Human Performance

in

Six Degree of Freedom Input Control

(Compact Edition)

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Human Performance in Six Degree of Freedom Input Control

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Abstract

This thesis investigates human performance in relation to various dimensions of 6 degree of freedom (DOF) interfaces, including device resistance, transfer functions, muscles groups and joints, and input display formats. These dimensions are analysed respectively in terms of human proprioception and control feel, mental processing in forming control actions, motor and sensory cortex representation, and the nature of various visual depth cues.

A series of five experiments are presented. Experiment 1 examined isotonic versus isometric resistance modes and position versus rate control transfer functions. A strong interaction was found between the resistance mode and the transfer function: in position control, the isotonic device outperformed the isometric device; whereas in rate control, the isometric device outperformed the isotonic device. Experiments 2 and 3 studied isometric versus elastic devices in rate control. When optimised between two opposing factors, i.e. proprioception and compatibility, the elastic device had performance advantages over the isometric device at the early stage of learning. Experiment 3 also revealed users' control strategies in terms of attentional priority to each degree of freedom. Experiment 4 investigated the effects of different joints and muscle groups on 6 DOF manipulation. The results showed that the participation of fingers significantly improved task performance. Experiment 5 studied the visual representation of users’ input control actions. It was found that partial occlusion through semi-transparency in 3D, a rather novel graphic technique, was strongly beneficial.

The major conclusions of the thesis can be summarised briefly as: (1) The physical properties of a 6 DOF input device should provide rich feedback so that the user can easily feel her control actions proprioceptively and thus learn the task quickly. (2) To the extent possible, fine small muscle groups and joints should be included in the operation of input devices. (3) The transfer function used to interface a device with the computer should be compatible with the physical device. (4) The visual representation of the user’s actions should be designed to allow immediate exteroceptive feedback and the application of semi-transparency serves this purpose well.

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For all the wonderful things she has done for me, this thesis is dedicated to my grandmother:

Wang Rui-Ying

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Summary

Progress in technology is continuously expanding the design space for 6 degree-of-freedom (6 DOF) human machine interfaces. It is both theoretically and practically necessary to understand how users' performance relates to various design dimensions for 6 DOF interfaces. This thesis investigates human performance in relation to the following critical issues: controller resistance in terms of isotonic, elastic, and isometric devices; transfer function in terms of zero order position control versus first order rate control; the size and the shape of the 6 DOF device that determine joints and muscle groups used, such as shoulder, elbow, wrist, and fingers; display methods to reveal users' input control action in relation to target objects in 3D, in particular stereopsis and partial occlusion through semi-transparency.

The methodology of this thesis is a pragmatic combination of analysis, literature review and experimentation. The cited design dimensions are analysed in terms of human proprioception and control feel (corresponding to device resistance), mental processing in forming control actions (corresponding to transfer function), motor and sensory cortex representation (corresponding to muscles and joints) and the nature of various visual depth cues (corresponding to display formats). The related literature in engineering psychology, human motor control, manual tracking and human computer interaction is also reviewed.

A series of five experiments are presented. Experiment 1 examined four 6 DOF manipulation techniques, based on a combination of isotonic versus isometric resistance modes and position control versus rate control transfer functions. A strong interaction was found between the resistance mode and the transfer function. In the position control mode, subjects had shorter mean completion times with the isotonic device than with the isometric device. In rate control mode, the relative advantage of isotonic and isometric device was reversed. This interaction pattern is the result of the compatibility between paired actions required in rate control and the self-centring effect of isometric devices.

Experiment 2 studied isometric versus elastic devices in rate control mode. Two factors, proprioception and compatibility, were identified as opposing properties in the design of elastic devices for rate control. As the stiffness of elasticity increases, the self-centring effect increases accordingly, hence enhancing the compatibility with rate control. On the other hand, stiff elastic controllers allow less movement, hence reducing proprioceptive feedback due to movement. In a 6 DOF docking task, Experiment 2 revealed that, if optimised between the two factors, the elastic device had performance advantages over the isometric device, but only at the early stage of learning. Experiment 3 pursued the same issue as in Experiment 2, but with a more demanding task: 6 DOF tracking. A more substantial difference was found between the two types of controllers but the general trend was the same as in Experiment 2: the elastic device was easier to learn than the isometric device, but the performance difference decreased as practice progressed. Consistent with many human motor control theories, the results of Experiment 2 and Experiment 3 imply that the basis of human motor skills shifts from closed-loop, feedback driven behaviour to open-loop, motor-program driven behaviours.

A detailed analysis of Experiment 3 results revealed interesting user strategies in 6 DOF tracking. In a rather consistent priority order, subjects tended to concentrate on fewer degrees of freedom at a time during early learning stages and progressed to cope with more

degrees of freedom together during later learning stages. Between horizontal, vertical, and depth dimensions, the horizontal dimension appears to take attentional priority. Between translation aspects and rotation aspects, translation appears to take higher priority. It was found that after 40 minutes of practice more than 80% percent of the subjects were able to control all 6 DOF simultaneously.

The issue of which joints and muscle groups should be used for 6 DOF manipulation was studied in Experiment 4. Two isotonic position control techniques were tested in a 6 DOF docking task. One technique utilised the user's wrist, elbow and shoulder, while the other technique made use additionally of the user's fingers. The results showed that the participation of fingers significantly improved the task performance.

Experiment 5 investigated the issues of visual representation formats of users' input control actions in relation to the target object. In a 3D dynamic target acquisition task, it was found that both binocular disparity and partial occlusion through semi-transparency, a rather novel graphic technique, were beneficial. In particular, the use of semi-transparent surfaces appeared to enhance human performance in discrete tasks more than the classical stereoscopic viewing technique.

The experimental and analytical studies in this thesis significantly contribute to the understanding of human factors in 6 DOF manipulation. The highlights of the results can be summarised briefly as: (1) The physical properties of a 6 DOF input device should provide rich feedback so that the user can easily feel her control actions proprioceptively and thus learn the task quickly. (2) To the extent possible, fine small muscle groups and joints (fingers) should be included in the operation of input devices. (3) The transfer function used to interface a device with the computer should be compatible with the characteristics of the physical device. (4) The visual representation of the user's actions in relation to target object should be designed to allow immediate exteroceptive feedback and the application of semi-transparency serves this purpose well.

Chapter 1

Introduction: Motivation, Literature Overview, and Methodology

1.1 Motivation and Research Goal

This thesis is concerned with design factors that influence human performance in manipulating the location and orientation of three dimensional (3D) objects with six degrees of freedom (6 DOF). The need for this research has emerged from the development of a variety of advanced technologies. Technologies such as virtual and augmented reality (Barfield and Furness, 1995) , telerobotics (Sheridan, 1992b), computer aided design (Majchrzak, Chang, Barfield, Eberts, and Salvendy, 1987), scientific data visualisation (Card, Robertson, and Mackinlay, 1991) , and 3D computer graphics and animation (Foley, van Dam, Feiner, and Hughes, 1990) all require designing interfaces to let human users control 6 degrees of freedom of objects (robot, data, or viewpoint) in 3D space.

Many devices, including various instrumented gloves, position trackers, and hand controllers have been developed for applications in these areas. Figure 1.1 shows a collection of such 6 DOF devices. Ideally, the development of such devices should have been guided by the knowledge of human characteristics and performance. However, in reality, the development of most of these products has been driven primarily by sensor technologies. Whenever sensors that can detect displacement or force/torque in six degrees of freedom are developed, they tend to be quickly incorporated into new 6 DOF control devices for human input into computers and other machines. Little systematic human factors research on 6 DOF manipulation has been available for guiding the development of 6 DOF interfaces.

In order to transform this trend of "technology push (or gadget-driven)" into "demand pull (or human-driven)" in the development of interactive devices (Jacob, Leggett, Myers, and Pausch 1993) , systematic studies of human capabilities and limitations as a function of various design dimensions are much needed. Design variations in many parts of an interactive system can influence how a user conducts input control tasks. To identify the key human factors issues in designing 6 DOF inputs, Figure 1.2 illustrates the major components* involved when a user exchanges information with a computer system (or any machine in general).

Block 1 in Figure 1.2 is the physical control interface between the user's limb and the machine (computer). This physical interface is also called a manipulandum in many fields. The currently most common 2 DOF example of such a physical interface is the computer mouse. A physical interface functionally consists of two parts, one part

* It should be noted that Figure 1.2 is a highly simplified diagram of human machine interaction system. Many components and links are omitted. For example, there could be a link from the manipulandum to exteroception, since the user may see her own hand actions.

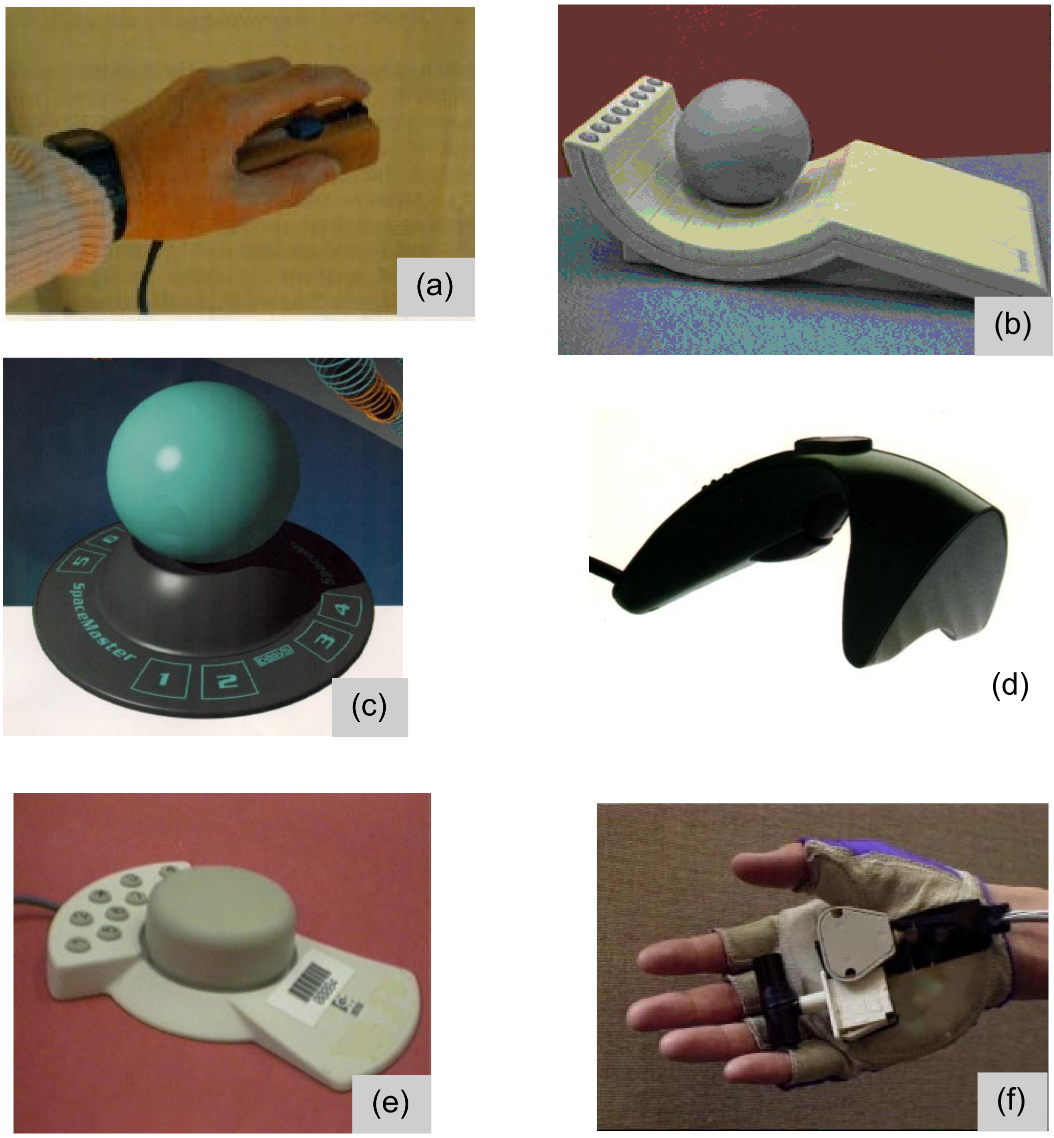

Figure 1.1 A sample of input devices for 6 DOF manipulation;. (a) The "Bat", designed by C. Ware (1990), consists of a Polhemus™ tracker and a handle. (b) The Spaceball™ is an isometric device manufactured by Spaceball Technologies Inc., Boston, MA, USA. (c) The SpaceMaster™ is an elastic device with a small range of movement (5 mm in translation and 15° in rotation), manufactured by BASYS GmbH, Erlangen, Germany. (d) The Cricket™, manufactured by Digital Image Design Inc., New York, NY, USA, is a free moving device consisting of a tracker inside of a handle. (e) The Space Mouse™ is an elastic device with slight movement (5 mm in translation and 4° in rotation). It is patented by DLR, the German aerospace research establishment, manufactured by Space Control Company, Malching, Germany and marketed by Logitech, Fremont, CA, USA. (f) The MITS Glove, designed by the author, consists of a Bird™ tracker and a clutch mounted on a glove.

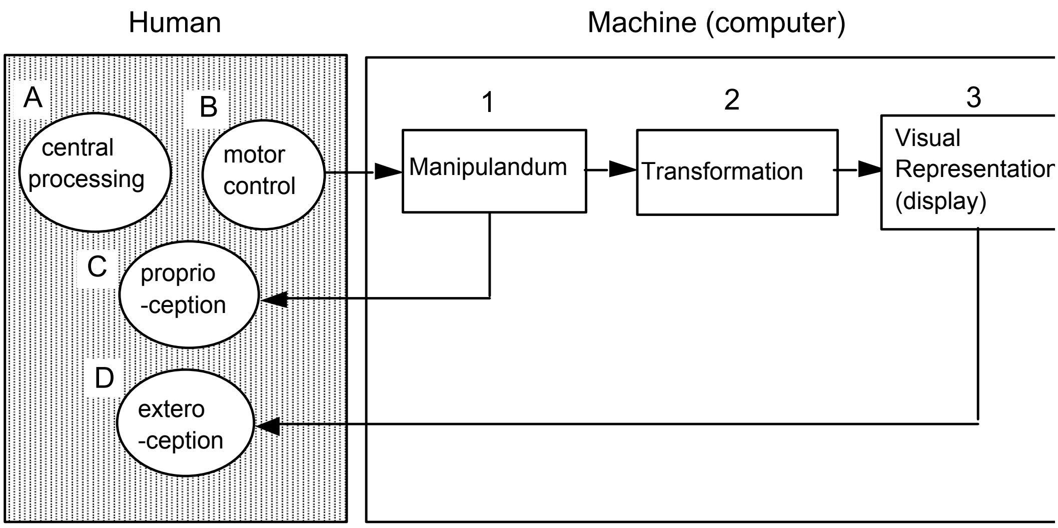

Figure 1.2 The human-machine interaction system

for sensing signals from the user's limb and one part, such as a handle or a glove, for the user to grasp. When narrowly defined, the term input device often refers to this physical interface. Interestingly, the information transfer between the human limb and the "input" device is in fact bilateral. In one direction, the user's motor actions manipulate the device and these actions are transformed into instructions for the computer. In the other direction, the user also receives certain control feel information via proprioception from the physical device. This bilateral nature of an input device can not be overlooked. An important issue is what resistance* the device should have in order to give the user a proper control feel. Should the designer choose a freely moving device (zero resistance, isotonic) such as an instrumented glove, a device with a certain type of movement resistance such as an elastic device, or a device with infinite resistance (isometric) such as the Spaceball™? How do different types of resistance affect the user's performance? To what extent does this resistance induce user fatigue? Two extreme cases, along the continuum of control resistance, an isotonic device versus an isometric device, will be studied in Chapter 2. Elastic resistance will be studied in Chapter 3.

The design of the physical size and shape of a physical device also has implications towards changing the particular muscle groups (limbs) used in manipulating the device, including the wrist, the arm, the hand, and the fingersesso d the hand, and the fingers (Card, Mackinlay, and Robertson, 1991). A relatively small handle may afford the user to use the fingers. On the other hand, when a tracker is mounted on the palm or the back of the user's hand, the 6 DOF manipulation will be done by the wrist, the arm, and the shoulder. Are

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*This research is concerned only with input control devices which produce various passive resistance forces to movement, such as elastic and isometric devices. Much work has been done in designing input devices that have *active* force reflection. See (Shimoga 1993a,b) for a survey on force-feedback devices. See (Brooks, Ouh-Yong, Batter, and Kilpatrick 1990) for force feedback applications in scientific visualisation. See (Massimino and Sheridan 1993) for substituting force reflection with audio feedback in teleoperation.

some of these body joints more suitable than others for 6 DOF manipulation? This will be addressed in Chapter 4.

Obviously, the interaction process goes beyond the physical device itself. Block 2 in Figure 1.2 represents the transformation from user's output to the computer display interface. There are many alternatives in designing this transformation to map the output of the physical device to object movement. An important decision to make is selecting the control order of this transformation. A zero order transfer function does not involve any integration (or differentiation) and the user's input variable (such as displacement or pressure) is directly mapped to a cursor's position. Zero order transformation is hence called position control. A first order transfer function has one integration which maps the user's input variable to the cursor movement by an integral. This means that the user's input is proportional to the velocity of the cursor movement. First order transformation is hence also called rate control. Control order can be also second order (acceleration control) or higher. The research questions here therefore are: How does the transfer function affect the user's performance? Does one type of transfer function make the input control more easily to learn than others? Is there any kind of relationship between transfer function and other dimensions, such as device resistance? Some of these questions will be addressed in Chapter 2, in conjunction with the study on isotonic and isometric resistance.

Following the transformation operation, the input will then be displayed by means of some visual representation, as illustrated by Block 3 in Figure 1.2. This visual representation (a cursor) can take many forms. For conventional 2D interfaces, it might be an arrow, a cross-hair, a dot, or any other symbol that reveals the user's input actions relative to other "target" objects, such as a button, a window or a file icon. For 6 DOF input, the unique challenge is to display the spatial relationships between the user's translational and rotational input actions and other objects in the depth dimension. Chapter 5 discusses ways to take advantage of the human perceptual system and present the depth information effectively. In particular, it studies a novel 3D cursor technique based on the partial occlusion effect.

The various components of the interaction system on the computer side have to be investigated on the basis of the understanding of perceptual, motor and cognitive functions of the human user, as illustrated by the left side of Figure 1.2. This thesis attempts to incorporate some research results from the behavioural sciences, such as psychomotor behaviour, neuromotor control, psychophysics and human perception. Literature in these fields that concerns the issues in input control will be reviewed in related parts of this thesis.

In summary, the alternatives associated with the human factors design of a 6 DOF interaction system form a very large design space spanning multiple dimensions, including but not limited to:

- The resistance of the 6 DOF input device.
- The transformation mapping the output of the physical device to the object movement.
- Different body parts used for manipulation.
- Visual representation (cursor display) of the user's input actions in relation to target objects.

As a general human factors principle, the final composition in the multi-dimensional design space of 6 DOF interface should aim at matching human capabilities and limitations so that the user can learn the 6 DOF manipulation task quickly, perform the task efficiently and work for long periods of time if necessary with minimal fatigue. However, the effects of variations along these design dimensions on learnability, performance and fatigue are often beyond designers intuition. The goal of this thesis is to provide designers with a human factors basis and rationale for the process of designing and selecting 6 DOF interfaces.

In addition to the above mentioned dimensions, there is also a more general distinction in terms of manipulation metaphor in high DOF input design. Two opposing metaphors present themselves with regard to manipulation in 3D space. One is to use the direct manipulation metaphor in which the user's hand motions are projected into the display space as isomorphically as possible (isomorphism). A glove input with 1 to 1 control-display mapping between the user’s hand and displayed hand in a virtual reality (VR) environment is an example of direct manipulation input. The opposite view to isomorphism is that the input devices should be designed as tools that transform human actions indirectly into the manipulation task. One such example is a rate control device, which converts the user’s motor action into an object’s movement velocity, rather than displacement. Obviously isomorphism may produce a more intuitive, more natural interface that directly takes advantage of the repertoire of skills acquired in daily life. Some researchers, however, suggest a “hands off my VR” approach and believe tools are more appropriate for manipulation in 3D space (Green, Bryson, Poston and Wexelblat, 1994). Tools may enable users to go beyond their physical limitations, to produce input control with better quality and with less fatigue.

Of course, rather than concentrate on the extrema, one should realise that there is a continuum between the completely isomorphic control interfaces and the totally artificial tool-like interfaces. What is important is to determine how each approach quantitatively affects human performance as learning progresses, so as to provide a basis for designers to choose compromising solutions for specific applications. Isomorphism versus tool-using is not independent of the design dimensions discussed above, particularly the transformation in the input process. For instance, perfect isomorphism requires position control with 1 to 1 control display ratio, whilst rate control is perhaps more suited for interfaces designed as tools. This notion of isomorphism versus tool using is therefore addressed throughout this thesis.

The design of controls and displays for human input to machines is a classic human factors research topic. It is by definition at the very heart of the study of human machine systems. Although 6 DOF manipulation is relatively new, a large body of literature related to 1 or 2 DOF input control is scattered across a variety of journals, conference proceedings, and technical reports in the areas of experimental psychology, human motor control, aviation and aerospace, teleoperation, human-computer interaction and so on. The present study builds upon this large body of literature, attempts to consolidate it to some extent and, in some respects, to advance it. Detailed references and reviews of the most relevant literature are made in each chapter of this thesis. In order to put the current study into a global context, a very general overview of representative works on input control is presented in the following.

1.2 Literature Overview

Primarily driven by applications in vehicle control and aircraft piloting, the first wave of human factors research on input controllers started in the 1940's and reached its apex in 1950's and early 1960's. Many issues discussed in the previous section, even though in the context of 1 or 2 rather than 6 DOF devices, were studied in this period of time. Orlansky provided one of the earliest comprehensive analyses of the human factors issues to be concerned with for the design of input controllers. His article (Orlansky, 1949) analysed factors such as maximum forces that may be exerted by a human pilot, the gradient of control forces and the manner of human movement. However those analyses were not supplemented with empirical experiments.

Researchers from the Applied Psychology Unit of the Medical Research Council in Cambridge, England, including K.J.W. Craik (Craik, 1943, 1944, posthumously published as Craik and Vince, 1963a, 1963b, after Craik's death in 1945) , C.B. Gibbs (1954; 1962) , E.C. Poulton (1974) and others, took leading roles in the early research on controls. These researchers were concerned with human performance affected by various type of controls. Gibbs, for example, hypothesised that isometric devices (force sticks) provide strong "proprioceptive discharge" in the human limb and therefore help the human operator's performance. Poulton, on the other hand, took a position opposite to that of Gibbs.

