brighly lit area. In the centre of the target was a 1 cm wide vertical line which the subjects were instructed to touch with the paper loop. Subjects signalled when they were satisfied with the position of the pointer, thereby ending the trial. If the pointer was compressed more than 7 cm, a buzzer sounded, indicating that the parcel had been touched by the disruptor and had "exploded". The buzzer was unpleasantly loud, to discourage the subjects from making contact with the parcel. To instil a sense of urgency, the subjects were told that the bomb had a random timer that would go off some time during the next 30 seconds.

Three measures were recorded for each run: time-to-completion, the distance which the paper was compressed, and magnitude of horizontal error. Each subject, after a controlled practice period of driving the robot using direct view to get used to the control dynamics, performed 16 trials using one video condition, followed by 16 trials using the other video condition. Four subjects began with a monoscopic display, the other five with a stereoscopic display.

Results. Figure 1 shows the mean time-to-completion in each video condition, averaged over subjects, plotted against run number. An analysis of variance of time-to-completion with the factors of video system (monoscopic or stereoscopic), and run number (1 to 16), indicated that both the main effects were significant (Video: $F(1,8) = 7.246$, $p<.03$; Run Number: $F(15,120) = 1.720$, $p<.06$), but that there was also a significant interaction (Video x Run Number: $F(15,120) = 1.959$, $p<.02$).

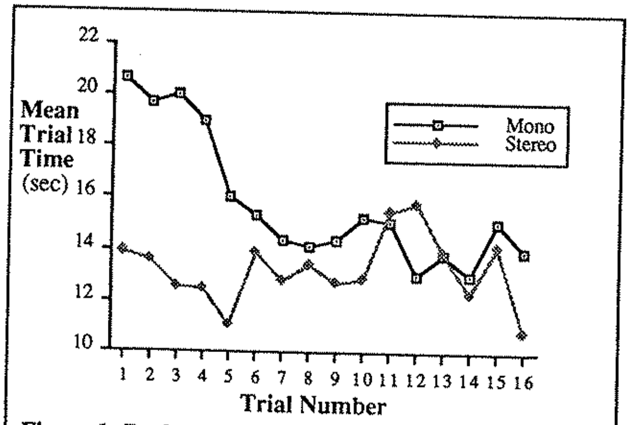

Figure 1: Performance Data for a Simple Pointing Task

While it is apparent in Figure 1 that there is no significant learning trend for the stereoscopic video (the slope of a linear regression is not significantly different from zero: $t(14)=.232$, $p<.8$), there is a marked improvement in performance in the monoscopic condition in the first 8 runs, which levels off to a rough plateau. Repeating the analysis for the 8 final runs of the two video conditions, there are no significant effects of either main factor. That is, performance in the monoscopic condition is as good as that in the stereoscopic condition, and there is no evidence of continued learning.

Experiment Two: The Fitts' Law Task

Method: In order to provide an elementary task with different difficulty levels for each of which the stereoscopic depth cues can be important, while still providing a link with EOD operations, the second experiment was set up as follows. A mock X-ray plate, in reality a suspended pointer, was mounted onto the RMI arm. The pointer was spring loaded and would sound a buzzer when pushed against a surface. The subjects (eight paid volunteers, all university students) were instructed to drive the RMI from a fixed starting position as quickly as possible towards a pair of parallel suitcases on a table 3 m away and to lower the pointer between them. The task was explained as an EOD X-ray task, where either of the two suitcases might have been the bomb. The bomb was expected to be touch sensitive, and so touching either suitcase counted as a failure.

Each run began with the arm of the manipulator, and thus the cameras mounted on it, aimed at the ceiling. Employing a Fitts' Law paradigm, the separations between the suitcases were used to vary the demand of the task. The separations used in the experiment were 8, 16, 32, and 64 cm. Then environment in which the task was performed was designed to have fewer monoscopic cues, particularly shadows and reflections, than the first experiment.

All subjects participated on two non-consecutive days. On the first day they performed the experiment with one video condition, and on the second the other. Using a balanced Latin square design for Part A of the experiment, each subject performed 16 consecutive runs in each of the four separations. When all four separations were completed, the subjects then performed Part B of the experiment, comprising another 8 runs at each separation, with a randomised rather than consecutive presentation order.