Another notable group of researchers, the "Ohio School", including P.M. Fitts (1951) , H.P. Bahrick (Bahrick, Fitts, and Schneider, 1955b) , D. Howland and M.E. Noble (1953) (primarily from the Ohio State University) made the most impressive theoretical contributions to the understanding of controls. Their central thesis was that human proprioception can be modelled by laws of physics. According to their theory, elastic loading on a control device augments the perception of displacement, due to the fact that the resistance force of a spring is proportional to displacement (Hooke's law). When a control device has viscous resistance, the human perception of velocity will be enhanced, due to the fact that viscous resistance is linearly related to velocity. Similarly, as revealed by Newton's second law, inertial resistance is proportional to acceleration, therefore the mass of a control device should augment the human perception of acceleration. This physics based model of proprioception was supported by a series of analyses and experiments (Fitts, 1951; Howland and Noble, 1953; Bahrick, Bennett, and Fitts, 1955a; 1955b; Bahrick, 1957). Notterman and Weitzman (1981) later confirmed this proposition in a more systematic manner.

The early research on controls was often concerned with dynamics. Aircraft, submarines and other vehicles all have complex dynamics. Birmingham and Taylor (1954, cited in Notterman and Page, 1962) hypothesised that human tracking performance would remain unchanged, despite variations in control device properties, if the overall transfer function relating the force applied to a control device to the system output remains unchanged. Notterman and Page (1962) conducted an experiment, however, that rejected Birmingham and Taylor's hypothesis. They studied systems that have the same overall transfer function (second order dynamics) but differ in where the dynamics was located within the control loop. In one system, second order dynamics was embodied in the input device's mechanical properties (elasticity, viscous damping, and inertia). In the other two systems, the input devices had negligible dynamics but the same second order dynamics was simulated in an analogue computer between the input device and the display. Notterman and Page demonstrated that the human operator had better performance with the first system, although mathematically the total system transfer function was comparable with the other two systems. They argued that the "local" (proprioceptive) feedback in the first system helped the subjects, since they could not only see the dynamic response from the visual display but could also "feel" the dynamics from the physical device.

Because of the importance of dynamics in early engineering systems, how humans handled the plant dynamics became more of a central theme in manual control research than the properties of input device themselves. Engineering models (particularly classical and modern control theories) were applied to describe and predict human behaviour in such a context. Sheridan and Ferrell (1974) provided a comprehensive summary of such efforts. In more modern control systems, however, automation of machines has reduced concern for the dynamics aspect of manual control. Much of the low level dynamics can now be handled by automatic controllers and the human's role has been increasingly elevated to supervisory tasks (Sheridan, 1988, 1992b) . Today's design of controls is therefore concerned mostly with facilitating human information input (or spatial instructions) into computer systems.

Research on input control has a strong two-way connection with the study of human motor skills. On the one hand, knowledge from human motor control research can clearly be applied to the design of control interfaces. On the other hand, many researchers have used different input control devices and manual control paradigms as vehicles for studying human motor control behaviour. The above mentioned research by Gibbs and by Fitts and colleagues all aimed at enhancing the understanding of human motor behaviour. Based on tracking research, Krendel's and McRuer's successive organisation of perception (SOP) theory hypothesised the general trend of human skill shift from closed loop to open loop behaviour (Krendel and McRuer, 1960) . Also based on tracking research, Pew (1966) proposed the hierarchical organisation of human motor control.

Interest in research on the properties of controls decreased in the mid-1960's, however. A. A. Burrows (1965) made a plea to continue studies on "control feel" and its related variables. He argued that "one would expect the relationship of the hand to the controlled element, being at the one time both an input and output, to be a fruitful area for research", but the reality is that little was well understood. He pointed out that the reluctance to conduct research in this area is understandable in view of the immensity of the possible interactions among the many dimensions of control feel.

In 1974, E.C. Poulton published his comprehensive review book on human tracking skills and manual control. The book (Poulton, 1974) covers much of the early research on design of controls. It was written in a very empiricist style, placing heavy emphasis on experimental data rather than theoretical issues and models. This was criticised at the time by other researchers (e.g. Pew, 1976) . In retrospect, Poulton's inclination towards empirical results was not necessarily unwise. Models and theories in research often change with the varying cultures in the scientific community but empirical data remain valuable. Taking human motor control as an example, cybernetic models were widely applied in early research, as evident in (Brooks, 1981) which surveys motor control research in the 1960's and 1970's, but decreased dramatically in later journal publications. Instead, artificial neural network models are currently on the rise.

Another important feature of Poulton's book is his critical discussion of "asymmetrical skill transfers" likely caused by within-subjects designs of experiments in the research literature. In within-subjects experiments, the same group of subjects is assigned to all experimental conditions; that is, each and every subject performs all experimental conditions. In between-subjects experiments, on the other hand, the subjects are divided into subgroups. Each subgroup of subjects perform in only one experimental condition. A within-subjects design needs fewer subjects than a between-subjects design and is therefore more commonly used. Apparently, in within-subjects experiments, subjects may carry over some effects, such as skills or fatigue, from earlier conditions to later conditions. In order to overcome this possible transfer effect, the sequencing of the experimental conditions in within-subjects designs is usually “balanced” by assigning subjects to the conditions in such a way that all experimental conditions have an equal number of times of being first, second, etc., or last condition. Poulton argues that although such an arrangement may balance the sequence of the conditions, it does not guarantee that the actual skill transfer from one condition to another is “symmetrical”. When transfer is asymmetrical, biased results can be produced. Poulton claimed that "once the biased results (due to asymmetrical skill transfer) are discarded, there emerges a clear and sensible description which differs in many respects from current views and practices". Asymmetrical skill transfer could indeed be a problem, but whether its effect is as important as Poulton believed is debatable. His repeated warnings (Poulton, 1966, 1969, 1973, 1989) have not been widely accepted by psychologists and human factors researchers, as within subject designs continue to be used frequently in experimental research.

Since the late 1970's, another wave of studies on input controls have been carried out as part of the research on human computer interaction (HCI). Card, English, and Burr (1978) conducted one of the most well known studies on the performance differences between various computer input devices (mouse, trackball, joystick, stylus, etc.). Card and colleagues also established the Fitts' law paradigm as the de facto standard task for computer input device research, even though Fitts' law is only one of the many theoretical products of decades of human motor control studies.

The often bewildering diversity of devices that can be possibly used for computer input has interested many HCI researchers. Significant effort has gone into building taxonomies for classifying the devices according to user behaviour. Buxton's taxonomy (1983) is among the best known taxonomies of computer input devices. It has been recently expanded by Card, Mackinlay, and Robertson (1990) . Bleser (1991) and Lipscomb and Pique (1993) are two other examples of taxonomy research on input devices.

Viewing human computer interaction as a human dialogue process with computers, Buxton introduced many concepts such as chunking and phrasing into research on computer input (Buxton, 1986, 1990, in press). Recent interest in computer input device research also includes utilising two hands in a co-operative manner, based on models from human motor control theory (Guiard, 1987; Kabbash, Buxton, and Sellen, 1994) .

As computer interfaces went beyond the limitations of flat 2D screens, input devices with multiple DOF caught the interest of HCI researchers. One question that needs to be addressed is what tasks are suitable for multiple DOF device applications. Extending the concepts of perceptual integrality and separability (Garner, 1974) , Jacob and colleagues suggested that the perceptual structure of the task should be considered in determining whether multiple DOF devices should be used (Jacob and Sibert, 1992; Jacob, Sibert, McFarlane, and Mullen, 1994). According to their view, when the multiple dimensions of a task are perceptually integrated, such as translations along each dimension of a 3D space, integrated multiple DOF devices are an advantage. When the multiple dimensions of a task are perceptually separated, on the other hand, such as adjusting the colour as well as the location of an object, it is easier to manipulate the separated variables one at a time with lower DOF devices. Similar thoughts are also reflected in other studies (see Fracker and Wickens, 1989; Wickens, 1992 for reviews). It has been found that when the dynamics of each DOF are alike, integrated control is superior to separated control. In contrast, when the two dimensions have different dynamics, for example when one is zero order and the other is second order, separated control works better than integrated control.

The newly arrived discipline of virtual environments (VE), and its older sister discipline , teleoperation, are naturally concerned with the performance of various types of multiple DOF control devices. A variety of control devices for teleoperation are reviewed by Brooks and Bejczy (1985) and by Jacobus, Riggs, Jacobus, and Weinstein (1992) . Similar to the contrast between isomorphism and tool using discussed earlier, there have been generally two streams of designs for teleoperation and virtual environments. One is the master-slave structure, in which the remote slave robot and the master controller with the human operator are geometrically isomorphic. The other is the tool-like hand controller approach. The merit of each of the approaches has been debated in the virtual environment community (Green, Bryson, Poston, and Wexelblat, 1994) . Sheridan's essay (1992a) defines the research questions on teleoperation and VR input control very well:

> "The research question here is: how do the geometric mappings of body and environmental objects, both within the perceived (virtual) environment and the true one, and relative to each other, contribute to a sense of presence, training, and performance? Control by the human operator, which requires some such mappings, may be easy, while others may be difficult. Some own-body to teleoperator/remote-environment control tasks or own-body to virtual-operator/virtual environment tasks may demand a high degree of isomorphism. In some cases there may be a need to deviate significantly from strict geometric isomorphism because of hardware limits, or constraints of the human body. At present we do not have design/operating principles for knowing what mapping or remapping from the lower set of vectors to the upper, or back again for feedback, is permissible, and which degrades performance."

In summary, a large body of literature is concerned with human factors in input control design. However, many issues listed in the beginning of this chapter have still not been agreed upon in the literature. There are multiple reasons for this dilemma. First, research is usually based upon available technologies and driven by applications relevant at the time of the research. One such limitation in the literature has been the number of degrees of freedom of the input devices. This thesis deals with 6 DOF manipulation, whereas the existing literature is concerned mostly with 1 or 2 DOF devices. A 6 DOF device can not simply be regarded as a summation of multiple lower DOF devices, due to the co-ordination required between the multiple degrees of freedom. For example, overall operating speed with 6 DOF devices may conceivably be slower than with low DOF devices. Hence, the bandwidth of a 6 DOF device may become less important while properties that facilitate co-ordination, the ability to simultaneously control all degrees of freedom, may become more important.

Secondly, the literature itself is not conclusive. Although a large body of data exists, each subset of these data may depend upon the particular experimental devices and methodology used by the researchers. The generalisability of experimental conclusions is a common open issue in human factors research.

Thirdly, the related literature is very scattered and comprehensive reviews are few and far between. It is therefore difficult even for researchers in the field to grasp a major part (not to mention the entirety) of the literature. For instance, many very important works, such as those of the Ohio school cited earlier, were overlooked in Burrows' critical paper on the state-of-the-art of research on control feel (Burrows, 1965). The later research on input devices in HCI, and research on controls for telerobotics and virtual environments also have made very little reference to the first wave of research on controls.

Finally, as Burrows (1965) pointed out, the subject of input control is much more complex than it first appears and firm conclusions are typically hard to draw. Human performance is a function of the interactions among many dimensions involved in the making of a control interface. For example, when taking certain mechanical properties of the control device as the variable of interest, subjects' performance may also change as a function of other dimensions, such as control gain, device bandwidth, learning experience, fatigue and so on. Furthermore, these variables may interact in complex ways. For instance, the optimal control gain could change with learning experience; that is, as subjects acquire more experience, the optimal control gain may be quite different from levels adopted during novice phase. Experimental studies addressing all possible combinations of different amounts of experience, different control gains, and so on therefore become too complex to conduct. However daunting this complexity is, researchers should not give up systematic study and thus fall behind technology.

1.3 Research Methodology

The research methodology in this thesis is a combination of experimentation, literature analysis and technical development of hardware and software. It is very difficult to arrive at decisive conclusions with each of the three methods alone. Experimentation is by far the best accepted method in human factors research. However, meaningful and significant experimental results depend not only on the execution of the experiment but also on the design of the experimental task and paradigm and, most importantly, on the formulation of the experimental hypotheses, which in turn relies on the theoretical analysis of the issues being investigated and the analysis of the related literature. Similarly, theoretical analysis alone is not sufficient. Due to the complex nature of human behaviour, conclusions drawn from a logical reasoning process based on first principles can hardly be accepted without experimental validation. Another important method in human interface research is creatively designing "artifacts" that are embodiments of ideas and theories (see Carroll and Kellogg, 1989) , but again one can not be sure about the validity of the resulting designs without experimentation.

This thesis takes a pragmatic approach by combining all three methods. Each chapter begins with a first-principle analysis, followed by a literature review. Interfaces that embody the issues being investigated are then designed and implemented with available state-of-the-art technologies. Experiments are then carried out for carefully designed representative tasks. Conclusions are drawn based upon rigorous statistical analysis of the experimental results. Finally, these results are discussed in relation to the literature.

Chapter 2

The Effects of Device Resistance and Transfer Function in 6 DOF Manipulation

2.1 Introduction

As discussed in Chapter 1, there are numerous existing and potential input control techniques for manipulation in 6 DOF. This chapter focuses on two of the many dimensions in 6 DOF input device design: controller resistance and transfer function. There were many reasons for choosing these two dimensions as the independent variables of the inaugural experiment. First, they cause very different user behaviours. Variations along each of these two dimensions change the way that a user performs manipulation tasks. Second, it is unknown whether and how much these behavioural differences alter users' 6 DOF manipulation performance. Third, many other design dimensions, such as desktop versus free-moving, or direct hand projection versus tool-using are related to these two dimensions. Finally, there existed a conceivable interaction between the two dimensions.

To span the entire space shown in Figure 2.1 in one experiment is not practical. This chapter treats only the four extreme cases, representing each corner of the X Y plane shown in Figure 2.1. In a counter clockwise direction around the X Y plane, the four cases are: isotonic position control, isotonic rate control, isometric rate control and isometric position control. The next two sections analyse the differences between these and review the literature on each of the two dimensions in Figure 2.1.

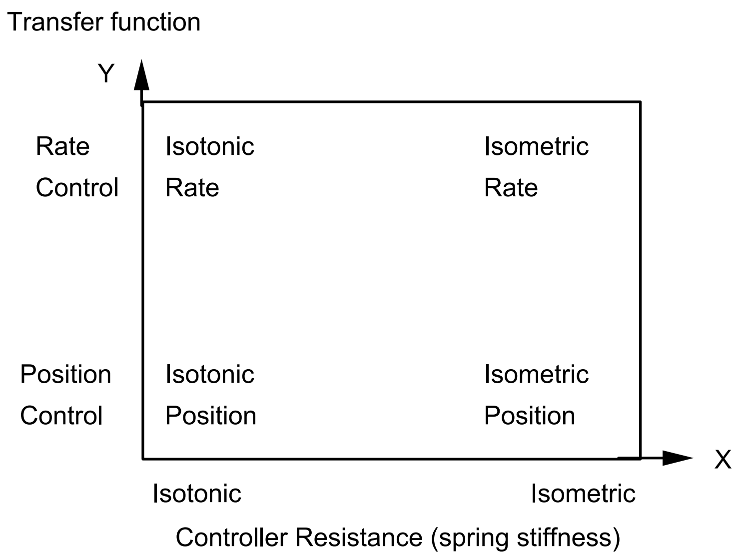

Figure 2.1 The design space of Experiment 1

2.2 Analysis and Literature on Isometric versus Isotonic Devices

2.2.1 Defining the Terms

The human limb can send and receive information through either force/torque or displacement/rotation. Correspondingly, an *isometric* device connects the human limb and machines through force/torque while an *isotonic* device does this through movement.

Isometric devices are also called pressure devices or force devices. Literally, the word isometric derives from the Greek "isos" meaning "same" or equal and "metric" meaning "measure" or in other words, constant length, or non moving. According to Webster’s Ninth New Collegiate Dictionary, isometric means "of, relating to, or being muscular contraction against resistance, without significant shortening of muscle fibres and with marked increase in muscle tone". By this definition, an isometric device is a device that senses force but does not perceptibly move.

Isotonic devices are also called displacement devices, free moving devices or unloaded devices. From the Greek, the word isotonic means equal "tonikos", or constant tension. According to Webster’s Ninth New Collegiate Dictionary, isotonic means "of, relating to, or being muscular contraction in the absence of significant resistance, with marked shortening of muscle fibres, and without great increase in muscle tone - compare *isometric*". An isotonic device should have zero or constant resistance. The mice that are used with most of today's computer systems are examples of isotonic devices.

Between the isometric (infinite resistance) and the isotonic (zero or constant resistance) are devices with varying resistance. When the device’s resistive force increases with displacement, the device is *elastic*, or spring-loaded. When resistance increases with velocity of movement, the device is *viscous*. Similarly, when the resistance increases with acceleration, it is an *inertial* device. In practice, all devices have some inertia. However, the device's inertia is usually ignored when it is relatively small compared to the inertia of the human hand or when the initial resistance is relatively small compared to other forms of resistance (e.g. elastic).

Some authors also use the term "moving device" as a short form for free moving (isotonic) device. Other authors have used it for all devices that move ("anisometric"). Anisometric devices however in fact include both free moving (isotonic) devices and elastic, viscous or inertial devices.

The peculiarities of many real world applications may favour either isometric or isotonic devices. For example, implementation with one device might simply be less costly than the other at a particular phase of technology development. Alternatively, certain work environments may not allow free hand movements due to physical workspace constraints or motion noise, such as in vehicles or aircraft. Leaving those special cases aside, however, the general performance differences between isometric and isotonic devices are of both theoretical and practical importance to human factors researchers, especially as they relate to modern multi-DOF controllers.

2.2.2 The Literature on isometric versus isotonic devices

Early research comparing isometric devices with isotonic devices, in the context of 1 or 2 DOF manual tracking, is well reviewed in Poulton (1974) . Poulton's hypothesis was that an isometric device ('pressure control' in his terminology) is in general advantageous whenever time is short, but disadvantageous when slow, accurate positioning is required. According to him, an isometric device has no travel time, which should make it quicker to control, but it can not be adjusted very accurately because it does not provide the human operator with any *displacement cues* proportional to its output. In contrast, an isotonic device or an elastic device ("moving control" in his terminology) does provide the displacement cue for accurate control .

Contradictory to Poulton's view, many other researchers, including Gibbs (1954) , Burke and Gibbs (1965) , argued that an isometric device should in fact provide stronger "proprioceptive discharge" and therefore should produce better performance for tracking tasks. Based on his experiments on manual tracking, Gibbs went on to advocate a "closed-loop" theory of motor control, since isometric controllers were believed to give more feedback to support closed-loop behaviour. Gibbs' work has been influential in the motor control literature. For example, Keele (1986) cited Gibbs and promoted "the better quality and greater rapidity of kinaesthetic information in isometric muscle contractions as opposed to isotonic contractions".

Note that both views, represented by Poulton and Gibbs respectively, emphasised the importance of feedback. What they disagreed on was which device provides stronger feedback. Gibbs believed that an isometric device should give stronger feedback due to the stronger "proprioceptive discharge" since force is being used. Poulton, on the other hand, believed that anisometric devices give stronger feedback due to the "movement cue".

Poulton (1974) compiled a comprehensive list of studies that covered works from 1943 to 1966. Out of 17 investigations that he cited, 12 strongly favoured pressure control, two slightly favoured pressure control and only three slightly favoured anisometric (isotonic or elastic) controls. These studies were conducted under various conditions, ranging from rate control to position control, from high frequency tracking to slow ramp tracking, from compensatory to pursuit displays. Other reviews, such as Boff and Lincoln (1988, section 12.421), also give similar conclusions that isometric joysticks yield better performance (e.g. smaller tracking error).

In his speculations upon reasons for this contradiction to his hypothesis, Poulton pointed out that most of the studies used the balanced treatment (within-subjects) experiment design. He has been strongly against this type of experimental design in many of his publications (Poulton, 1966, 1969, 1973, 1974, 1989) . With a within-subjects design, he argued, the actual skill transfer from one condition to another might not be symmetrical, even when subjects' exposures to the two conditions are equalised. In particular, for the case of isometric vs. isotonic control, the skill transfer might favour the isometric control. Poulton also noted that isometric devices are always spring centred while isotonic controls are not and he thus suspected that it might be the spring centring that caused the performance difference. Poulton (1974) concluded that in order to reach a definitive verdict between isometric and anisometric devices more experimental research was needed. Unfortunately, no further studies that explicitly followed Poulton's analysis have been found.

Notterman and Tufano (1980) took Gibbs' belief in the superiority of isometric kinaesthetic information and tested the so-called *inflow-outflow* debate in human motor control. Inflow theory proposes that human motor action fundamentally relies on feedback, the information flowing into the central nervous system (CNS) from the periphery. In contrast, outflow theory proposes that human motor control is primarily a result of executing motor commands flowing out of the CNS to the peripheral motor organs. On the basis of Gibbs' conclusion that isometric devices should give stronger feedback than isotonic devices, Notterman and Tufano argued that the relative human performance with an isometric device versus an isotonic device would be an indicator of the validity of inflow versus outflow theory. If superior performance were to be found with isometric devices, implying stronger feedback does improve human motor performance, inflow theory would be supported. On the other hand, if superior performance with isotonic devices were to be found, implying that human motor performance is actually better without or with less proprioceptive feedback, outflow theory would be supported. What Notterman and Tufano actually found was more complicated: (1) the isometric condition was better for randomly moving targets (0.33 Hz Gaussian noise) while the isotonic condition was better for predictably moving target (0.5 Hz sine waves). (2) the isotonic stick was better than an elastic stick at the beginning of training but worse by the end of training. They concluded that the inflow and outflow dispute was overly simplified. "Subjects profit from whatever exteroceptive and proprioceptive cues are available and efficacious and they organise their behaviour accordingly". Since Gibbs' notion of isometric superiority in proprioceptive feedback is questionable in any case, Notterman and Tufano's study did not actually have a solid basis for testing the inflow-outflow debate.

Jones and Hunter (1990) conducted a systematic study on elastic resistance ranging from isotonic to isometric in a step tracking experiment. The major findings of their study confirmed what many early researchers had believed: stiffer devices can be used to generate faster responses, as indicated by (1) shorter times to reach 50% step responses and (2) smaller human-machine closed loop system delays. However, the implications of the relative rapidity of isometric (or stiffer) devices should be interpreted very carefully. Jones and Hunter (1990) also found that as stiffness increases, subjects' accuracy tended to decrease. This means that the shorter 50% response time may not result in better performance. A "fast" system with large overshoot may have a shorter response time, but the final settling time (time to reach and remain within 2% of the final target) could be even longer than a "slower" system. Unfortunately Jones and Hunter did not report on the settling times for each condition tested.