Training each day included a warm up period of driving the RMI around the using both direct view and the remote display, and practice, using direct view and the remote display, of the X-ray task with an intermediate separation of 24 cm. The subjects had to continue practicing until they were able to complete four consecutive runs without errors, in less than 6 seconds. The measures recorded were time-to-completion, and the type of error that occurred.

Results. The results of Experiment 2 are shown in Figure 2 for Part A, and Figure 3 for Part B. An analysis of variance on the time-to-completion with respect to the factors of Video (monoscopic or stereoscopic), Separation (8, 16, 32, or 64cm), and Experience (trial number 1 to 16) was done for Parts A and B with the results summarised in Table 1:

Table 1: Analysis of Variance for Experiment 2

Expt 2	Video	Separation	Experience	Video x Sep
Part A Consecutive Trials	F(1,7) = 7.708 p<.03 *	F(3,21) = 25.979 p<.001 ***	F(15,105) = 2.048 p<.02 *	F(3,21)=6.442 p <.003 **
Part B Random Order	F(1,7) = 33.309 p < .001 ***	F(3,21) = 29.043 p <.001 ***	n/a	F(3,21) = .971 p < .5

The results of Part B clearly indicate the Fitts' Law relationship between time-to-completion versus Index of Difficulty for both the monoscopic and stereoscopic conditions. Linear regression of the time-to-completion with Index of Difficulty shows that there is no significant difference between the slopes of the two lines (t(6) = .929, p < .25).

Discussion

It is clear from the results of both Experiment 1 and Experiment 2 that a significant difference does exist between skill acquisition patterns for stereoscopic versus monoscopic video display systems. When using a monoscopic display, the performance of the subjects at the end of the set of trials for each separation was, on the whole, markedly better than their performance at the beginning of the condition, on the order of 20 – 30%. When using a stereoscopic display, such dramatic improvements were not found; the subjects ended the set of trials with essentially the same proficiency as when they began it.

Experiment One was designed to isolate factors related to how subjects learned to interpret depth cues provided by the display of the remote environment. This was done by reducing the effects of other learning factors. For that very simple task, which was rich in monoscopic depth cues, it did not take long for the subjects to learn how to use the monoscopic display as proficiently as the stereoscopic display. However, there is no evidence of *any* learning taking place with the stereoscopic display. That is, at the beginning of the trials, the subjects were able to use the information displayed essentially just as well as when they finished. This has dramatic implications for

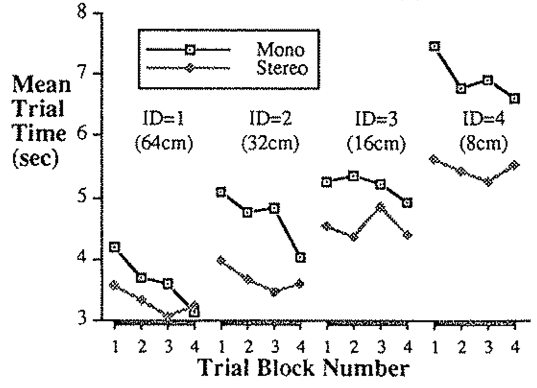

Figure 2: Positioning Task Part A: Performance vs Trial Block Number

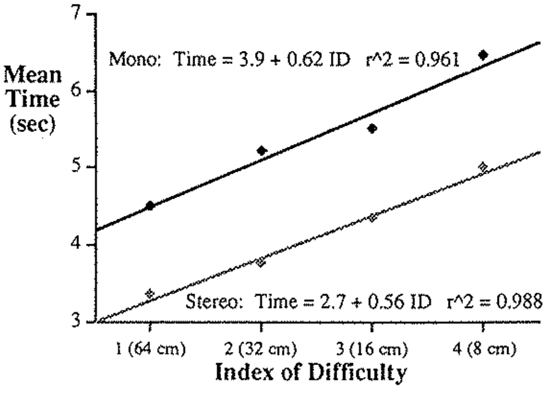

Figure 3: Positioning Task Part B: Performance vs Index of Difficulty

operator training, and for situations where operation of the remote manipulator is infrequent.