Using a two dimensional positioning task, Mehr and Mehr (1972) did a comparative study between (1) a spring centred joystick in position control mode, (2) an isotonic joystick in rate control mode, (3) a thumb-operated isometric joystick in rate control, (4) a finger operated isometric joystick in rate control mode, and (5) a trackball. It was found that condition (4), which involved an isometric device, showed superior performance (in terms of both completion time and error) than condition (2) which employed an isotonic device. However, one can not identify the cause of the performance differences since the three factors, i.e., resistance, transfer function and body parts, were all confounded in that study.

Dunbar, Hartzell, Madison, and Remple (1983) presented a comparison study in the context of helicopter control. Conventional helicopters have three separate controllers, namely cyclic, collective, and rudder pedals, controlling pitch/roll, heave, and yaw respectively. Dunbar and colleagues compared a set of conventional separated controls with two integrated controllers, one isotonic and one isometric, in a 3 axis (pitch, yaw, roll) compensatory tracking task. Under all three levels of task difficulty (as defined by bandwidth of the signal being tracked), the RMS tracking errors with the isometric controller were found to be significantly smaller (i.e. better performance) than the RMS errors with the isotonic controller.

Dunbar and colleagues were surprised with the fact that the isotonic controller showed even worse performance than the conventional, separated controllers. The authors speculated on three causes for the results. (1) Display. A 2D, compensatory display was used in the experiment, with pitch error displayed along the y-axis, yaw error displayed along the x-axis, and roll error as angular rotation in the plane of the display. The authors believed that a compensatory display might have suited the isometric controller while a pursuit display might been more suitable for the isotonic controller. (2) Task. The tracked target (signal) had relatively high bandwidth and the isometric controller may have an inherently higher bandwidth than isotonic controllers. (3) Implementation. The gains were not necessarily set at an optimal value for every type of controller.

Ware and Slipp (1991) did an informal comparison study with a 3D navigation task. They used a 6 DOF Spaceball™ (isometric) and a 6 DOF Flying Mouse™ (isotonic) to control the velocity of the user's viewpoint. Subjects were asked to navigate through a tunnel simulated in a graphical display. They found that on average the Flying Mouse traversal times were 66% of those obtained with the Spaceball™. The subjects also did a free scene exploration task and reported their subjective evaluations. It was reported that the subjects felt that they were able to control six DOF simultaneously with the isotonic controller but not with the Spaceball, with which they could effectively control only one dimensional translation or rotation at a time. However, the users also complained of arm fatigue with prolonged use of the six DOF isotonic device, but not with the isometric controller.

To summarise, the literature on the relative advantages and disadvantages of isometric versus isotonic devices has not been conclusive. Some reports support isometric devices while others support isotonic devices. The definitive answer may depend upon dimensions of the controllers other than resistance and also on the tasks used for the experiment. Bandwidth (response speed) and extent of feedback have been the two major underlying factors that researchers have believed to account for the theoretical differences between isometric versus isotonic devices.

With regards to the response speed, it can easily be concluded that human response with an isometric device is faster than a comparable isotonic device, since no transport of limb or device is needed. However, whether humans can effectively make use of this rapid response, while maintaining acceptable accuracy, is questionable.

With regards to the feedback, in the literature just reviewed, there appears to be a tacit agreement, either explicitly or implicitly, that proprioceptive feedback from the control device is a facilitator of control actions. However, different researchers disagree on which device actually provides stronger feedback: the isotonic devices that afford movement cues or the isometric devices that afford force cues? This question should be addressed in the neuromotor and psychomotor control literature. More theoretically, whether feedback is indeed needed for manipulation control is also a relevant question. This again is in the domain of human motor control. Part of chapter 3 of this thesis will review some of the literature in human motor control relevant to input device design and address these questions.

2.3 Analysis and Literature on Position versus Rate Control

2.3.1 Theoretical Analysis of Position versus Rate Control

Position control refers to the control mechanisms by which the human operator controls object positions directly. More precisely, the transfer function from human operator to object movement in position control is a constant (i.e., a *zero order* transfer function). In contrast, *Rate control* maps human input to the *velocity* of the object movement. In other words the transfer function from human input to object movement is an integral (i.e., *first order* transfer function).

It has been conclusively demonstrated that position control and rate control are both superior to higher order control in most tracking tasks (Wickens, 1992; Poulton, 1974). Acceleration control, for example, is usually more difficult and unstable than position and rate control. This has also been verified in 6 DOF placement tasks (Massimino, Sheridan, and Roseborough, 1989) .

The performance difference between position control and rate control is less obvious. Much work has been done in comparing position control with rate control, again mostly in 1 or 2 DOF tasks. The majority of these studies concluded that rate control is inferior to position control. From an isomorphism point of view, position control can be considered more direct (more isomorphic) than rate control. It has 1-to-1 (or 1-to-K) correspondence between input and output, requiring little mental transformation in generating control actions (Figure 2.2). It therefore provides a more intuitive control mode to the human operator. Note that the directness of position control is still subject to other design considerations, including stimulus-response compatibility (Fitts and Seeger, 1953) .

Rate control, on the other hand, controls movement through velocity. As illustrated in Figure 2.2, input control patterns for rate control are more complex than for position control. In order to cause a change of state from one level to another, a pair of reversal control actions has to be given. Figure 2.2 shows only idealised control patterns. In reality, control motions will not be instantaneous but the basic feature of paired reversal inputs for rate control (speed-up, maintain a level of control and then slow down) remains.

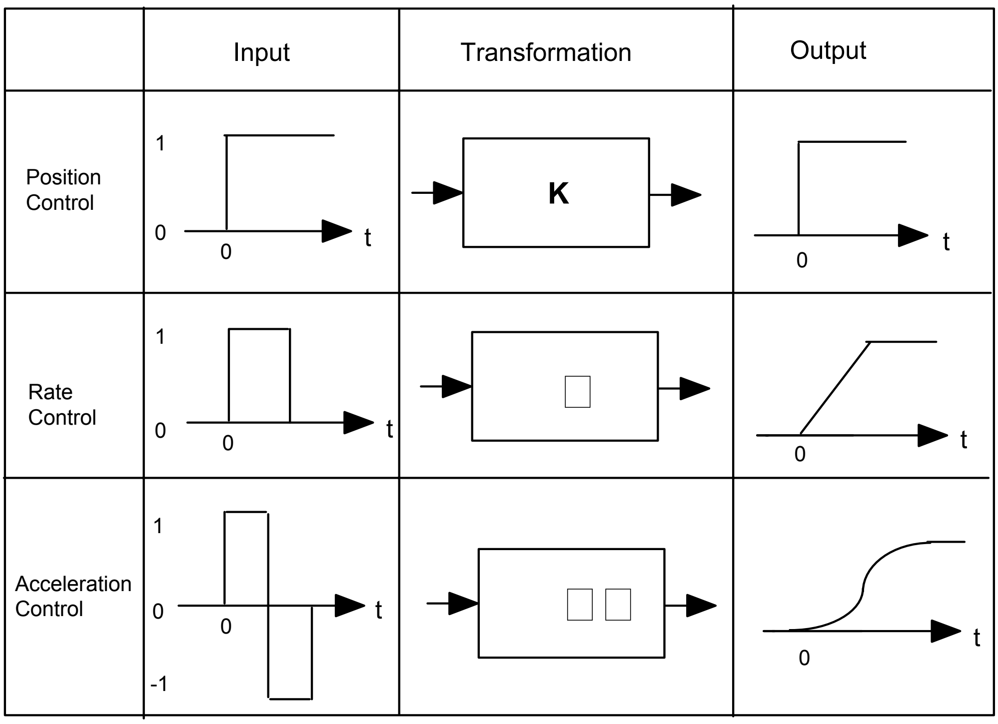

Figure 2.2 Idealised control inputs (left column) for obtaining step changes in output level (right column) for position, rate and acceleration control

Position control also has its conceivable disadvantages relative to rate control. First, it transfers all human limb movements, whether voluntary or involuntary, to the manipulation task. In contrast, the low pass filtering effect introduced by the integral function in a rate control scheme will suppress many high frequency involuntary noises. Second, by definition, rate control lets the user control the velocity of the controlled object, resulting in smoother movement. With position control, on the other hand, it is more difficult to maintain control of the velocity of the movement, increasing the likelihood of jerky motions. Third, with position control, the maximum operating range is limited unless clutching or indexing (Johnsen and Corliss, 1971) is adopted, whilst rate control has an effectively unlimited operational range (auto-indexed).

2.3.2 The Literature on Position versus Rate Control

The literature on position and rate control is more consistent than that of isometric versus isotonic devices. It is generally found that position control is superior to that of rate control. Lincoln (1953) , in one of the early studies, showed that subjects' tracking performance (time on target) with position control was substantially better than with rate control. The experiment was done with a mechanical manual tracking system described in (Lincoln and Smith, 1950) . Subjects tracked an irregularly moving target mounted on the circumference of a rotating wheel with a cursor mounted on a smaller concentric wheel driven by a hand crank.

Jagacinski, Hartzell, Ward, and Bishop (1978) studied position control versus rate control in a Fitts' law task, both with an elastic joystick. They found that, in Fitts' law modelling, the linear regression line of rate control mode had a steeper slope than that of position control mode and the two linear regression lines intersected at 4.7 bits of index of difficulty. When the index of difficulty was below 4.7 bits, position control was slower. Above 4.7 bits, rate control was slower. In other words, position control was better for higher index of difficulty (precise) tasks while rate control was good for lower index of difficulty (coarse) tasks. However, two years later in a very similar study, Jagacinski and colleagues (Jagacinski, Repperger, Moran, Ward, and Class, 1980) found that rate control consistently gave lower performance than position control at all levels of difficulty.

Driven by teleoperation applications, Kim, Tendick, Ellis, and Stark (1987) did a comprehensive comparison study of rate control versus position control with two types of tasks. One was a 2 DOF pick and place task. The second was tracking a one dimensional sinusoidal movement. They ran only two subjects in their experiments, much less than the minimum number of subjects (six) recommended for this type of research by Poulton (1974). Some of the primary researchers seemed also to have served as their own experimental subjects. Nevertheless, this was still a very comprehensive (in terms of factors investigated) and valuable comparison of rate versus position control. In their first task, position control yielded better performance than rate control, with completion time about 1.5 times faster for the position control. This was true with both an isometric joystick and an isotonic joystick, even though the magnitude of the difference varied with the joystick type, with the difference between position and rate control being larger when the joystick was isotonic. Kim et al concluded that rate control generated longer mean completion times because rate control required a pair of opposite movements to reposition the manipulator while position control required only one movement. In their second task (sinusoidal tracking), position control had consistently smaller RMS error than rate control.

In summary, the literature generally supports the conclusion that position control is superior to rate control.

2.4 Rationale and Hypotheses for New Experiment

The previous two sections analysed the pros and cons of isometric versus isotonic devices and position versus rate control and reviewed relevant literature. In relation to 6 DOF control, however, there exists a number of reasons that make it impossible to conclude anything definitively about the four control techniques that were introduced in section 2.1 merely on the basis of the analysis and review, due to the controversy in the literature and to the particular tasks that have been used in the studies. Given that most of the earlier studies have been carried out for 1 or 2 DOF tasks, this difficulty to generalise is especially true for 6 DOF control. Human manipulation of 6 DOF is much more complex and under most circumstances may be relatively slower than 1 and 2 DOF manipulation. This means that the advantages of higher response speeds that one obtains with isometric devices may not be as useful in 6 DOF tasks. Another shortfall of the literature is that most of the studies draw conclusions based on one dimension of interest at a time, while interactions among dimensions are often overlooked.

As discussed in the preceding section, rate control requires paired reversal actions in step tracking. The user has to go through a cycle of start - speedup - maintain velocity - slow down - stop. With an isotonic device, the latter half of the cycle, slow down and stop, has to be executed in such a way that when the cursor is approaching a target, the user has to return the isotonic device to its null position with correct timing. This may be very difficult to do. In pilot studies carried out by the author, it was found that it was very difficult to return precisely to the 6 DOF null position with an isotonic device. It was even more difficult to return to the null position with correct timing. When returned to the null position too early, the cursor would not hit the target (undershoot). When returned to the null position too late, the cursor would overshoot. An improvement to this problem was made by employing a clutch; once the clutch is released, the input becomes zero (null).

With an isometric device, on the other hand, the self-centring scheme will automatically bring the control action to zero once the human releases muscular tension. This means that part of the control task in rate control with isometric devices is performed automatically by the device itself.

In position control mode, the self-centring effect with isometric devices does not work as an advantage, since position control normally requires control movement in only one direction. Instead, for such cases, the user has to *overcome* the self-centring force with isometric devices to maintain position. This may not only make it very difficult for the user to maintain output accurately, but can also cause fatigue. In fact, a pilot study by the author showed that it was almost impossible to overcome the self-returning force and perform steady control with a 6 DOF isometric device. In order to have a practical isometric position control technique, a clutch had to be added to engage and disengage the control actions so that the user could do the position control in steps.

What the above analysis indicates is that one should expect an interaction between device resistance (isotonic versus isometric) and transfer function (position versus rate). Isometric devices, in other words, are more compatible with rate control and isotonic devices are more compatible with position control.

With the two compatible modes, i.e. isotonic position and isometric rate control, the former should be easier to learn, due to the presumed simpler mental processing in position control, which should simply be a 1-to-1 (or 1-to-K) mapping in forming control actions. The latter may thus impose a higher mental load on the user in forming the rate control actions, even though part of the work (returning to zero) is facilitated by the self-centring force of isometric devices.

To test these hypotheses, a 6 DOF docking experiment[*] was conducted with two modes of device resistance (isotonic vs. isometric device) and two modes of transfer function (position vs. rate control). All four of these input techniques, namely isotonic position, isotonic rate, isometric position and isometric rate, had 6 degrees of freedom.

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[*] Preliminary analyses of this experiment were published in (Zhai and Milgram, 1993a) and (Zhai, Milgram, and Drascic, 1993).

2.5 Experiment 1 Set-up

2.5.1 Experimental Platform

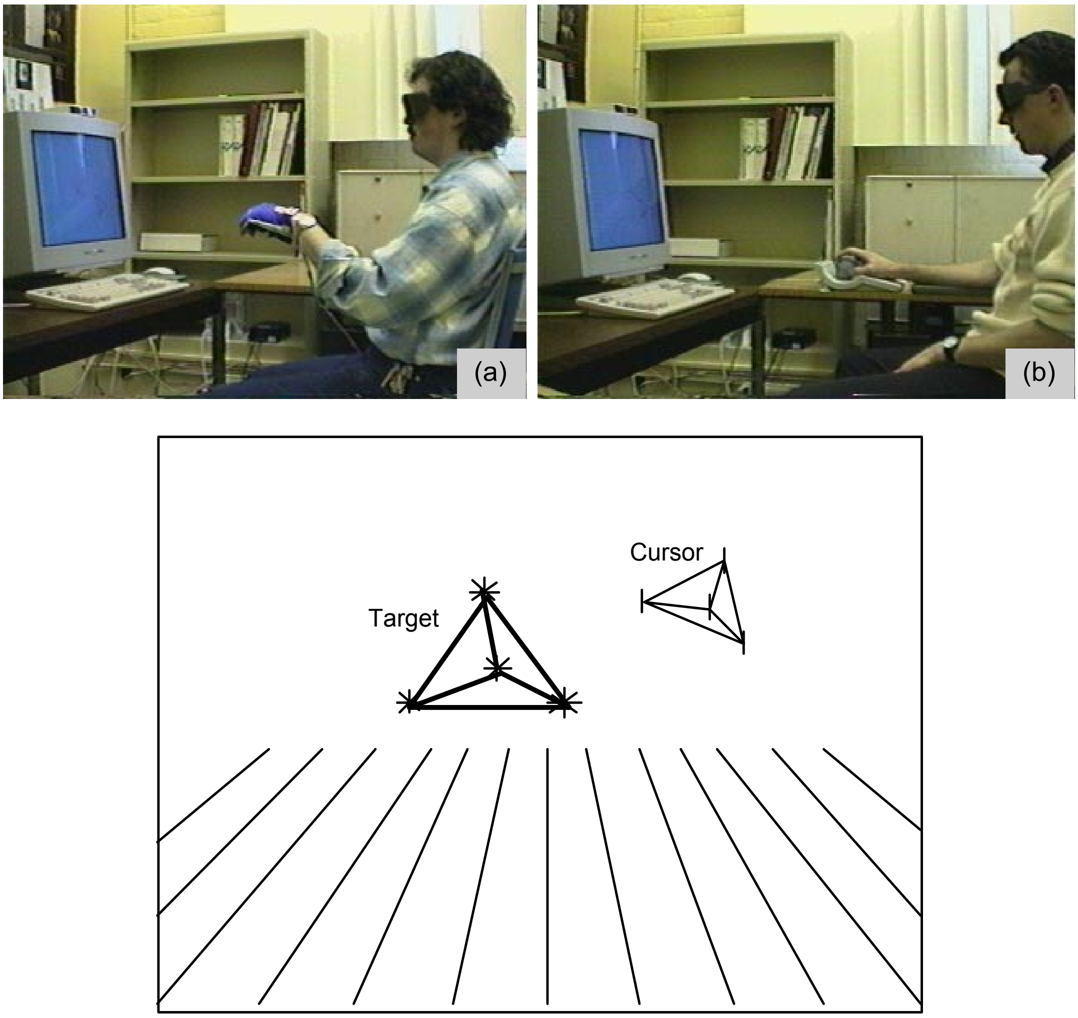
A desktop stereoscopic virtual environment, MITS (Manipulation In Three Space), was developed to conduct the experimental research in this thesis. MITS consists of a SGI IRIS 4D/310 GTX graphics workstation, a Spaceball™, an Ascension Bird™, CrystalEyes™ stereoscopic glasses, several input controllers and a software system developed in C and GL by the author. MITS allows the user to perform a variety of 3D object manipulation tasks in 6 DOF with various display options (e.g. monoscopic or stereoscopic) and control modes. Unless otherwise specified, the default display update rate was 15 Hz.

The origin of the {x, y, z} co-ordinates of the MITS virtual environment was located at the centre of the computer screen surface, with the positive x axis pointing to the right, the y axis pointing upwards and the z axis pointing towards the viewer. All objects were drawn using perspective projection. MITS also provided feedback and instructions to the subjects, regulated the procedures of the experiments and logged experimental data. This ensured that minimum interference was needed from the experimenter when collecting subjects' data with MITS.

2.5.2 Experimental Task - 6 DOF Docking

Figure 2.3 illustrates the 6 DOF docking task used in the experiment. The aim in designing this task was to incorporate all 6 degrees of freedom in 3D object manipulation and yet be *simple* enough to be generalisable to various applications in 3D graphics, virtual environments and telerobotics. In the experiment, subjects were asked to move a 3D cursor as quickly as possible to align it with a 3D target. The cursor and the target were two tetrahedra of equal size. The tetrahedra edges and vertex markers (bars and spherical stars) were coloured so that there was only one correct match in orientation. The markers superimposed on each corner of the tetrahedra served multiple purposes. The stars on the target tetrahedron indicated the acceptable target tolerance for each vertex. The two types of markers (stars and bars) served also to differentiate the target from the cursor, as seen in Figure 2.3(c).

The target stayed at the centre of the screen throughout the experiment. At the beginning of each trial, the cursor appeared in one of four locations/orientations in the periphery, according to a random order within a block of 4 trials. During the trial, whenever a corner of the cursor entered into the tolerance volume surrounding the *corresponding* corner of the target, the star on that corner changed its colour as an indication of capture. If all four corresponding corners stayed concurrently matched for 0.8 seconds, the trial was deemed completed. At the end of each trial, the trial completion time was printed on the screen. The beginning of each trial was signalled with a long auditory beep and the end of each trial was signalled with a short beep.



(c)

Figure 2.3 Experiment 1 set-up* .

(a) with isotonic device (b) with isometric device (c) The displayed task

2.5.3 Display

Since the objective of this experiment was to evaluate 6-DOF input interfaces, the emphasis in designing the display was to provide the largest possible number of 3D spatial cues. This

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* To conform with experiment ethics, photos in this thesis illustrating experimental set-up were not taken with real participating subjects. Note also the experimental room was darkened during the experiment.

* To conform with experiment ethics, photos in this thesis illustrating experimental set-up were not taken with real participating subjects. Note also the experimental room was darkened during the experiment.

was to ensure that the task performance was driven predominantly by differences in input controller conditions rather than by difficulties in perceiving depth information (visual feedback). A 120 Hz sequential switching stereoscopic display was employed, which has been shown to be a necessary feature for this kind of experiment, because without stereopsis, much more orientation ambiguity would be perceived by the subjects. To enhance the 3D effect, perspective projection and interposition cues were also implemented. The tetrahedra were drawn in wireframe so that all edges and corners of the objects could be perceived simultaneously. Subjects were asked to sit on a chair approximately 60 cm away from the computer screen for all experimental conditions.

2.5.4 Subjects

Eight paid volunteer subjects completed the experiment. All subjects were screened with a Bausch and Lomb Orthorater. Two of the original ten applicants were rejected, one for having poor stereopsis and one for having poor (corrected) near vision. All of the eight accepted subjects were (incidentally) male and right handed, as determined by the Edinburgh inventory (Oldfield, 1971). Four of them were undergraduate engineering students, three were graduate engineering students, and one was a software engineer. All of the subjects had experience with a computer mouse but none had previous experience with 6 DOF input devices. All subjects were asked to use their dominant hand to manipulate the input devices. Subjects' ages ranged from 20 to 40.

2.5.5 Experimental Design and Procedure

Each subject participated in four separate experimental sessions ranging over four consecutive days, one session per day. Each session involved only one of the four control techniques and was divided into four phases (Figure 2.4). Each phase comprised 10 minutes of training, followed by 12 trials of data collection. Each training phase consisted of demonstrations and suggestions by the experimenter, combined with practice trials. The data from the 12 trials were grouped into 3 blocks of 4 trials, each block comprising 4 different randomly shuffled starting locations for the manipulated cursor. After every set of 12 trials, the mean completion time was shown to the subject.

A within-subjects design was used in the experiment. In order to minimise fatigue and skill transfer (either positive or negative) from one technique to another (Poulton, 1974), three preventive measures were taken. First, different manipulation schemes were tested on

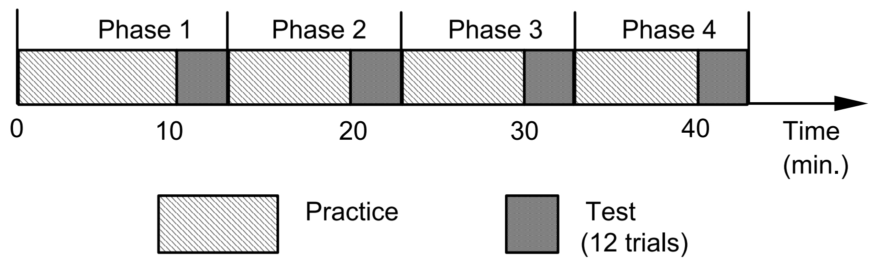

Figure 2.4 Experiment 1 procedure for each experimental session

different days, so that different conditions for any one subject were at least 12 hours apart. Second, the 10 minute practice and training session preceding the first set of data collection trials served as a buffer to reduce transfer from the session of the previous day. Third, the order of the four conditions being tested was counterbalanced over the eight subjects by using two Latin square patterns, which resulted in every control interface being presented an equal number of times as the first, second, third or fourth condition.

A subjective evaluation of each condition was collected after each subject completed all four conditions.

2.6 Descriptions of the Four Techniques in Experiment 1

This section provides brief descriptions of the four input techniques used in Experiment 1. More formal and detailed descriptions of these input schemes are provided in Appendix 1.

2.6.1 Isotonic Position Control

The physical interface for the isotonic position control condition in Experiment 1 was the MITS glove, designed and built by the author. An Ascension Bird™ magnetic tracker was attached to the centre of the palm of the glove, the rotational centre of the hand. Also mounted on the palm of the glove was a clutch with a T-bar. The clutch could easily be pressed down by closing the fingers (Figure 2.5).

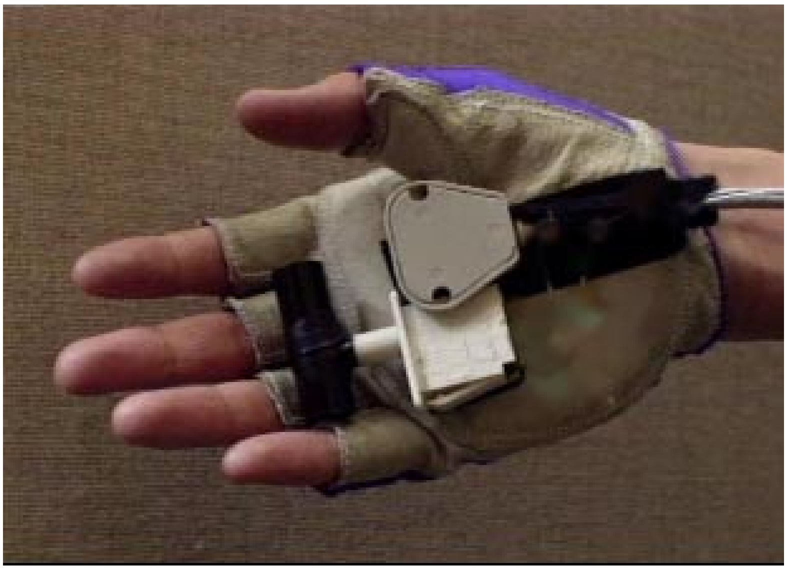

Figure 2.5 The MITS Glove

While using the isotonic position control technique, the user operated the input device in one of two interaction states. When the user's hand was open, the hand movement did not have any effect on the cursor. When the user's hand was closed (by pressing the clutch down), the controller became engaged and the manipulated object would be slaved to the hand motion. The operation of the isotonic position control technique is described more formally and in more detail in section A1.1 of Appendix 1.

2.6.2 Isotonic Rate Control

The isotonic rate control was similar to the isotonic position control (two states), but the cursor velocity, rather than the cursor position, was proportional to the hand displacement. The more a user's hand moved after closing the clutch, the faster the cursor moved. Objects stopped instantly after the clutch was released (see A1.2 in Appendix 1 for detail).

2.6.3 Isometric Position Control

The 6 DOF isometric sensor used in the experiment was a Spaceball™ (Figure 2.6), manufactured by Spaceball Technology Inc., Boston, MA.

Figure 2.6 The Spaceball™

With the isometric position control scheme, the user also operated in one of two interaction states. The button on the Spaceball (situated beneath the membrane of ball at the front) was employed to switch between the two states of operation. When the button was pressed, the controller became engaged and the cursor's movement was proportional to the force/torque that the user applied to the ball. Once the button was released, the cursor remained where it was. The user might have to switch between the two states several times in order to move the cursor over large distance without exerting excessive force/torque. The operation of the isometric position control technique is described more formally and in more detail in section A1.3 of Appendix 1.

2.6.4 Isometric Rate Control

The isometric rate control was a single state scheme. The object's velocity was proportional to the force/torque applied on the Spaceball (see A1.4 in Appendix 1 for detail).

2.7 Optimisation of the Input Techniques

There is a basic dilemma in conducting interface comparisons. On the one hand, it is impractical to do an absolutely fair comparison across different input interfaces. One common pitfall is "comparing apples with oranges", due to the multi-dimensional properties of interfaces. That is, one interface might be good with respect to one aspect of performance, such as speed, while another interface could be more suitable with regard to another aspect, such as control precision. On the other hand, comparison is often fundamental to our understanding of the operation and performance of various interfaces in relation to each other. It is also a practical concern to have quantitative data about how interfaces differ from each other so that designers can decide what device to use for specific applications.

Facing this dilemma, one should keep two things in mind when conducting comparative research. First, the goal of the research should not be limited to a narrow minded comparison across interfaces, but rather should be geared towards gaining a deeper and better understanding of the behaviour and performance of the human machine system, by comparatively evaluating different input control schemes. Second, a great deal of attention should be paid to ensuring that all of the interfaces in the experiment operate under similar conditions*. Optimising the control gain of each control technique is one such aspect.

The effect of control sensitivity (or gain) has attracted the attention of many researchers (e.g. Arnaut and Greenstein, 1990; Buck, 1980; Jellinek and Card, 1990) but is still not completely understood. The most common view is that performance is best at moderate gain levels. Very high gains give poor results because of the difficulty in making precise movement, even though initial gross positioning is more rapid. Very low gains allow precise movement and therefore more rapid fine positioning, but require a longer initial gross positioning time. The trade-off between initial gross positioning versus final fine adjustment typically results in a U shape gain-performance (completion time/error) curve with best performance at a moderate gain level. This view has been supported both by performance

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* It should be pointed out that one can do only an "approximate optimisation" of each interface. Strictly speaking, optimal performance is a function of many parameters of an interface, with respect to the task used in evaluation *and* with respect to each individual subject. Furthermore, the optimal settings of the parameters for each individual may themselves change as the individual gains more experience. Optimising multiple variables with each subject as his/her experience progresses is clearly too complex for human experimentation, although this could be an interesting topic for adaptive interfaces research in its own right. In the literature, the parameters of an input device are typically "subjectively selected". In this thesis, parameters were set through systematic search during pilot experiments. In most cases, the pilot subject was the author himself, an "expert subject" who was most familiar with the task and the interfaces. In order to confirm the settings for Experiment 3, a novice subject was recruited as the second pilot.

measurements from experiments, such as (Gibbs, 1962), and by subjective ratings, such as Hess (1973).

This view has been challenged by many other researchers, however. Hammerton (1981) argued that because a joystick can have only limited travel, there is a downward limit to control gain. He asserted that for all controls of joystick type, the lowest possible gain is the best. In an effort to test if power mice - i.e., computer mice that have variable control gain - improve user performance, Jellinek and Card (1990) concluded that user performance should be independent of mouse gain. In one of their experiments, Jellinek and Card (1990) did find that performance declined as the mouse gain increased from the standard value (1:2), but they argued that this was an artifact of mouse resolution limitation, rather than a result of human characteristics. For the gain value that was smaller than the standard, performance also declined but this was because subjects had to lift and reposition the mouse more frequently, as Jellinek and Card suggested. Jellinek and Card further argued that gain *should not* affect user's performance, because that would violate Fitts' law. This argument is difficult to accept, however, because Fitts' law was not meant to address variables other than movement amplitude and precision. Finally, in a recent study, MacKenzie and Riddersma (1994) found that although subjects had the shortest mean movement times with a medium mouse gain (approximately 1:5, in comparisons with a low gain of 1:2 and a high gain of 1:7), they also had the highest mean error rates in a Fitts' law task. MacKenzie (1995) concluded that the claim that an optimal control gain exists is weak at the best.

In the present experiment, it was found that performance with each input control technique was indeed a function of control gain or sensitivity. The relationship between task completion time and sensitivity appeared as a U-shaped function with sensitivity plotted on a logarithmic scale. Taking isometric rate control as an example, Figure 2.7 shows the experimenter's mean task completion times (over 15 trials) for different sensitivity settings. The horizontal axis was normalised by the lowest control gain tested. Note that there was a wide range of settings at the bottom of the U shape, for which performance differences were relatively small. The control gain eventually used in the experiment for the isometric rate condition was set at the value corresponding to the bottom of the U shape. The gains for the other three experimental conditions were optimised through similar systematic parameter searching. In the case of the isotonic position mode, the optimal control gain was 1. At this value, the hand motions and object motions had a one to one correspondence, thus taking the maximal advantage of the directness of isotonic position control. This is particularly important for rotation control.

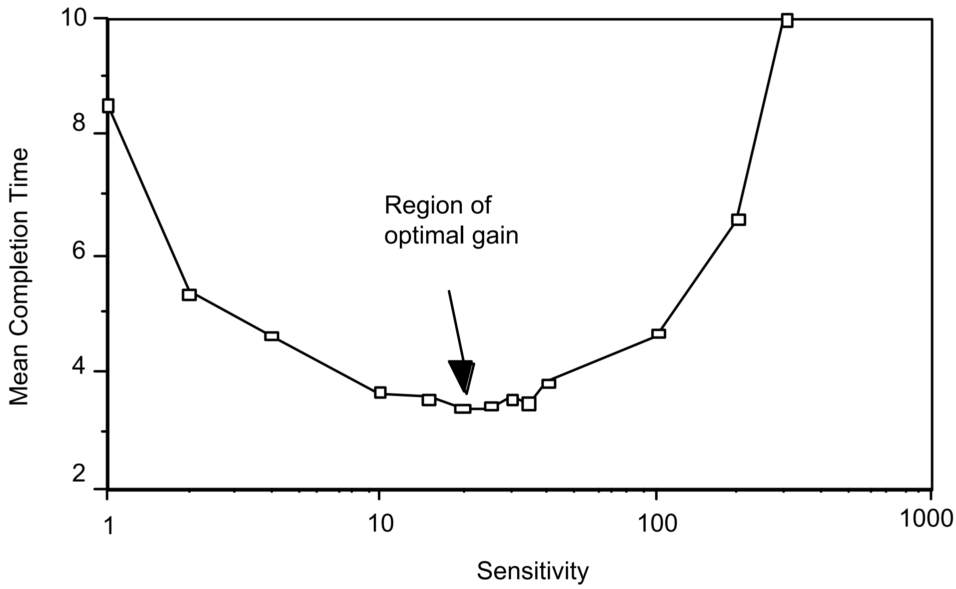


Figure 2.7 Optimisation of the sensitivity of the isometric rate control

Judging from above pilot data and the literature, a tentative conclusion about control gain is as follows. Performance is indeed a function of control gain and in general follows a U shape curve when the gain is plotted on a logarithmic scale. This is obviously true for the extreme cases. For a very low gain, such as 1: 0.01 for a position control system, the user needs a longer time to reach the target. For a very high gain, such as 1:100, precise positioning will be difficult. Performance improves as the gain shifts to more moderate values. However, for a large range (many folds) of moderate gain values, including those used by MacKenzie and Riddersma (1994) , user's performance change is relatively small.

Another important dimension of optimisation is to create appropriate non-linearities in the input devices to accommodate the human sensorimotor system. Orlansky (1949) speculated various non-linearities suitable for controls in aircraft. Rutledge and Selker (1990) reported a study of non-linear transfer functions for a miniature isometric joystick mounted between the G and H keys of a keyboard for portable computers. They found that a "two-plateau" non-linear transfer function to be their "current favourite". Similar effort was also spent in optimising the Spaceball (personal communication with Spaceball Technologies Inc.) and the chosen non-linear mappings of the Spaceball were:

for translation outputs:

$x = F^{2.75}$, F is the force applied to the Spaceball;

for rotation outputs:

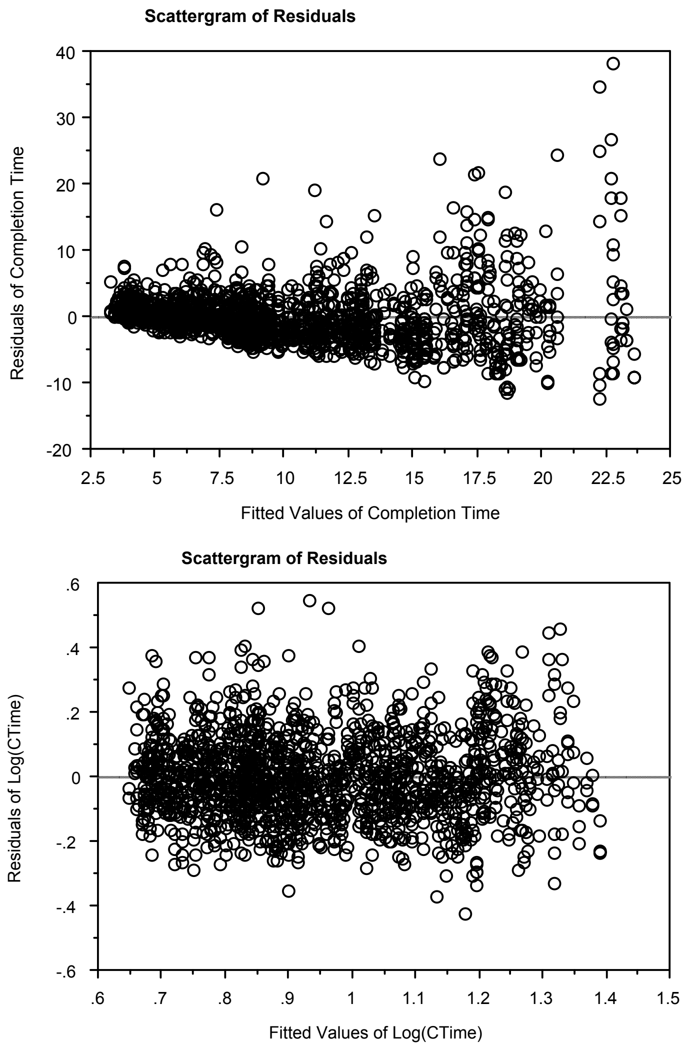
$\theta = T^{2.2}$, T is the torque applied to the Spaceball.

The author also experimented with various non-linear mapping functions for the 6 DOF isotonic device (the bird), including a "power-bird" mode (making the gain of the bird proportional to the speed, as in a "power mouse"). None of these non-linear mappings, however, appeared to be advantageous. Linear mappings were therefore kept for the isotonic conditions.

2.8 Experiment 1 Results

2.8.1 Data Transformation

In the following data analysis, statistical model residuals were first analysed and it was found that the residual distribution was skewed towards lower scores (Figure 2.8a). This is typical when completion time is used as performance measure. Log transformation was then imposed, in order to meet the residual distribution requirement for analysis of variance (ANOVA) (Howell, 1992) . Figure 2.8 (a) and (b) show the residual distribution before and after the log transformation. The same procedure and treatment were carried out for the subsequent experiments in the following chapters; however, for the sake of brevity, the residual plots are not shown further. For ease of comprehension, all figures that illustrate results will still be drawn according to the original, untransformed scale.



(a)

(b)

Figure 2.8 Residual distributions before (a) and after (b) log transformation in Experiment 1 data.

2.8.2 General Results

Figure 2.9 displays the means and standard errors of each control technique over the four phases of the experiment. The detailed results of a repeated measure analysis of the entire data set are summarised in Table A3.1.1 in Appendix 3. The performance difference caused by different techniques was statistically significant: $F(3, 21) = 40.18$, $P < 0.0001$. In addition, subjects' performances improved significantly with practice: $F(3, 21) = 54.6$, $P < 0.0001$. No other independent variable or interactions between the variables were statistically significant ($p>0.05$).

The ranks of the four techniques, as measured by average completion time over all four phases, was as follows: isotonic position (6.71 sec), isometric rate (6.97 sec), isotonic rate (10.55 sec), and isometric position (16.93 sec). Statistical comparisons between the four techniques, as summarised in Table A3.1.2 in Appendix 3, shows that the performance differences between every pair of techniques were statistically significant, except the difference between the isotonic position and the isometric rate mode.

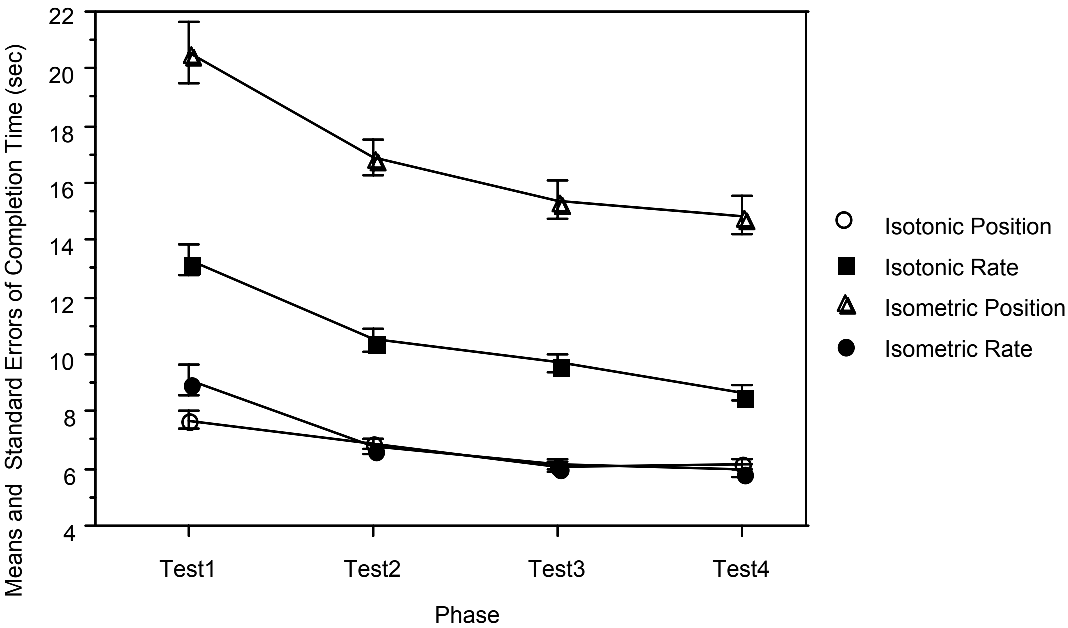


Figure 2.9 General results of Experiment 1

2.8.3 Performance in Early Experiment Phase

Whereas the preceding section analysed the overall performances of the four techniques over all four phases of the experiment, the present section focuses on the initial test. Repeated measure variance analysis (Table A3.1.3 in Appendix 3) showed that the major conclusion drawn from Test 1 was the same as that drawn from the overall data: Technique resulted in a significant performance difference. Pairwise comparisons between conditions (Table A3.1.4 in Appendix 3) showed that all pairs were significantly different from each other, except the isotonic position versus the isometric rate (See also Figure 2.9). The mean values of these two techniques were 7.68 and 9.07 seconds respectively, i.e. the isotonic position mode produced shorter mean completion times than the isometric rate control in phase I (after 10 minutes of practice). However, this difference was not statistically significant ($F(1,7) = 0.654$, $p = 0.43$), possibly due to the relatively small number of degrees of freedom in the repeated measure analysis. Repeated measure analysis is a conservative test, in which subject and effect interactions are used as error terms.

When a full factorial analysis was used, the difference between the isotonic position and the isometric rate mode was detected as statistically significant (Fisher's Protected LSD post-hoc test: $p < 0.01$). Full factorial analysis, using Subjects as one of the factors and using model residual as error term, is much more sensitive. The implications of full factorial analysis and repeated measure analysis are different, however. Factorial analysis computes the probability that the differences between means are caused by chance, as reflected by model "residual" after removing all the variance caused by all other independent variables and their interactions, including subjects (individual differences). Repeated measure analysis, on the other hand, does not remove all the variance caused by individual differences and other factors from its error term. The results of repeated measure analysis are therefore more generalisable to larger populations of users.

2.8.4 Performance in Final Phase of Experiment

Figure 2.10 shows the results for Test 4, which took place after the subjects had had 40 minutes of intensive practice. Repeated measure analysis of variance (Table A3.1.5 in Appendix 3) showed that technique was still a statistically significant factor. Pairwise comparison showed that the difference between every pair of techniques was significant, except the isotonic position vs. the isometric rate (Table A3.1.6 in Appendix 3).

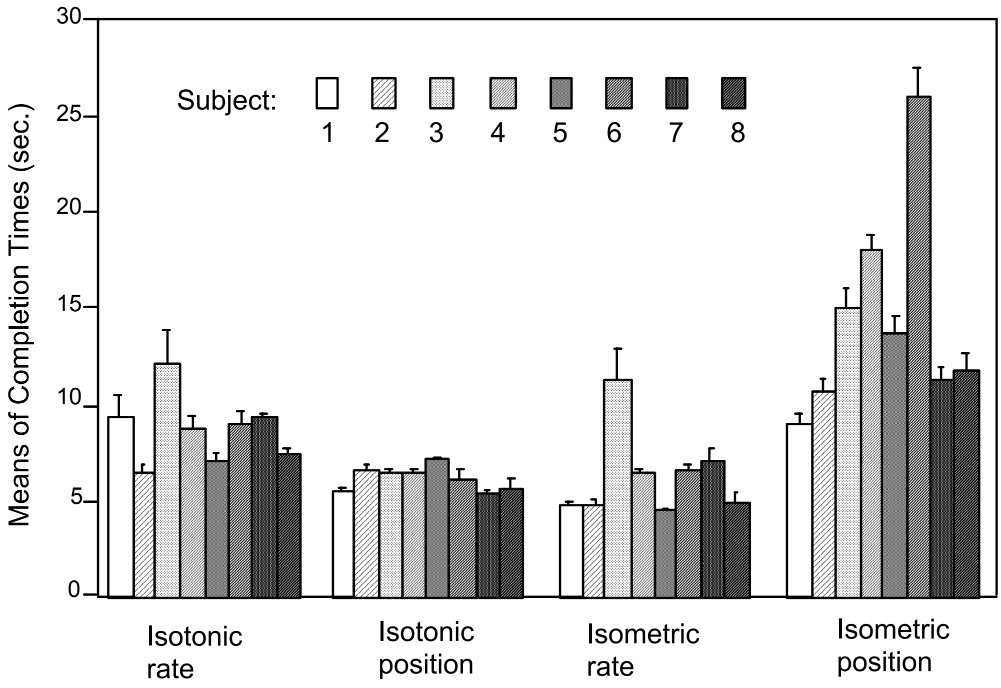


Figure 2.10 Individual subject results for Test 4 of Experiment 1

2.8.5 Ease of Use

After the entire experiment was over, subjects were asked to rate each of the techniques according to "Ease of Use", "Fatigue" and "Overall Preference"*. Figure 2.11 summarises the subjective ratings on ease of use. The isotonic position mode and the isometric rate mode received higher average ratings than the other two modes. Technique caused a statistically significant difference on these ratings: $F(3, 21) = 12.9$, $P < 0.0001$. Fisher's Protected LSD

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* Subjective data were collected after each of the experiments in this thesis. They were intended to be supplementary to performance measures. The reliability of statistical results (e.g. ANOVA) from subjective data is debatable, since subjective rating scales are not necessarily equal interval (in some cases they are merely ordinal). ANOVA analyses were, nonetheless, applied to the subjective rating data in this thesis, based on the following considerations. First, some researchers (e.g. Hess, 1973) found that subjects could accurately transpose their impressions of a task directly to a linear numerical index. In this thesis, adjectival scales (e.g. very difficult, difficult, OK, easy, very easy) were bound with linear numerical values, in an attempt to create such a linear index. Second, ANOVA analysis is very robust against violations of its basic assumptions (Howell, 1992). Non-linear transformations are often deliberately applied to raw data before ANOVA analysis. In such cases, if the data are originally equal interval, they are transformed into an non-linear (non-interval) scale by this operation. The essence of ANOVA analysis is to examine the consistencies (or variances) in data, not the absolute values per se. Third, all subjective rating raw data are directly plotted in the thesis for visual inspection. Statistical analyses were only meant to be a quantitative verification.

post-hoc test (Table A3.1.7 in Appendix 3) showed that the difference between every pair of techniques was significant, except the isotonic position and the isometric rate mode. Note that the results were based on data collected after 40 minutes of practice with each mode. It was observed that users usually found isometric rate control more difficult to use than isotonic position control at their very initial stage of experiment.