Experiment 2 was designed to examine whether using stereoscopic displays can facilitate motor task learning, and how the type of display used can affect the demands of the task. The first two internal model acquisition factors discussed above, learning how to interpret the depth cues of the display (i), and learning how to control the RMI itself (ii), were minimised by means of training, and residual effects were balanced out by the experimental design. The remaining dimension of learning is how to coordinate the various control actions comprising the task; that is, how to drive from a fixed position and lower the pointer between two separated suitcases. It was not obvious a priori that there should be a relationship between this sort of learning and the type of video display used.

With respect to task difficulty, the data of Experiment 2 verify the expected result that mean performance time does increase monotonically with task difficulty, as expected by Fitts' Law, which predicts that task completion time (MT) will vary linearly with the *Index of Difficulty* (ID), i.e. **MT** = **a** + **b ID** [14]. For Experiment 2, **ID** is determined by the suitcase separation **S** such that **ID** is proportional to **log (1/S)**. For convenience, **ID** is set to 1, 2, 3, and 4, for the separations 64, 32, 16, and 8 cm, respectively. The parameter **a** can be regarded as a Minimum Response Time (MRT), a constant reflecting the overhead associated with accomplishing the task, related to the composite time it takes to drive from the starting position to the suitcases, the time it takes to interpret the image on the display, etc. If there was no difference in the MRTs associated with monoscopic versus stereoscopic displays, we would expect that the two Fitts' Law lines would have the same intercept. The parameter **b** can be seen as being related to *Information Processing Requirements* (IPR) of the task, or the rate at which information is processed (i.e. **b** has the units seconds/bit), a measure of the difficulty of the task.

Figure 3 shows the Fitts' Law relationship clearly. The data are from Part B of Experiment 2, where the separation between the suitcases was changed for each trial, making the task much less repetitive. By this point in the experiment each day, the subjects had considerable practice using the displays and the RMI, and were quite familiar with the control motions necessary to accomplish the task. Clearly, for these "experts", Fitts' Law applies. The fact that the slopes are not significantly different implies that the IPRs of the positioning task are equal when using monoscopic or stereoscopic displays, and that the differences in performance are due to differences in the MRTs of the two conditions.

Figure 2 shows the learning trends in Part A of Experiment 2, for the two video displays used and the four separations. Each point represents the average of four consecutive trials, so that each set of sixteen trials is represented by four points.

Note that the learning curves in the easiest condition (the 64 cm separation) are similar to those in Experiment 1 (Fig. 1); that is, the learning trend for the monoscopic condition is much more pronounced than that for the stereoscopic condition, and, with experience, the difference between the two curves diminishes. In the other difficulty conditions, however, such behaviour is not evident. In all separations, the mean time using the monoscopic display begins considerably higher than the stereo, and decreases from trial to trial at a faster rate than the stereoscopic performance. It is not clear, however, whether or not, in these more difficult conditions, performance with monoscopic displays will eventually approach that with stereoscopic displays, or whether some constant difference between them will remain.

The Fitts' Law model is a useful tool for illuminating this aspect of skill acquisition. If it is assumed that Fitts' Law applies at all skill levels, then it is possible to observe the changes in the Fitts' Law regressions as learning progresses. To do this, the sixteen trials for each separation in Part A were divided into four groups of four trials, as shown in Figure 2. It was then possible to fit the Fitt's Law model to the means of corresponding group scores for each separation. That is, the Fitts' Law line representing the least experienced performance is fit to the first group of four trials for the four different separations, and so on. This results in four different sets of Fitts' Law parameters, each representing a different level of experience.