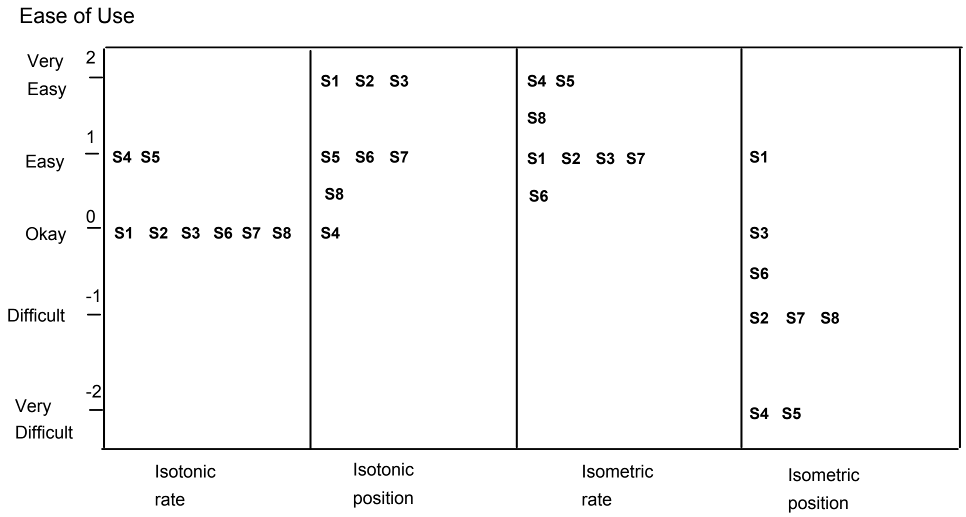


Figure 2.11 Subjective ratings of ease of use in Experiment 1

2.8.6 Fatigue

Figure 2.12 summarises the subjective ratings of fatigue. Technique caused a statistically significant difference on the ratings on fatigue: F(3, 21) = 10.9, P = 0.0002. Fisher's Protected LSD post-hoc test (Table A3.1.8, Appendix 3) showed that the differences between every

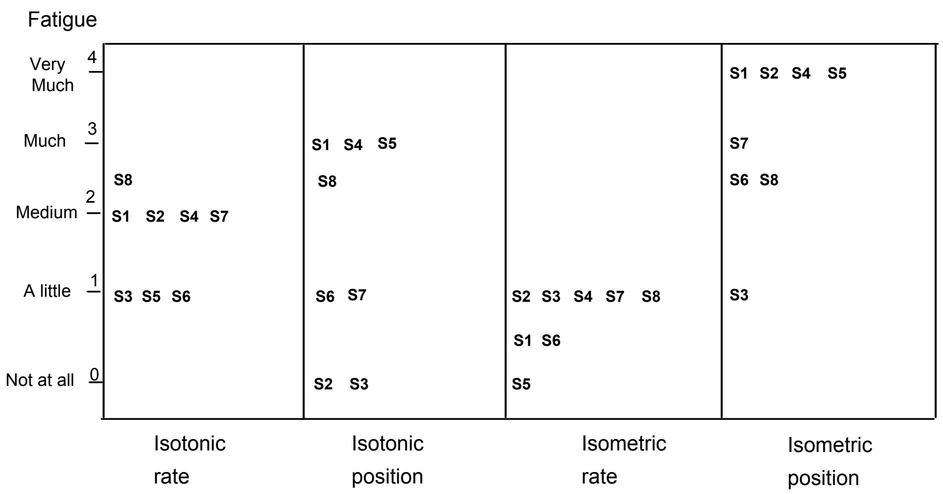


Figure 2.12 Subjective ratings of fatigue in Experiment 1

pair of techniques were significant, except the isotonic position and the isotonic rate mode.

The isometric position technique was felt to be the most fatiguing and the isometric rate technique the least fatiguing. It is important to note that the isotonic position technique was significantly more fatiguing than the isometric rate technique, even though it produced scores similar to the isometric rate control on some other measures (e.g. ease of use and time performance). This is due to the fact that with isotonic sensing users have to perform unsupported hand movements.

2.8.7 Subjective Preference

Overall, users preferred the isotonic position control and the isometric rate to the other two techniques. A significant difference in preference ratings existed between techniques: $F(3, 21) = 19.3$, $P < 0.0001$. Fisher's Protected LSD post-hoc test (Table A3.1.9, Appendix 3) showed that the differences between every pair of techniques were significant, except for the isotonic position versus isometric rate mode comparison. Users' overall subjective preferences were very similar to the result from time performance measurement .

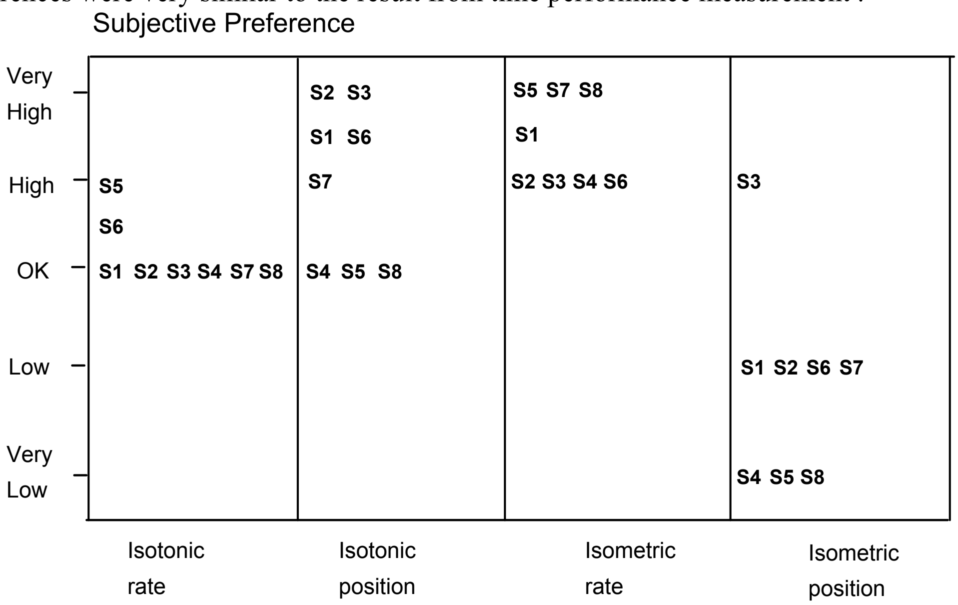


Figure 2.13 Overall subjective preference in Experiment 1

2.8.8 Interaction between Resistance and Transfer Function

Figure 2.14 illustrates one of the most important results from this experiment. A strong interaction was found between the transfer function and the resistance of the control techniques by a repeated measure variance analysis (Table A3.1.10, Appendix 3). Even though both resistance ($F(1,7) = 8.6$, $p < 0.05$) and transfer function ($F(1,7) = 12.8$ $p < 0.01$) significantly affected completion time, the interaction between these two variables was much more significant ($F(1,7) = 182.4$, $P < 0.0001$), suggesting that simply to compare resistance (isometric versus isotonic) or transfer function (position versus rate control), as was found in some of the literature reviewed, is misleading. This important conclusion is illustrated further in Figure 2.15, which is a revised version of Figure 2.14 plotted in 3D.

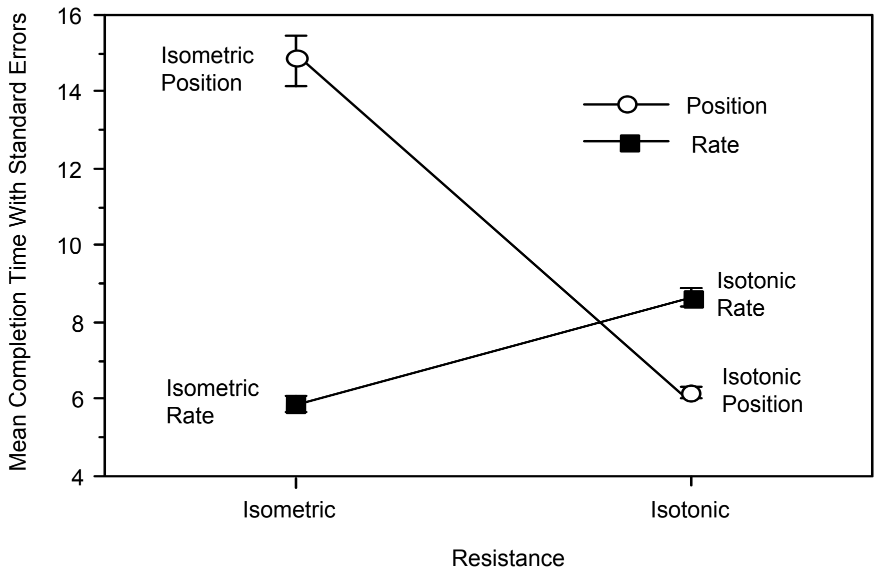


Figure 2.14 Interaction between resistance and transfer function (2D plot)

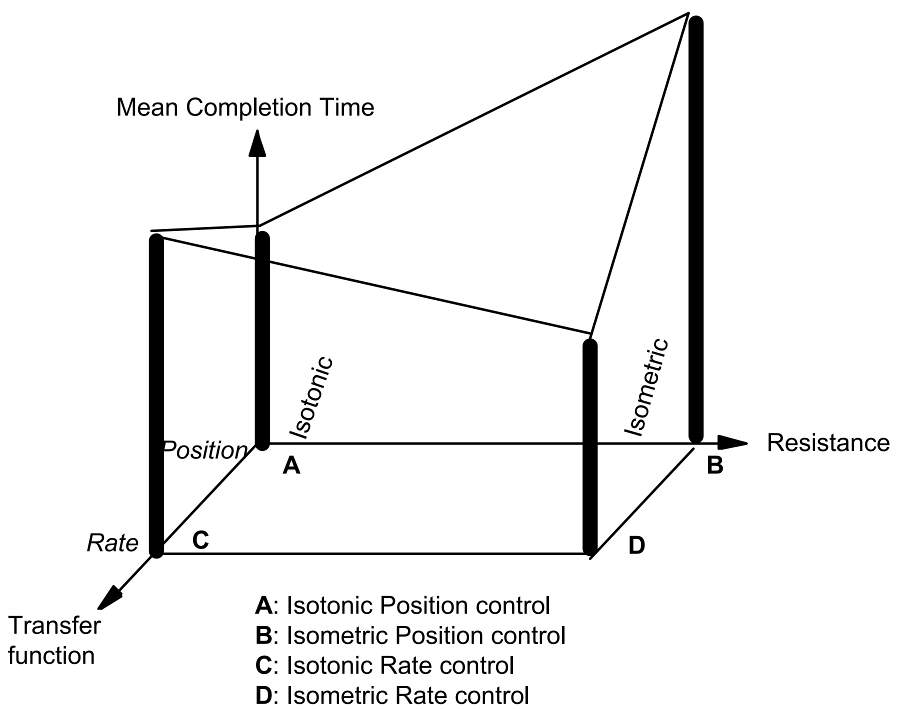


Figure 2.15 Interaction pattern between resistance and transfer function (3D plot)

2.9 Conclusions and Discussions

It is difficult to compare the current study with previous ones in the literature, since earlier studies of this kind have all been done in 1 or 2 DOF, instead of for 6 DOF tasks. One also has to be cautious about the validity of generalising the results of experiments on input control, including the present one, since they are usually carried out with specific devices and for one specific task. Nonetheless, this section summarises the results from this experiment and relates them to the previous literature.

The experiment has largely confirmed the hypotheses laid out in section 2.4. The strongest conclusion we can draw from the data is the interaction between device resistance and transfer function. The isotonic device performed better than the isometric device in position control mode. This ranking of isometric and isotonic devices was reversed in rate control. Hence, we draw the following conclusion:

Conclusion 2.1. The compatibility principle in input technique design: for certain types of physical devices, the transfer function has to be designed accordingly. In particular, for isometric devices, rate control is more compatible. For isotonic devices, position control is more compatible.

Some of the controversy in the literature can be explained in part by the interaction pattern found in this study. Taking Gibbs' studies as an example, Gibbs (1954) strongly advocated the superiority of isometric control, which produced consistently smaller tracking errors than did isotonic control across tests spanning 6 days (15 minutes each day). In that study *rate* control was used as the transfer function in both isotonic and isometric conditions. Eleven years later, Burke and Gibbs (1965) repeated Gibbs' (1954) experiment in position control mode. They made the conclusion that the isometric device was still better than the isotonic device even in position control mode. However, this later conclusion was not as strong as the original conclusion with respect to rate control mode made in (Gibbs 1954) . As the authors claimed, "the relative superiority of pressure control was approximately 10 per cent in the present (position control) study, as compared with values of approximately 25 per cent to 50 per cent established by Gibbs (1954) (rate control)".

In checking the details of Burke and Gibbs (1965) , it is questionable whether the conclusion of 10 per cent was reliable. Burke and Gibbs (1965) had a within-subjects design with two groups of 5 subjects. Group A tested with an isotonic stick in the first five days (15 to 30 trials per day) and Group B tested with an isometric stick in the first five days. Tracking errors with Group A (with isotonic position) were consistently smaller than Group B (with isometric position) in the five days. On day 6, the two groups switched devices and Group A (now with the isometric device) had better performance. On Day 10, the two groups once again switched devices and this time Group A (now with isotonic device again) had smaller tracking errors. Judging from their plot (Figure 3 in Burke and Gibbs, 1965), had the authors counted the performance difference only in last day, or the means of each device across all days, the isotonic device would have "won". However, the authors decided to draw their conclusion only from the data across Day 9 and Day 10, which supported their hypothesis of isometric superiority, even in position control mode.

Taking Lincoln (1953) as another example, the work is a classic study in demonstrating that position control is better than rate control, as cited in Poulton (1974) . But in reviewing the study with the interaction pattern in mind, it is found that Lincoln used only an isotonic controller in his experiment. With that controller, position control was substantially better than rate control. Clearly, these results might have been different had an isometric controller been used.

The interaction between device resistance and transfer function can also be found by examining the list of experiments reviewed in Poulton (1974, Table 15.3, page 308-309). Eight experiments on the list used rate control, and all supported isometric superiority. Of the two experiments that used position control, one made no conclusion, and one, which was Burke and Gibbs (1965) , questionably supported isometric superiority. Poulton also surmised that Burke and Gibbs (1965) should have supported isotonic superiority, but from his methodological asymmetrical skill transfer point of view, rather than from the present interaction point of view.

The interaction pattern can also be seen in the data from Kim et al. (1987) . In rate control mode, the isometric joystick performed much better than the isotonic joystick. In position control mode, the isometric joystick performed only slightly worse than the isotonic joystick. Unfortunately one can not draw a firm conclusion from their data, since only two subjects were tested.

There are also exceptions to the interaction pattern found in the current study. For example, Dunbar, et al. (1983) found that an isometric 3 DOF controller produced lower RMS errors than an isotonic controller, even when position control mode was used.

The differences between the two compatible modes in this study, namely the isotonic position control and the isometric rate control, can be summarised as follows.

Conclusion 2.2 Isotonic position control is more intuitive than isometric rate control

Isotonic position control is intuitive and therefore imposes lower mental load on the user. The user can form control actions more directly with position control than with rate control and therefore it is easier to learn. However, the advantage of isotonic position control due to intuitiveness, in comparison with isometric rate control, decreases as practice progresses.

Conclusion 2.3. Isotonic position control is more fatiguing than isometric rate control

It is difficult to provide support to the users' hand without changing the characteristics of 6 DOF isotonic position control. Prolonged (in tens of minutes) unsupported hand movement is bound to causes some fatigue. In contrast, isometric rate control does not move, so the user can rest her hand on a support stand (or desktop).

Conclusion 2.4. Isometric rate control produces smoother control trajectories.

By definition, with rate control the user has control of the velocity of the controlled object. Since the integrator in the rate control transfer function has a low pass filtering effect, the trajectories generated by isometric rate control therefore tend to be smoother than trajectories generated by isotonic position control. In many applications, this is particularly important. For instance, when controlling the entire graphics world, or moving the virtual camera in 3D graphics, we need the control motion to be as smooth as possible. Many VR demos suffer from jerky motion on displays, as a result of the combination of low update rate, noise and position control. Smooth motion is also important in telerobotic tasks.

Another advantage related to rate control is the fact that control motions are not restricted by hand anatomy. The user can perform an unlimited range of 6 DOF motions with rate control. With position control, some motions are limited by the hand joint angles, even though this can be partially solved by indexing (clutching).

Given the desirability of rate control in many respects, it is therefore important to look into ways of improving isometric rate control. As discussed earlier, the key to rate control is the self centring effect in isometric control. In the following chapter we compare performance of the same isometric rate control device with another device that is self-centring: a device which provides elastic resistance feedback.

Chapter 3

Elastic versus Isometric Rate Control: The Effects of Proprioception, Control Feel and Learning

3.1 Analyses and Literature on Elastic versus Isometric Devices

3.1.1 A Preliminary Analysis

This chapter explores the differences between a 6 DOF elastic rate controller and a 6 DOF isometric rate controller. Since both isometric and elastic devices are self-centred, they both should be compatible with rate control, in light of the analysis and experimental results in the preceding chapter. The difference between the two is that the elastic device allows a certain extent of movement. Is the movement in an elastic device an advantage comparing to pure isometric (stiff) device? Do isometric and elastic devices afford a different "control feel" (Burrows, 1965) ? It is clear (by definition) that the only control feel the human gets from an isometric device is force resistance. Also by definition, the user feels both force resistance and the displacement proportional to the force from an elastic device. The two variables (force and displacement) in an elastic controller co-vary (or even linearly co-vary if the springs used follow Hooke's law). This could imply that an elastic device gives a richer control feel than an isometric device, since the elastic device gives the same information in more than one form (force and displacement).

3.1.2 The Controversy Surrounding Isometric Versus Elastic Devices

Researchers have not had much agreement on the preceding hypothesis. Poulton, for example, firmly believes in the advantage of elastic devices: "Spring centring is the best kind of control loading", "... the man feels a pressure which is proportional to the distance of the control from its centre. The pressure cue augments the usual position cue, and help the man track more accurately" (Poulton, 1974, page 306). In practice, most commercial 2 DOF joysticks are elastic, but we do not know whether they have been constructed that way due to human performance considerations or due to manufacturing cost considerations. For the purpose of developing 6 DOF hand controller for teleoperation, McKinnon, King, and Runnings (1987) suggested that the controller should involve some displacement. They stated that pure isometric controllers may cause instabilities and over control, but this was concluded solely from their anecdotal observations; no formal study was reported.

Other researchers, such as Gibbs and Notterman, strongly believe in the advantages of isometric devices over elastic devices. As discussed in section 2.2, Gibbs (1954) argued that "the discharge in some primary endings is considerably boosted in isometric conditions". Notterman further argued "When using the spring-loaded control, subjects had to learn to use feedback from the linearly related, theta-proportional reactive forces determined by Hooke's law, *conjointly* with movement cues and centrally stored information". In other words, Notterman considered the redundancy in elastic devices a burden to the human information processing system.

The literature review in the previous Chapter (section 2.2) has examined many aspects of isometric devices in relation to isotonic devices. Many of the studies reviewed there remain relevant to the comparison of isometric and elastic devices. The following subsections review issues related to isometric and elastic devices in more depth, with emphasis on empirical studies on force versus movement as proprioceptive cues.

3.1.3 Studies on Control Accuracy as a Function of Force and Movement and as a Function of Control Loading

Weiss (1954) reported a study on a positioning task without immediate visual feedback of cursor position (i.e. open-loop positioning). In one set of conditions, Weiss varied the maximum angular displacement of an elastic control stick from 3° to 30° while keeping the same pressure range from 1 to 30 lb. In another set of conditions the maximum pressure was varied from 0 to 30 lb while keeping the same movement range (30°). He found that the relative positioning error and its variability decreased with the extent of movement but pressure variation had no effect on accuracy. He thus concluded that movement was the more crucial dimension than force in proprioceptive feedback. Unfortunately Weiss' study did not include a pure isometric condition for comparison.

Results contrary to Weiss' (1954) were reported by Bahrick, Bennett, and Fitts (1955) . Bahrick and colleagues studied the accuracy of blindfolded subjects in positioning a 1 DOF horizontal rotary arm control as a function of spring loading. Subjects made rotary movements of 17.5°, 35°, and 70° with various starting torque and terminal torque conditions. They found that subjects had smaller relative errors when (a) amplitude of movement was larger, (b) terminal torque was larger, and (c) relative torque change per unit movement was larger. The positioning errors were smallest when the ratio of relative torque change to displacement was largest. In conclusion, Bahrick et al found that force could provide useful cues in movement control. This was contrary to Weiss' finding.

Briggs, Fitts, and Bahrick (1957) studied a compensatory tracking task of simulated aircraft dynamics (comprising simple integrators), with an elastic stick. Two levels of force and two levels of amplitude were tested in an experiment, with Time on Target (TOT) as performance measure. They found that "both force and amplitude (of movement) cues significantly affected performance, amplitude cues apparently exerting the greater influence". The best TOT measure was obtained with both sources at the largest extent. As with Weiss' study, a pure isometric condition was not tested by Briggs et al. (1957) .

Notterman and Tufano (1980) did include both isometric and elastic conditions in a tracking task in position control mode. They found that the elastic controller was better than the isometric device in tracking predictable target motion and that the isometric device was better than the elastic device in tracking unpredictable target motion but these findings were true only in early learning stages.

Howland and Noble (1953) comparatively studied controls with no loading (isotonic), elastic loading, viscous loading, inertial loading and various combinations of them. No isometric controls were included in their study. Subjects were asked to track a horizontally moving bar driven by a 15 cycle per minute harmonic signal in position control mode. Ranked by percentage of time-on-target (TOT), subjects' performance with various loadings in decreasing order of TOT were: (1) elastic only, (2) elastic and viscous, (3) viscous only, (4) no loading (isotonic), (5) inertial only, viscous and inertial, elastic and viscous and inertial (not much difference among these three), (6) elastic and inertial. Howland and Noble attributed the superior performance with the elastic loading to two factors. (a) The elastic loading aids the reversals needed in harmonic movement. In other words, subjects may utilise the device dynamics in generating movement that coincides with the target signal (We return to this point in 3.1.5). (b) The feel of control handle position is augmented with elastic loading and therefore the "kinaesthetic stimulation" is enhanced. This study is often cited in the literature on the effect of control loading. It should be noted, however, that the control handle in the study was rotary and the advantage of natural mapping in isotonic controls might not be well taken in rotary controls. However, the key conclusion that elastic controls augment position sense is agreed upon by many other researchers.

3.1.4 Psychophysical Findings on Force and Movement JND

Some psychophysical experiments have been conducted recently on human (finger) sensitivity in discriminating length and force. Durlach, Delhorne, Wong, Ko, Ranbinowitz, and Hollerbach (1989) and Tan, Pang, and Durlach (1992) found that human discrimination of length did not follow Weber's law. The just noticeable difference (JND) was 8.1% for a reference length of 10 mm, 4.6% for 40 mm and 2.8% for 80 mm. In comparison, Pang, Tan, and Durlach (1991) and Tan et al. (1992) found that *force* JND did follow Weber's law. The average force JND was around 7-8%, independent of reference force. It appeared that human sensitivity to force is lower than sensitivity to length, particularly for large ranges of length (>10 mm) or force (>2.5 Newton). For smaller ranges of force (<2.5 Newton) or length (<10 mm), the JNDs are about the same (See Figure 3 and 4 in Tan, et al. (1992)). One has to be cautious in applying these psychophysical studies to input control device design, however, since in these studies, the force JNDs were not obtained with isometric force.

3.1.5 Time Related Effects of Control Loading

When performing manual control tasks, the process is not static. The dynamic aspects of the task can not be overlooked, especially in rate control. It has been found that control loading can also affect human judgement of dynamic properties of control tasks.

Adams and Creamer (1962) made the distinction between regulatory proprioceptive stimulation (RPS) and anticipatory proprioceptive stimulation (APS). RPS refers to the functions that proprioceptive feedback has on aiding users in judging their control actions (as reviewed in section 3.1.3). In addition to RPS, Adams and Creamer hypothesised that proprioceptive feedback might also have the properties of aiding users in anticipating the timing of their motor response (e.g. positioning a carriage along a trackway in 2.0 sec). Researchers found that control loading such as elastic springs indeed improve subjects' accuracy in estimating elapsed time. (Adams and Creamer, 1962; Ellis, Schmidt, and Wade, 1968; and Ellis, 1969) . This is in agreement with Treisman's suggestion that subjects estimate time by "counting" external stimuli (Treisman, 1963).

The notion that the human may dynamically make use of proprioceptive cues provided by a control device is further demonstrated in Pew, Duffendack, and Fensch (1967) . Pew and colleagues studied sine wave tracking with elastic controls in position control mode at various frequencies. With extended practice, subjects' performance was disproportionately better at certain critical frequencies. Furthermore, it was found that these critical frequencies changed with the elastic stiffness. This means that the subjects learned to use the natural resonant frequency of the arm-stick combination to match the frequency of the target movement being tracked.

3.1.6 The Neurophysiological Sources of Proprioception

Since proprioceptive feedback is one of the key issues in the debate on isometric versus elastic controllers, a brief review of the basic literature on the mechanism of proprioception (or kinaesthesia) is provided here. For details of the basic science of proprioception, the reader is suggested to consult McCloskey (1978) , Roland (1978) , Clark and Horch (1986) or Matthews (1981) .

Neurophysiological research has found that a multiplicity of somatosensory receptors (mechanoreceptors) can be involved in providing information to the central nervous system (CNS) (Sage, 1977; Schmidt, 1988; Gandevia and Burke, 1992) . Each type of receptor has its unique functions. The CNS integrates signals from these different types of receptors, producing an ensemble of somatosensory information.

Joint receptors In early research, joint receptors were considered the most important source of proprioception. It was hypothesised that different groups of receptors at the same joint were tuned to particular joint angles; as a joint moved from one angle to another, different populations of receptors on the joint would be fired, much like how a mechanical-optical encoder works. Today's view, however, is that joint receptors are sensitive only when a joint approaches one of the limits of its range (Clark and Horch 1986) . As Matthews (1988) put it "Thirty years ago things looked relatively simple. The joint receptors were in, and everything else was out. ...This simplicity has now vanished; joint receptors are largely out and muscle receptors are in".

Muscle spindles Muscle spindles are currently considered the major source of proprioception (Matthews, 1981, 1988) . They are believed to be sensitive to both tension and movement, but more so to movement. Many studies suggest that "The muscle spindle receptors appear quite capable of encoding muscle length" (Clark and Horch, 1986) .

Golgi tendon organs According to early thinking, Golgi tendon organs were considered inaccurate protective measures, that is, they would signal only whenever the muscles approach their safe operation limits (Schmidt, 1988) . Recent work, however, has found that they are actually very sensitive, but only to active tension, not passive tension (Jami, 1992) . In fact they are considered as the major sensors of tension, although muscle spindles are also sensitive to tension. "Tendon organs, by nature of their response properties, appear the most likely candidates to signal forces" (Clark and Horch, 1986, page 13-55).

Cutaneous receptors The bending of joints will stretch some regions of skin around the joints and relax others, causing the receptors in the skin to provide signals with regard to the position and movement. Experimental studies do not generally find an important role for cutaneous receptors in signalling positions, however, due to their slowly adapting nature. Anaesthesia of the skin around the knee joint had no effect on knee positioning, for example (Clark and Horch, 1986) . However, this was not true of finger joints. The skin of the fingers might play a special role in proprioception (Clark and Horch, 1986) .

In light of above review, we can surmise what types of proprioceptors are approximately involved with each type of control devices. For example, when manipulating an isometric device, involving no movement and only tension, Golgi tendon organs should be the major source for proprioceptive feedback, although muscle spindles may also contribute to a lesser extent. With an isotonic device, where movement is involved but not tension, joint receptors, muscle spindles and cutaneous receptors in the skin around the joints might contribute to proprioception in varying degrees. When using an elastic device, on the other hand, both movement and tension are involved, and therefore joint receptors, muscle spindles and cutaneous receptors in the skin around the joints and Golgi tendon organs all may contribute to the proprioception of hand action. Collectively these hypotheses suggest, therefore, that all other factors being equal, an elastic controller should elicit response from more proprioceptors than any other class of device, because it allows movement while providing force feedback through the elastic elements.

3.1.7 The Role of Proprioception in Motor Control

Thus far we have reviewed issues related to proprioception in order to understand the difference between isometric controls and elastic controls. However, we have not addressed the question of how important proprioception is in motor control tasks in general. That is, to what extent does motor control rely on peripheral feedback, or can most tasks be performed in an open-loop fashion with commands originating centrally only?

Motor behaviour accompanying our daily activities involves very complex coordination and regulation of joints and muscles, with a great number of degrees of freedom. Each hand alone has 17 active joints and 23 degrees of freedom, excluding another 6 degrees of freedom of the free motion of the palm. How such a complex system is controlled has interested many psychologists, physiologists, physical educators and human factors specialists. In general, two opposing views have been taken towards issues in motor control and have been the subject of a long-standing debate in the psychomotor literature (See Schmidt, 1988; Stelmach, 1979; and Singer, 1980 for general overviews). The centralist view emphasises the dominance of centrally stored motor programs and posits that human motor control comprises mainly open-loop behaviours. In contrast, the peripheralist theory stresses the importance of information feedback and posits that human motor control comprises mainly closed-loop behaviours. Both camps have found abundant evidence in support of their theories. The centralists have found cases which show that precise movement can be produced after deafferentation, either surgically with animals or accidentally with humans. Centralists also argue that proprioception is too slow for useful movement control. The peripheralists, on the other hand, have found much empirical counter-evidence to support their arguments against the centralist view. Although the debate is likely to continue, many other researchers suggest that the human motor control system actually operates under both modes, and that the role of feedback is a positive one in any case, even if central control is paramount.

3.1.8 Summary of the Reviews on Isometric and Elastic Devices

The foregoing reviews, as well as the related ones in section 2.2 on isometric and isotonic devices, are by no means complete and exhaustive. Two facts are nonetheless apparent: (1) The human performance differences between isometric and elastic devices are a function of multiple factors and to understand these is much more complicated than one might expect. (2) The literature is controversial and definitive conclusions can not easily be drawn. Nevertheless, the analysis of the literature reveals the following major points.

1. Both isometric and elastic devices are self-centring and therefore compatible with rate control, in light of the results in Chapter 2.

2. By definition, isometric devices operate on force alone while elastic devices involve both force and movement that are proportionally related.

3. Some researchers believe in the overall superiority of elastic devices (e.g. Poulton). Others (e.g. Gibbs, Notterman) consider isometric devices superior.

4. Human control accuracy increases with the amplitude of both movement and force, as evident in Bahrick et al (1955) and Briggs et al (1957) . Weiss (1954), however, found that only movement contributes to control accuracy .

5. Displacement JND is smaller than force JND, that is, we are better able to perceive relative changes in position than changes in force.

6. Proprioception, as introduced by different types of control loading (e.g. elastic), may not only improve static control performance (accuracy) but also may improve dynamic aspects of control performance.

7. There are multiple neurophysiological sources of proprioception, some of which respond to force stimuli and others to movement stimuli. Elastic devices may elicit activation of more sources of proprioception.

8. Points 4 - 7 collectively suggest that elastic devices might be superior to isometric devices due to potentially richer proprioceptive feedback, however, the general role of proprioception in motor tasks is controversial. Different schools of thoughts put different degrees of emphasis on its importance in motor control.

3.1.9 A Two-Factor Theory

Based on the above review, this section proposes a two-factor theory for understanding the difference between isometric rate control and elastic rate control. In contrast to isotonic or isometric devices which have fixed resistance (either zero or infinite), the resistance of elastic devices ranges between zero and infinity, depending on the stiffness of the elasticity. In light of the compatibility principle proposed in the previous chapter, a controller has to be self-centred in order to facilitate rate control processes. This self-centring effect decreases as the stiffness of the device decreases. When the elastic stiffness reaches zero, the elastic controller becomes a freely moving, isotonic controller without any self-centring effect. When the stiffness is infinite, on the other hand, the elastic controller becomes a non-moving, isometric device which has the strongest self-centring effect. In short, in order to maintain compatibility for rate control, the optimal stiffness for an elastic controller should be close to the infinite stiffness of an isometric device.

In light of the analysis of proprioceptive feedback, on the other hand, a greater extent of displacement may allow the human operator to have more accurate perception of her control actions. For this reason, an elastic device should have a relatively low elastic stiffness to allow a greater extent of movement with the same range of force.

Apparently, these two factors, compatibility and feedback, dictate conflicting requirements for the magnitude of the elasticity. An optimal design will thus be a result of a trade-off between these two factors. It should be stiff enough so as to be compatible with rate control but loose enough to allow accurate proprioceptive feedback.

3.2 Experiment 2 - Isometric and Elastic Rate Control in 6 DOF Docking

3.2.1 Experiment 2 Set-up

3.2.1.1 Experimental Platform, Task, and Display

The experimental platform, task, and display in this experiment are the same as those used in Experiment 1. A preliminary analysis of this experiment was published in (Zhai, 1993).

3.2.1.2 Controllers Used in the Experiment - the Design of the EGG

In this experiment, the *isometric rate* control mode was implemented by means of a Spaceball™.

In order to carry out research on isometric and elastic 6 DOF input, the EGG (Elastic General purpose Grip), a 6 DOF elastic device, was designed, as shown in Figure 3.1.

The EGG was implemented with an egg shaped handle suspended in a 17 cm x 17 cm x14 cm frame by eight sets of elastic bands joined to each corner of the frame. The handle, with horizontal diameter 6.5 cm, same as that of a Spaceball (model 2003), and vertical diameter 8 cm, is grasped by fingers in the gesture of a “precision grip” (MacKenzie and Iberall, 1994) . An electromagnetic tracker (the Ascension Bird) is mounted in the centre of the handle for acquiring the 6 DOF data. The elastic suspension was arranged such that the grip did not bias the manipulation in any particular direction. In comparison with other proposed elastic 6 DOF designs (e.g. McKinnon et al., 1987) , where the handle is either suspended from the ceiling or supported on a base, the EGG provides a substantially uniform compliance in all directions for both rotational and translational movement, thereby allowing control actions to be decoupled. Another decoupled elastic 6 DOF design is described by Hayward, Nemri, Chen, and Duplat (1993) , in which a mechanically much more sophisticated design is proposed.

The EGG allows movement of 20 mm in translations and 30° in rotations, which are much greater than the currently available commercial 6 DOF devices (see Figure 1.1).

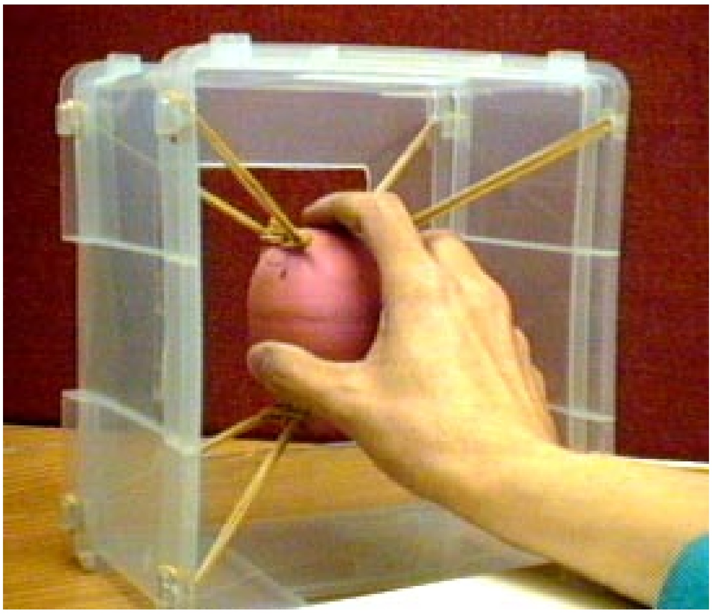


Figure 3.1 The EGG - Elastic General-purpose Grip

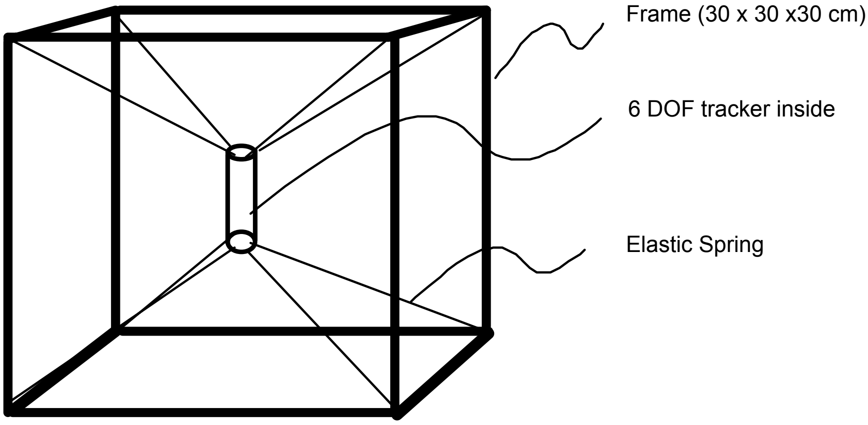


Figure 3.2 Early design of the elastic 6 DOF controller

Another 6 DOF elastic controller prototype was also developed, as illustrated in Figure 3.2. It had a larger frame and a bar handle to be grasped with the gesture of a "power grip" (MacKenzie and Iberall, 1994) . The EGG was chosen for the present experiment, however, because its handle has dimensions similar to those of the Spaceball (Model 2003). In comparison to the design in Figure 3.2, the EGG also has the advantage of allowing utilisation of the fine muscle groups (fingers) instead of the wrist, elbow and shoulder alone. Neurological studies have shown that the fingers have a rich representation in the somatosensory and motor cortex. In Chapter 4, a separate study is presented to test the advantages of using fingers in 6 DOF manipulation.

The structure of the EGG also made it very simple to adjust the elastic stiffness, since the number of suspending elastic bands could be easily changed. As discussed before, the optimal elasticity for such as device is a result of the trade-off between compatibility with rate control (requiring stiff loading) and proprioception (requiring loose loading). Indeed, a pilot study with the EGG showed that both extremes of elasticity settings produced poorer performance. Optimal performance was found when the elasticity was around 120g/cm in each of the X, Y, Z directions.

3.2.1.3 Models of the Input Controls

Both the isometric rate control and the elastic rate control have the same mathematical model as the isometric rate control model described in Appendix 1, section A1.4.

3.2.1.4 Optimisation of Control Gains

The control gains (sensitivities) for each condition were optimised through systematic parameter searching, as described in section 2.7. For the isometric rate controller (Spaceball), the same gain selected for Experiment 1 was used here (see Figure 2.7). U shaped performance-gain curve was also found for the EGG (Figure 3.3). The elasticity of the elastic rate controller was optimised in a similar fashion. In order to equalise the operating conditions of the two controllers as much as possible, the non-linear transformations of the translation and rotation degrees of freedom embedded in the Spaceball, as described in section 2.7 of Chapter 2, were also applied to output variables from the EGG.

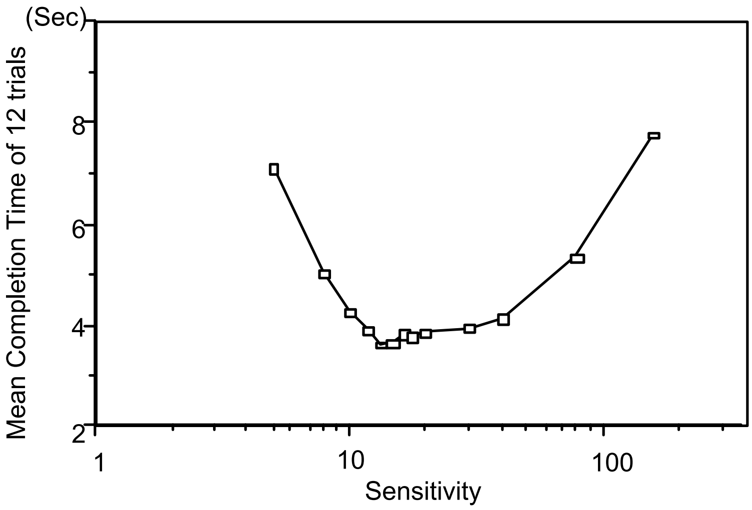


Figure 3.3 Optimal gain search for the elastic rate controller for Experiment 2

(The horizontal axis is normalised)

3.2.2 Experimental Design

3.2.2.1 Subjects

A between subjects design was employed in this experiment. Each of the subjects served in only one condition: isometric rate control or elastic rate control. One of the pitfalls of between-subjects designs is that individual differences may bias experimental results. Pitrella and Krüger (1983) have suggested using matching tests to form equal groups for tracking experiments. However, choosing a suitable matching test is a very delicate task, since the test has to be sufficiently similar to the experimental conditions that measured and matched subjects' capabilities will be relevant to the experimental task. On the other hand, the test also has to be such that the amount of skill transferred from the matching test to each of the experimental conditions is equal, so that the matching test does not introduce a bias into the actual experimental results. It is often impossible to design such a test to fit all these requirements.

In this experiment, randomisation and a relatively large number of subjects were used to dilute any possible individual difference effects. 35 paid volunteer subjects were recruited by advertising through posters and electronic network news groups on the University of Toronto campus. People who participated in Experiment 1 were excluded from this experiment. All subjects were screened using a Bausch and Lomb Orthorater. Five of the subjects were rejected for having poor (corrected) near vision acuity. Another four were rejected for having weak stereo-acuity.

Among the 26 subjects accepted, two were left-handed, as determined by the Edinburgh Inventory (Oldfield, 1971). One of them was assigned to the elastic rate control condition and the other was assigned to the isometric rate control condition. The controls were set at the side of the subjects' dominant hand. Three of the 26 accepted subjects were female. Two were put into the elastic rate control condition and one was assigned to the isometric rate condition. The remaining 21 male right handed subjects were randomly assigned to the two conditions. The balance of composition of the two groups of subjects was checked by age, profession, etc. No obvious bias against any condition could be found.

The accepted subjects' ages ranged from 16 to 38, with the majority in their early to mid-20's. Most of the subjects were engineering or computer science undergraduate students. All had experience with computer mice but none of them had used a 6 DOF input device before the experiment.

3.2.2.2 Experimental Procedure

Each experimental session consisted of a 10 minute vision screening test, 5 minutes of instruction, 40 minutes of experiment, and a 5 minute questionnaire survey. The 40 minute experiment was divided into four phases. Each phase comprised 10 minutes of training, followed by 12 trials of data collection. Each training phase consisted of demonstrations and coaching by the experimenter, combined with practice trials. The data from the 12 trials were composed of 3 blocks of 4 trials, each block comprising 4 different randomly shuffled starting locations for the manipulated tetrahedron (the cursor). The procedure was the same as Experiment 1, except that Experiment 1 had a within subject design and this had a between subject design.

3.2.3 Results

3.2.3.1 Performance Results

Figure 3.4 displays the means and standard errors of the two techniques over the four phases of the experiment. The results of a repeated measure variance analysis of the entire data set are summarised in Table A3.2.1. The performance difference between the two input techniques was not statistically significant: $F(1, 24) < 1$. However, the Phase x Input interaction was weakly significant: $F(3, 72) = 2.57$, $p = 0.061$. This means that the relative performance with each of the two input techniques is likely related to learning experience. As shown in Figure 3.4, on average the elastic rate control outperformed the isometric rate control in Phase 1. In later phases, however, the difference between the two was reduced to practically zero.

Learning was therefore the most important factor affecting performance. Subjects' performances improved significantly with practice for both input techniques: $F(3, 72) = 90.5$, $p < 0.0001$. The initial target location was also significant in affecting trial completion time: $F(3, 72) = 4.5$, $p < 0.01$. This was because two of the initial locations were much farther from the target than the other initial locations.