Plotted in Figure 4 are the intercepts of the four Fitts' Law lines, the Minimum Response Times, for the four levels of experience. (The MRTs for Part B are included for reference.) These intercepts are have been defined for the **ID** = 0 line, which theoretically corresponds with a suitcase separation of 128 cm. In Figure 4 the MRTs of both the monoscopic and stereoscopic conditions can be seen to be decreasing with experience. It would be unreasonable to assume that the MRTs will continue to decrease linearly to zero, however; more likely they will gradually approach some minimum value. An analysis of variance of the MRTs with the factors of Video and Experience reveals that the only significant factor is Experience (F[3,24]=4.136, p<.02). This is very different from the MRT of Part B, where Video does indeed have a significant effect. One explanation for these differences in the MRTs of the two Parts may lie in the observation that in Part A, where the same suitcase separation was used for 16 consecutive trials, the subjects seemed able to learn and retain the timing of the control pulses needed to drive the RMI to the suitcases much better than they could for Part B. With experience, the driving segments of Part A tended to become increasingly automatic, and thus less dependent on the video display used. It is reasonable to consider much of the driving time to the the suitcases to be part of the Minimum Response Time of the task, and so this explaination would account for the lack of a difference in the MRTs for mono and stereo in Part A, and the presence of one in Part B.

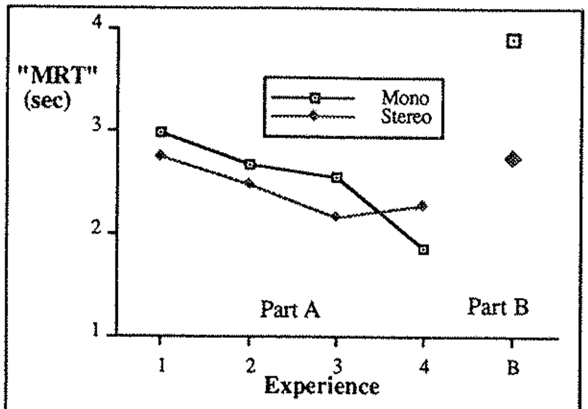

Figure 4: Positioning Task Part A: Fitts' Law Intercept vs Experience

Plotted in Figure 5 are the slopes of the four Fitts' Law lines, the Information Processing Requirements (IPRs), representing how effective difficulty of the tasks in Part A change with experience. The IPRs for Part B are also shown for comparison. An analysis of variance reveals that, for the Part A IPRs, only Video is a significant factor (F[1,24]=21.723, p<.001). This, again, is very different from the results of Part B, where the IPRs for the monoscopic and stereoscopic conditions are indistinguishable.

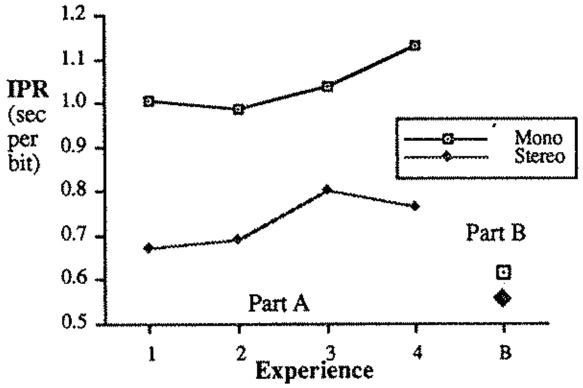

Figure 5: Positioning Task Part A: Information Processing Req'ts vs Experience

The differences in the IPRs of the monoscopic and stereoscopic display conditions of Part A, seen in Figure 5, imply that, for highly repetitive tasks, it is less demanding to perform the task using a stereoscopic display than a monoscopic display, at all levels of experience. In other words, using Fig. 2 as an example, this implies that as the Index of Difficulty of the task increases, the incremental difference in performance due to the video display used will also increase. The harder the task, therefore, the more the benefit of using a stereoscopic display; similarly, the easier the task, the less the benefit. That the Information Processing Requirements of the tasks do not decrease with experience is counter-intuitive. It could be that the number of runs used was too small to find any downward trend.

The differences in the Fitts' Law parameters for Parts A and B of the Experiment must somehow lie in the fact that Part A is highly repetitive compared to Part B.

Conclusion

For simple teleoperated approach and touch tasks, novice operators can be expected to perform considerably better using stereoscopic displays initially. If the simple task is repeated, the differences in performance may vanish with sufficient training.

For a highly repetitive positioning task, it was found that at least short term improvements were due to a reduction of the minimum response time for the task, and not due to a reduction in the difficulty of the task.

Acknowledgement

The work described here was carried out under contract W7711-7-7009/01-SE with Supply and Services Canada for the Department of National Defence.

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