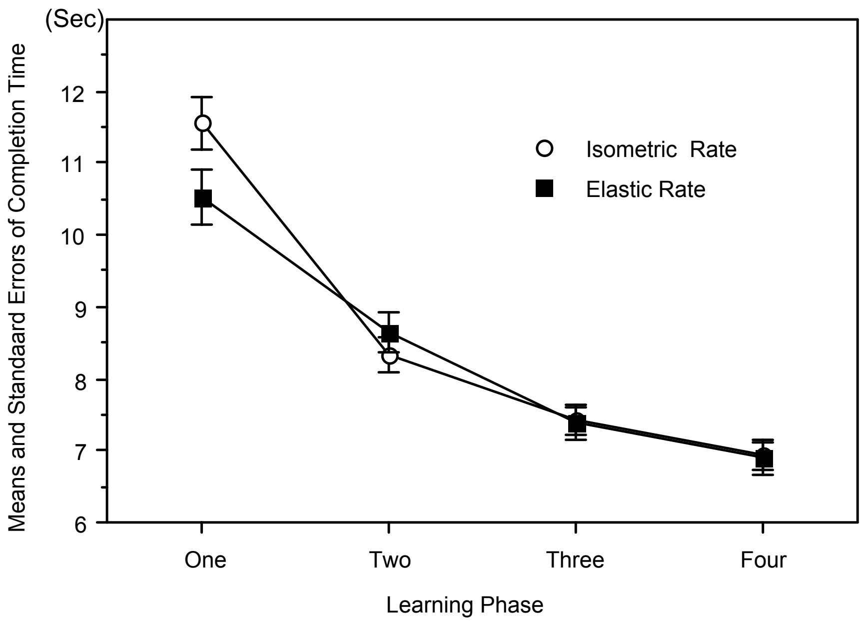


Figure 3.4 Task mean completion times in four phases of Experiment 2

3.2.3.2 Subjective Ratings

Immediately after each session of the experiment, the subjects were asked to comment on the ease of use/ difficulty and the degree of fatigue for the controller that they had just used. The subjective opinions between the two controllers were not statistically different. For ease of use: $F(1, 24) < 1$, $p > 0.5$, and for fatigue, $F(1, 24) < 1$, $p > 0.5$ (See Figures 3.5 and 3.6).

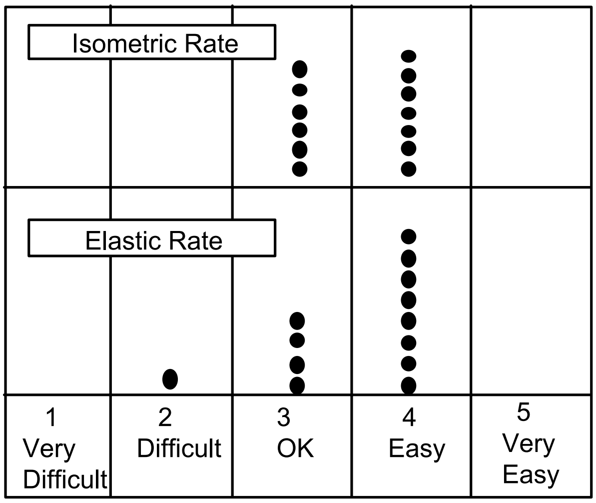


Figure 3.5 Subjective ratings of ease of use in Experiment 2

(Each dot represents one subject's rating).

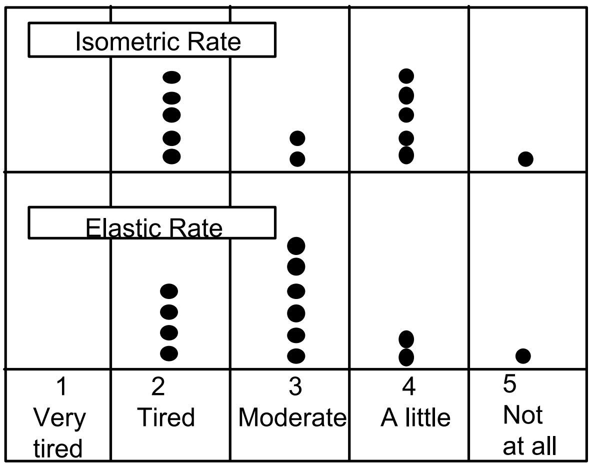


Figure 3.6 Subjective ratings of fatigue in Experiment 2

3.2.4 Conclusion

On the average across the four experimental phases, the results of Experiment 2 did not show substantial differences between the two controllers used in the experiment. It therefore did not provide strong evidence for either the superiority of elastic devices, as suggested by researchers such as Poulton, or the superiority of isometric devices, as suggested by researchers such as Gibbs. Interestingly, the relative advantage of the isometric and the elastic device appears to be related to learning, as reflected by the interaction between experimental phase and control technique, since a modest advantage for the elastic device was shown in the first but not in the later experimental phases.

The 6 DOF docking task used in this experiment was a relatively easy task and thus performance ceiling effects could have concealed the differences between the two modes. It was therefore decided to further test the two types of controllers by conducting a more demanding task - 6 DOF tracking. Preliminary results of the tracking experiment were published in (Zhai and Milgram 1993b) and (Zhai and Milgram 1994b). A more complete description of the experiment is presented in the following section.

3.3 Experiment 3 - Isometric and Elastic Rate Control in 6 DOF Tracking

3.3.1 Experimental Set-up

3.3.1.1 Platform

The same experimental platform as in Experiments 1 and 2 was used in this experiment.

3.3.1.2 Experimental Task

A 6 DOF pursuit tracking task was designed for this experiment. Subjects were asked to continuously control a cursor and track (capture) a target which moved unpredictably (in both translation and rotation) within a 3D virtual environment (Figure 3.7). The tracking target was a wireframe tetrahedron. In order to overcome any orientation ambiguities due to the symmetry of the tetrahedron shape, two connected edges of the tetrahedron were coloured blue and the remaining edges were coloured red.

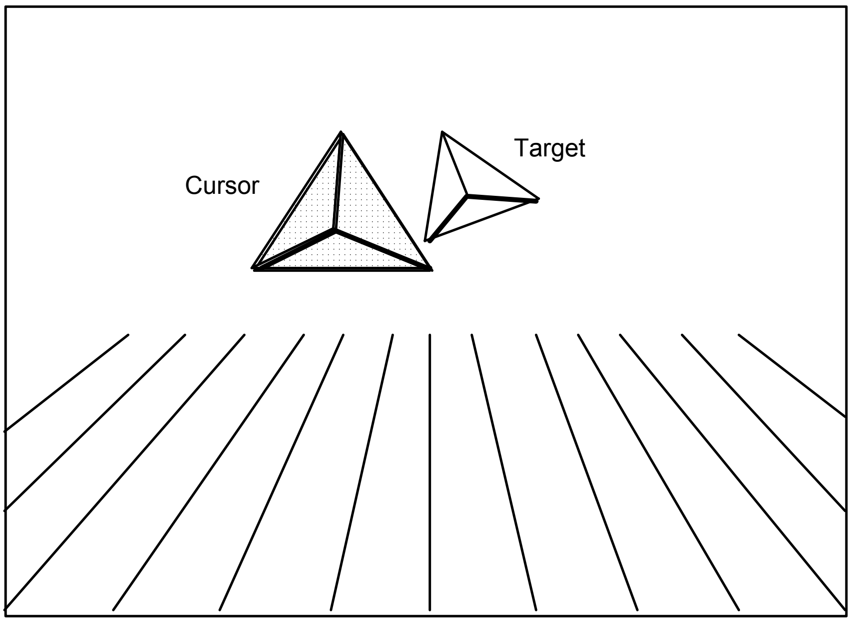


Figure 3.7 6 DOF tracking task: subjects were asked to track the randomly moving target with the cursor

The tracking cursor was of the same shape as the target tetrahedron but differed from it in three ways. First, the radius (from the centre to each vertex) of the target tetrahedron was 3.55 graphic units (1 graphic unit = 1.4 cm, all lengths in this experiment are measured in the same scale) while the cursor was 1.3 times as large as the target. Second, the cursor had semi-transparent surfaces (indicated by dots in Figure 3.7), while the target was drawn in wireframe. Third, the cursor edges were slightly brighter than the target, although they were of identical hue (i.e. two blue and four red edges).

Each degree of freedom of the target was driven by an independent forcing function. In order to make the target path sufficiently unpredictable to the experimental subjects, each forcing function was derived from a weighted summation of 20 sine functions, i.e.,

$$x(t) = \sum_{i=0}^{19} A\, p^{-i} \sin(2\pi f_0 p^i t + \phi_x(i)) \qquad (3.1)$$

Here t is the time duration from the beginning of each experimental phase (measured in seconds); constants A = 3.5, p = 1.25, f_0 = 0.01; $\phi_x(i)$ is a pseudo-random number, ranging uniformly between 0 and 2π.

Similarly, y and z dimension translations were driven by:

$$y(t) = \sum_{i=0}^{19} A\, p^{-i} \sin(2\pi f_0 p^i t + \phi_y(i)) \qquad (3.2)$$

$$z(t) = \sum_{i=0}^{19} A\, p^{-i} \sin(2\pi f_0 p^i t + \phi_z(i)) \qquad (3.3)$$

Rotations about x, y, z axes (i.e. pitch $\varphi(t)$, yaw $\theta(t)$, roll $\Psi(t)$) were driven by similar forcing functions:

$$\varphi(t) = \sum_{i=0}^{19} B\, p^{-i} \sin(2\pi f_0 p^i t + \phi_\varphi(i)) \qquad (3.4)$$

$$\theta(t) = \sum_{i=0}^{19} B\, p^{-i} \sin(2\pi f_0 p^i t + \phi_\theta(i)) \qquad (3.5)$$

$$\psi(t) = \sum_{i=0}^{19} B\, p^{-i} \sin(2\pi f_0 p^i t + \phi_\psi(i)) \qquad (3.6)$$

where B = π/R, and R is the radius of the target tetrahedron.

These forcing functions are similar to those used by Tachi and Yasuda (1993) , but more complex than the once conventional sum-of-sines method (e.g. Poulton, 1974).

3.3.1.3 Task Performance Measure

In traditional 1 or 2 DOF tracking experiments, the tracking error at any moment is defined simply as the distance between the target centre point and the cursor centre point. However, defining the tracking error between two 3D objects, both of which have 6 DOF, is much more complicated and needs to be elaborated further. One way of analysing the tracking performance in such a task is by studying each degree of freedom separately. This approach will be presented in Appendix 2. However, an overall single measure of the tracking quality is necessary both for feedback to the subject (at the end of each trial) and for general data analysis. In the experiment, subjects were instructed to track the target as "closely" as possible, which therefore requires *both* a translational and a rotational match.

We have therefore adopted an *integrated* measure for evaluating the tracking quality. At any tracking instant k (t = kT, where T is the sampling period), the tracking error e(k) is defined as:

$$e(k) = \sqrt{dist^2(V_{c1}, V_{t1}) + dist^2(V_{c2}, V_{t2}) + dist^2(V_{c3}, V_{t3}) + dist^2(V_{c4}, V_{t4})} \quad (3.7)$$

where dist(X_1, X_2) is defined as the Euclidean distance between two points X_1 and X_2 in 3D space. V_{t1}, V_{t2}, V_{t3} and V_{t4} are the four vertices of the target tetrahedron and V_{c1}, V_{c2}, V_{c3} and V_{c4} are the four vertices of an equivalent imaginary tetrahedron with the same size as the target but coinciding with the centre and orientation of the cursor (Figure 3.8). This integrated error measure is based on both psychological and mathematical considerations. Psychologically, this measure is meant to correspond with the subjects' perception of the "distance" between two 3D objects; that is, when subjects perceive the two objects to move closer, this measure indeed decreases monotonically. Mathematically, this measure converts rotation to an equivalent translational distance. For each trial (40 seconds, 800 tracking steps) overall tracking performance was calculated by root mean square (RMS) error, as conventionally accepted in the literature (e.g. Poulton, 1974):

$$\text{RMS error} = \sqrt{\frac{\sum_{k=1}^{N} e_k^2}{N}} \quad (3.8)$$

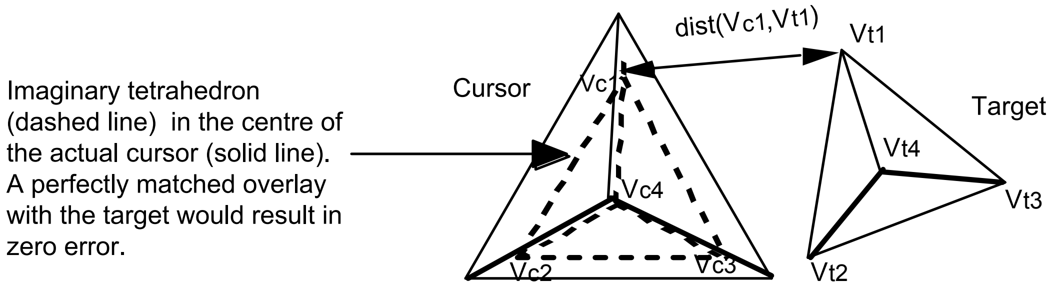
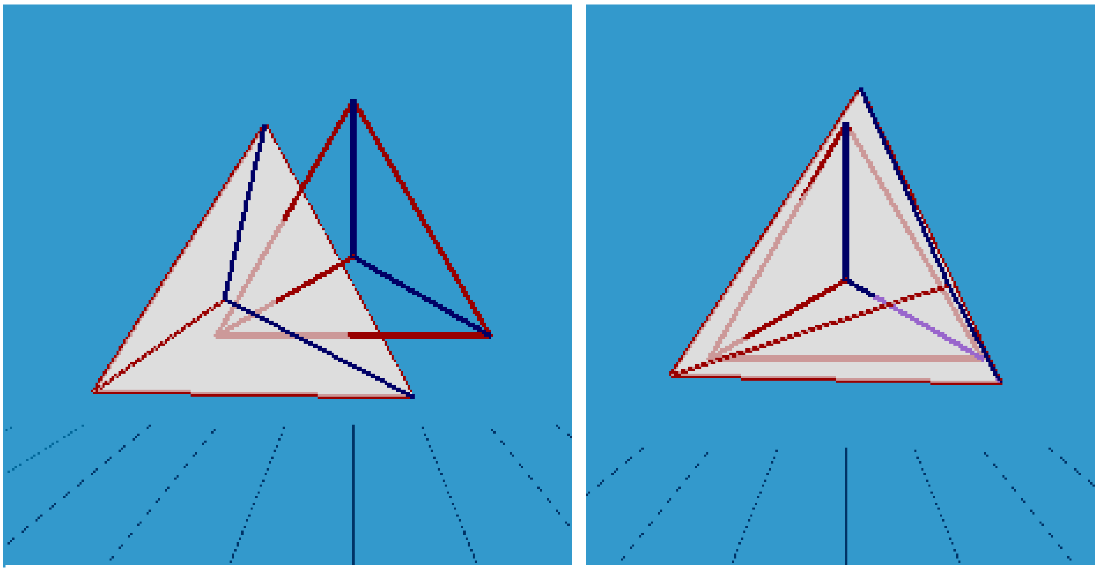


Figure 3.8 The integrated tracking error is based on combined distances between corresponding vertices.

3.3.1.4 Display

The graphical display used in this experiment was very similar to that of Experiments 1 and 2. For two reasons, semi-transparency was used in addition to all the other depth cues that were implemented in Experiments 1 and 2. First, as shown in Figure 3.9, the partial occlusion effect introduced by semi-transparency may help the subjects in perceiving the relative displacement (location and orientation) between the cursor and the target. It is well known that the occlusion cue is among the strongest depth cues in human perception. If object A is being obscured by object B, object B will appear closer to the viewer. However, complete occlusion may not be very useful for graphical computer displays since the occluding objects will block the user's view of the background completely. When semi-transparent surfaces are used, on the other hand, objects being blocked by a semi-transparent surface appear in lower contrast (i.e. partially occluded) but remain visible. The question of whether this partial occlusion technique will in fact serve as a useful and strong depth cue is addressed in a separate experiment (Experiment 5) presented in Chapter 5.



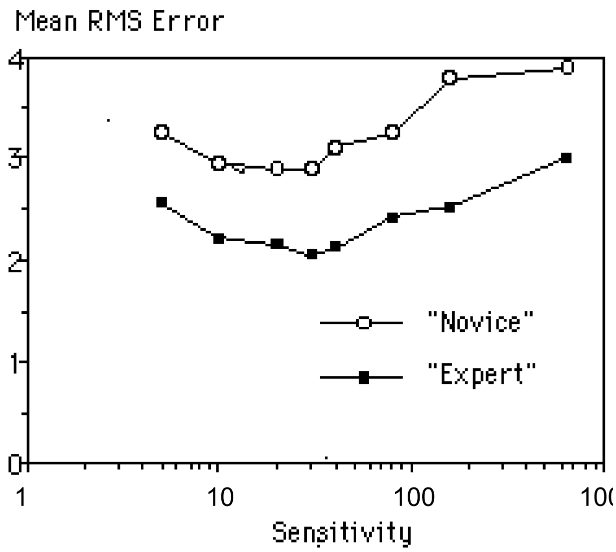
(a) (b)

Figure 3.9 Silk Cursor - Volume cursor with semi-transparent surfaces used in Experiment 3. Semi-transparency was used to help subjects in perceiving the relative displacement in location (a) and orientation (b) between the cursor and the target.

The second reason for using semi-transparency was to make the cursor appear very different from the target. The 6 DOF tracking task required the design of two 3D objects (cursor and target) that are sufficiently similar so that the subjects could perceive the correspondence of the two to perform the task. Conversely, the task also required the two objects to be distinctively different so the subjects could know which one was the autonomously moving target and which one was the cursor under her control. Before the semi-transparent surfaces were implemented, pilot subjects often mistakenly identified the cursor as the target and tracked their own motion. In that case, the control loop became positive feedback: the harder they pushed (twisted) their input in order to minimise the distance between the cursor and the target, the larger the distance became! An attempt was made to implement the cursor using dotted lines or blinking at certain frequencies but none of these techniques proved to be acceptable.

3.3.1.5 Controllers and Optimisation

The controllers used in this experiment were the same as in Experiment 2. The control gains (sensitivity) for each controller were optimised again in this task through systematic



(a) The isometric controller

parameter searching with two pilot subjects, one experienced and one naïve. U-shaped performance-gain curves were again found for both control modes (Figure 3.10). The optimal gains found in this task were very close to the optimal value previously found in the docking task. Fortuitously, although the experienced pilot subject and the naïve pilot subject produced different absolute error scores, the optimal gain values were approximately the same for both of them, which made it straightforward to select the optimal gains for the experiment.

Other parameters such as the elasticity of the elastic rate controller, were optimised in a similar fashion. Same as in Experiment 2, non-linear transformations identical to those embedded in the Spaceball were implemented in the EGG condition.

3.3.2 Experimental design

3.3.2.1 Subjects

30 paid volunteers who had not participated in Experiment 1 and 2 were recruited. All of them had experience with a computer mouse but none of them had used a 6 DOF control device before the experiment. All subjects were screened using a Bausch and Lomb Orthorater. Three subjects were rejected for having weak stereo-acuity, and one was rejected for having poor corrected near-vision acuity. The remaining 26 male and female subjects completed the experiment. As in Experiment 2, a between-subjects design was employed. The 26 accepted subjects were alternatively assigned to two experimental groups, with consideration of balanced gender composition in each group. Each group had 9 male subjects and 4 female subjects. Three subjects were left-handed and the others were right-handed. Each controller was located at the side of the subject's dominant hand.

3.3.2.2 Procedure

Each experimental session was preceded by a 15 minute vision screening test, handedness check and signing of a consent form. A 3 minute long questionnaire survey was also conducted at the end of each session. The data gathering was divided into five phases, as illustrated in Figure 3.11. Each phase consisted of practice, followed by a test comprising 4 trials of tracking. Each trial lasted 40 seconds. In contrast to Experiment 1 and 2, the first test, Phase 0, was conducted before the subjects had much experience. This change was

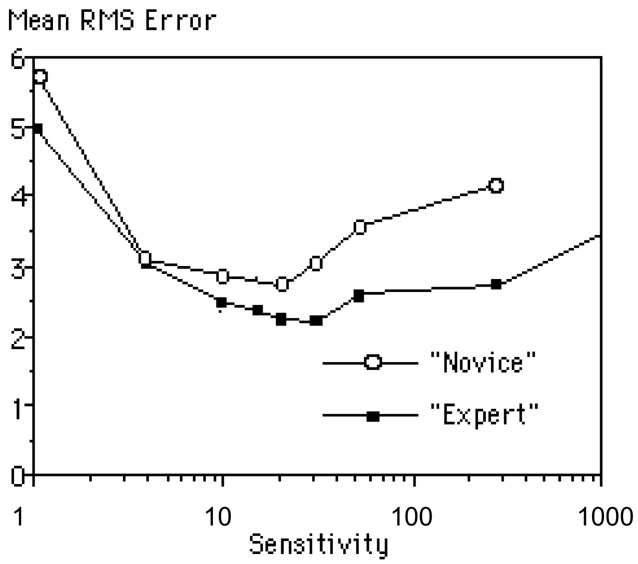


Figure 3.10 Optimal sensitivity search for Experiment 3
(The horizontal axes are normalised)

made in light of the results from Experiment 2: the principal difference between the isometric and elastic controllers appeared to be affected mainly by learning, much of which could have occurred in the first 10 minutes. Practice in *Phase 0* was therefore arranged as follows: The subject was first showed how to use the assigned controller by the experimenter. He/she was then asked to control each of the six degrees of freedom (x, y, z, pitch, yaw, roll), as well as translations and rotations in/about arbitrary axes. After that, the subject was asked to do one trial of tracking, to learn what was required in the task. The total duration of Phase 0 practice was about 3 minutes (Figure 3.11). Practice in Phases 1, 2, 3 and 4 lasted 7 minutes each, and consisted of demonstrations and coaching by the experimenter, together with actual practice trials.

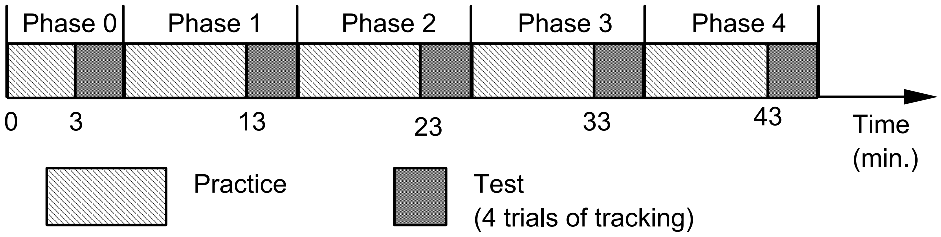


Figure 3.11 Experiment 3 procedure: each phase consisted of practice and a test of 4 trials of tracking.

A short beep signalled the end of each trial, after which the integrated RMS error was presented. The subject was asked to press the spacebar of the workstation keyboard to start the next trial. At the end of each test, a text file containing the RMS errors for each trial, as well as the average score over the four trials, was displayed to the subject.

Each of the four trials in a test had a distinct target trajectory. Each trial began with the cursor coincident with the target (zero error). During the experiment, subjects were instructed to track the target as closely as possible in both translation and rotation.

3.3.3 Experimental Results

3.3.3.1 Performance Results

Figure 3.12 displays the means and standard errors of the two techniques over the five phases of experiment. The results of a repeated measure variance analysis of the entire data set are summarised in Table A3.3.1 in Appendix 2. The differences between the controllers appeared in the same pattern as in Experiment 2. The mean difference between the two input techniques across the entire experiment was not statistically significant: $F(1, 24) < 1$, $p = 0.52$, although the elastic controller had smaller RMS error on average. The interaction Phase x Input, however, was significant: $F(4, 96) = 2.52$, $p < 0.05$. This again indicates that the relative performance differences between the elastic and the isometric controllers are related to learning. Repeated measure analysis (Table A3.3.2, Appendix 3) showed that RMS error with the elastic rate control was significantly smaller than that of the isometric rate control in Phase 0: $F(1, 24) = 4.7$, $p < 0.05$. This difference decreased as learning progressed, however.

Subjects' performance improved over the five experimental phases significantly: $F(4, 96) = 113.7$, $p < 0.0001$, indicating significant leaning over the course of the experiment. The different tracking paths were also a significant factor in affecting trial completion time: $F(3, 72) = 12.7$, $p < 0.0001$, as shown in Figure 3.13. This was due to two reasons. First, since the four paths were arranged in a fixed order (path1, path2, path3, path4), learning tended to improve for the performance in paths tested later in any particular sequence. Second, since the paths were randomly generated, some of them were apparently more difficult than others.

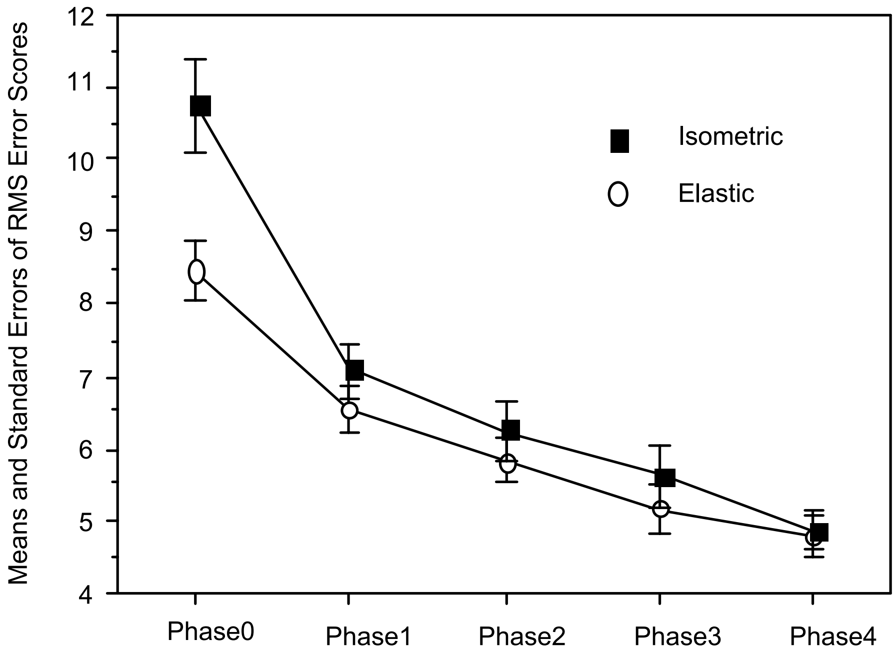


Figure 3.12 RMS integrated error for the five phases of Experiment 3

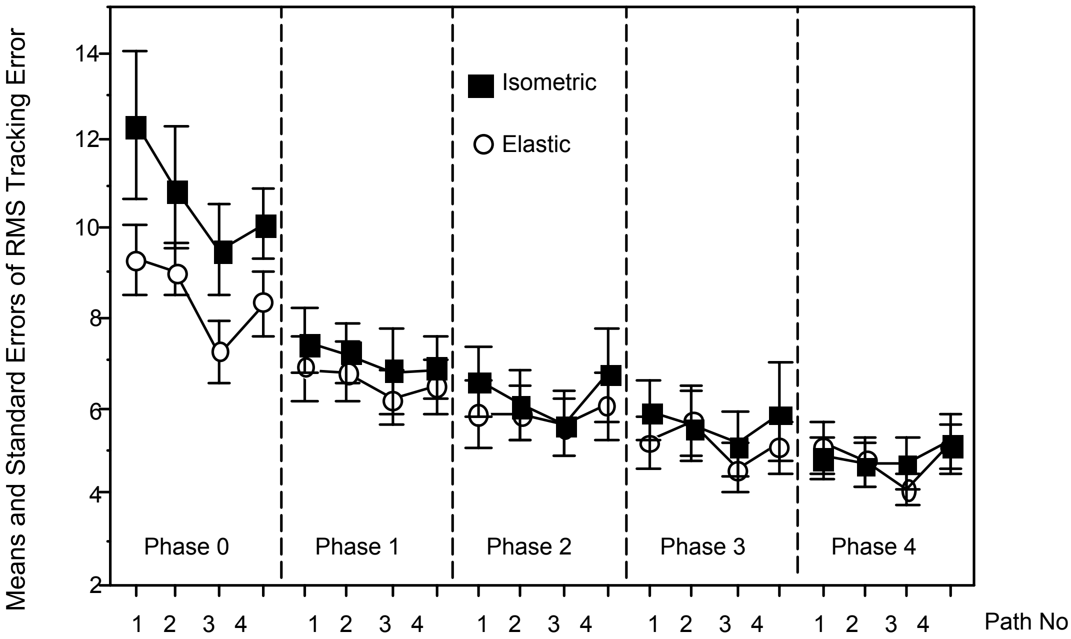


Figure 3.13 RMS error means with all tracking paths

3.3.3.2 Subjective Ratings

After each session of the experiment, the subjects were asked to comment on the ease of use/difficulty and the degree of fatigue caused by the controller used. As in Experiment 2, subjects were told that they were randomly assigned to a particular controller whose quality was unknown and that their honest opinion was needed for the evaluation.

The subjective ratings on ease of use and fatigue are shown in Figure 3.14. The elastic controller received a slightly higher average score than the isometric controller (3.23 versus 3.15). With respect to fatigue, the results appear to be more clearly in favour of the elastic controller (2.85 versus 2.23). However, these differences are not strong enough to produce statistical significance. For ease of use: $F(1, 24) = 0.058$, $p = 0.81$; for fatigue, $F(1, 24) = 2.46$, $p = 0.13$.

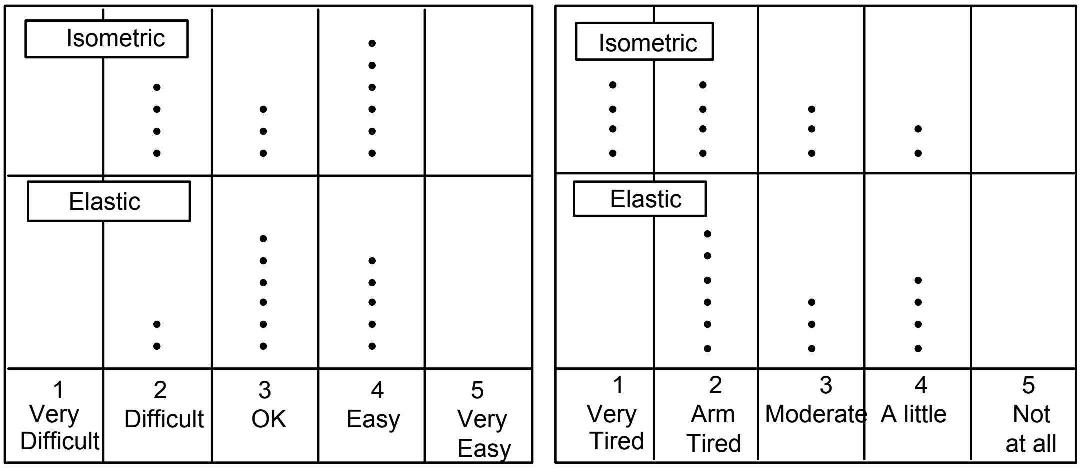


Figure 3.14 Subjective ratings of ease of use and resulting fatigue in Experiment 3 (Each dot represents one subject's rating).

3.3.3.3 Dimensional Analysis

The above RMS error analysis was conducted based on the integrated RMS error. The experimental results were also analysed by decomposing the tracking process into separate dimensions. This dimensional analysis did not provide additional information with regard to the main topic of this chapter: the differences between isometric and elastic rate control. However, it did produce some very interesting results regarding the isotropy of manipulation in 6 degrees of freedom. By decomposing the performance scores in this integrated tracking task into separate dimensions, an opportunity was created to observe the differences and similarities (or isotropies) among the 6 degrees of freedom. The degree of the difference between the Z dimension and the X, Y dimensions served as a measure for the quality of the 3 dimensional interface. As expected, subjects' performance in the Z (depth) dimension was poorer than in the X (horizontal) and Y (vertical) dimensions. The extent of performance reduction in the Z dimension was not very large, however, indicating the effectiveness of the 3D displays used in the experiment. Interestingly, the mean tracking error in the Y dimension was larger than the mean error in the X dimension and this trend was related to experimental phase, indicating a probable learning process. The complete dimensional analysis is presented in Appendix 2.

3.3.4 Conclusions

The same performance pattern in Experiment 2 reappeared in Experiment 3, although to a more obvious extent. The relative advantages of the isometric and the elastic devices were affected by experimental phase and thus were clearly a function of learning. That is, the elastic device was advantageous in the early but not later learning phases.

3.4 Discussion of Experiments 2 and 3

The first part of this chapter discussed various views on the relative advantages and disadvantages of isometric versus elastic devices. The two experiments with 6 DOF docking and tracking tasks in this chapter found that the elastic controller, when optimised to accommodate the conflicting requirement of enriching proprioceptive cues and maintaining compatibility with rate control, was indeed superior to the isometric controller. However, the magnitude of this advantage was strongly affected by learning. When enough practice was given to a particular task, subjects performed equally well with both controllers.

The findings in this chapter are in fact in general agreement with some of the recent motor learning theories and empirical studies which compromise earlier more extreme centralist versus peripheralist views. One such example is the schema theory in motor behaviour (Schmidt, 1975, 1988), which states that the human motor control system comprises two types of schemata, recall and recognition schema, similar to the recall and recognition processes found in memory schema research. The recall schema, corresponding to central resources and information outflow, form the relationship between initial conditions, response specifications and response outcome. In contrast, the recognition schema, corresponding to feedback and information inflow, form the relationships among initial conditions, *sensory feedback* and response outcome. Both recall schema and recognition schema play important roles in motor movement. Their relative contribution depends on the pace of the task and the subjects' experience with the task.

The fact that as learning progresses human motor strategies shift from closed loop behaviour towards open loop behaviour, typically with decreasing importance of visual feedback, has been demonstrated by many researchers. In studying the organisational structure of human motor skills, Pew (1966) , for example, found that motor skills were initially based on feedback but progress towards a hierarchical structure that is more centrally based. Pew reviewed many other motor control theorists' views and asserted: "The underlying themes of these proposals is the hierarchical nature of the control of skilled acts which develop with practice beginning with strict closed-loop control and reaching levels of highly automatized action with occasional 'executive' monitoring". Kohl and Shea (1992) recently replicated Pew (1966) and confirmed Pew's findings.

Based on tracking skill research, Krendel and McRuer (1960; also see Jagacinski and Hah, 1988 for a recent review) proposed their so called "successive organisation of perception (SOP)" theory. Krendel and McRuer identified three modes of tracking behaviour: error nulling, input reconstruction and precognitive behaviour. In the error nulling mode, subjects rely primarily on visual, exteroceptive information to minimise tracking error. In input reconstruction mode, subjects utilise additional proprioceptive information to form control actions. In precognitive mode, subjects depend on open-loop tracking patterns reproduced from memory, while exteroceptive and proprioceptive feedback become less important. With practice, in other words, subjects' behaviour progresses from the error nulling mode to the input reconstruction mode to the precognitive mode, while the source of information used shifts respectively from the visual exteroceptive to the proprioceptive and then to internal memory.

The results of the present experiments appear to support the above theories and findings. In the early learning stage, when control behaviour was dominated by closed-loop inflow processes, the richer proprioceptive feedback from the elastic controller provided an advantage to the subjects in the elastic group relative to the subjects in the isometric group who had less rich proprioceptive feedback. As learning progressed, information feedback became less important and internal open loop mechanisms (motor programs) began to play a more important role, i.e., the motor control behaviour became more open-loop. Similar performance for the elastic and the isometric rate control conditions was therefore found in the later stages of the experiment.

The practical implications of the results can be interpreted a number of ways. First, the elastic controller is indeed a more advantageous device for 6 DOF manipulation, in comparison with the isometric device. In 6 DOF manipulation, the widely presumed rapidness of isometric devices can hardly be utilised, due to the complexity of spatially and temporally co-ordinating all six degrees of freedom. On the other hand, isometric devices are limited relative to elastic devices in offering less rich proprioceptive cues, which can have a more pronounced effect in 6 DOF tasks. Second, with enough practice, performance with isometric devices can catch up with that of elastic devices but the time required might be much longer than indicated in the particular experimental task performed here (i.e. 20 to 40 minutes). In the experiment, subjects allocated full attention to the task and were coached thoroughly. In reality, especially in practical computer applications, where the users might not be trained *operators* as in aircraft piloting and teleoperation, users might take a long time to reach stable performance with isometric devices. Third, equal performance does not mean equal *effort*, hence the differences between the two controllers may reappear when the user has higher workload or under stress conditions. In the progression-regression theory of human motor skills, Fuchs (1962) and Jagacinski and Hah (1988) suggest that when under stress, subjects may return to early behaviours. In the current context, users might therefore perform better with an elastic device when facing stress. Other authors, such as McKinnon et al. (1987) and McKinnon and King (1988) , have also pointed out the probable disadvantages of isometric devices in stressful teleoperation tasks.

3.5 Summary

The chapter began with analyses and literature reviews of elastic and isometric devices. It was realised that two factors, compatibility with rate control due to self-centring and proprioceptive feedback, play the most important roles in determining the differences between isometric and elastic devices. The literature suggests that an elastic device may provide richer proprioceptive feedback than an isometric device. Two experiments involving 6 DOF manipulation showed that the difference between an elastic device and an isometric device was not great with respect to performance, but rather with respect the ease of learning. Due to its richer proprioceptive feedback, the elastic device was easier to learn than the corresponding isometric device. After sufficient practice, subjects' control behaviour apparently became more open-loop, with motor program based skills, and therefore the richer proprioception provided by the elastic device was no longer a critical determinant of performance.

Chapter 4

The Effects of Utilising Fine Muscle Groups

4.1 Introduction

This chapter focuses on the effects of using different muscle groups in 6 DOF manipulation. In particular, it investigates human performance differences in 6 DOF input control with and without the involvement of the small muscle groups (fingers). The issue of using different muscle groups in manual control has been studied in low degree of freedom manipulation (e.g. Gibbs, 1962; Hammerton and Tickner, 1966) . 6 DOF manipulation poses a greater challenge to the ergonomic design of input devices, however. If muscle group differences have a minor effect on relatively easy 2 DOF control tasks, they might affect 6 DOF control tasks much more significantly.

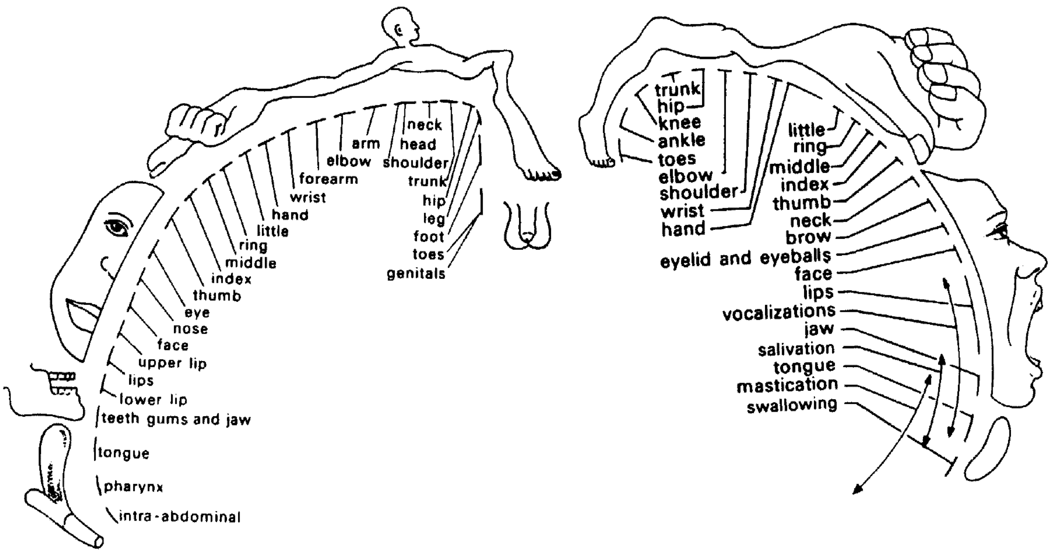


Figure 4.1 Homunculus model of somatosensory (left) and motor (right) cortex;: showing the mapping between different body parts and the brain (Adapted from Sage 1977).

Neurophysiological studies have shown that various parts of the human body are represented in the brain disproportionately relative to their physical size and mass as illustrated in Figure 4.1. Of particular interest to this chapter is the fact that the representations of the fingers and the hands in both the somatosensory cortex and the motor cortex are much richer than those of the wrists, elbows and shoulders, as illustrated in the homunculus model of the somatosensory and motor cortex.

The homunculus model suggests that a potential performance enhancement will result if fine muscle groups (i.e. fingers) are allowed to take part in handling an input device. Indeed, this potential has already been considered in the use of the Spaceball and the EGG in this thesis, where subjects in Experiment 2 and 3 were asked to use their fingers to grip the control handle during the experiments. Interestingly, one of the most common types of virtual reality input devices, the instrumented glove, such as the one shown in Figure 4.2, does not utilise this potential advantage. When using a glove, all translation and rotation operations are carried out by the user's shoulder, elbow and wrist. i.e. the gross joints and muscle groups in the human limb. The smaller, finer joints and muscle groups on the fingers are not utilised.

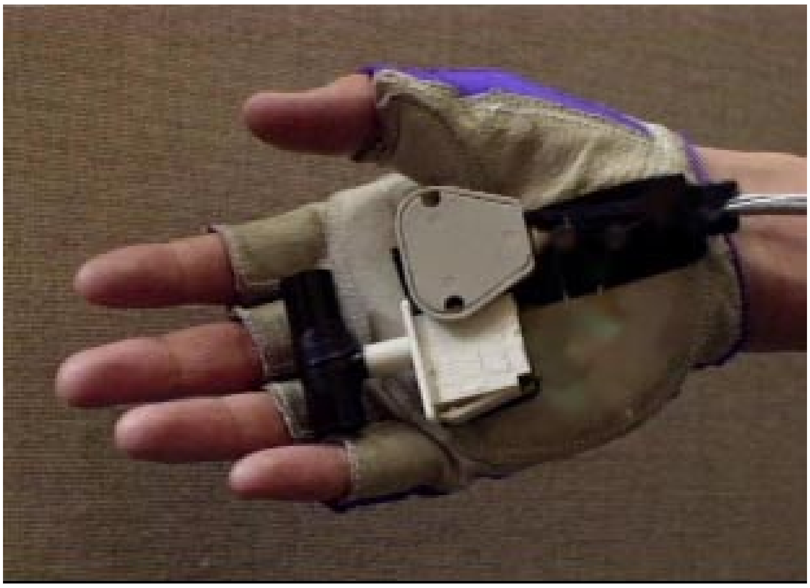


Figure 4.2 The glove used in Experiment 4

Experiment 1 showed that the glove as an isotonic device performed well in position control mode. Can an even better 6 DOF isotonic device that also utilises small muscle groups, with a concomitant increase in the number of effector degrees of freedom, be designed and implemented? Will such a device in fact outperform the glove? Before addressing these questions, the related literature on one and two degree of freedom devices is reviewed.

4.2 Literature and Analysis

Gibbs again took the leading role in studying the effect of different body parts in manual control. In a one dimensional target acquisition task, Gibbs (1962) studied the effect of three different body parts: the thumb (activated by the carpometacarpal joint), the hand (activated by the wrist), and the forearm (activated by the elbow) in both position and rate control systems with various control gains and time delays. Subjects' performance in Gibbs' study according to the ranking was: hand, forearm, and thumb.

Hammerton and Tickner (1966) later replicated Gibbs' study in a 2 DOF target acquisition task. Although Gibbs subsequently argued with Hammerton and Tickner about experimental methodology and credit ownership (Gibbs, 1967; Hammerton and Tickner, 1967) , the two studies in fact arrived at a very similar conclusion, that performance with the hand (wrist movement) was superior to that of the thumb and the forearm. This advantage was greater in more difficult tasks such as those with long time delays (Hammerton and Tickner, 1966) . Note that both studies found that the wrist was more effective than the thumb. Neither Gibbs nor Hammerton and Ticker included fingers in their studies, however.

The motor performance of different limbs has also been investigated in various Fitts' law studies. Fitts' law (Fitts, 1954) established the simple linear relationship: MT = a + b ID in tapping tasks, where MT is the movement time, ID = $\log_2(2A/W)$ is the Index of Difficulty, A is the movement amplitude and W is the width of the target area. The slope parameter b, in units of seconds/bit, is the inverse of the motor system information processing rate. Fitts' law studies typically found this rate (1/b) to be in the vicinity of 10 bits/second when the arm was involved in the movement. Fitts (1954) speculated that other limbs such as fingers may show different processing rates. Later studies supported this hypothesis. Langolf, Chaffin, and Foulke (1976) investigated the Fitts' law relationship using amplitudes of A = 0.25 cm, A = 1.27 cm and A > 5.08 cm. For the first two amplitudes, the experiment was carried out using a microscope. For the large range (>5.08 cm), the experiment was carried with direct vision. Langolf and colleagues observed that for A = 0.25 cm subjects moved the stylus tip (a 1.1 mm peg) primarily with finger flexion and extension. For A = 1.27 cm, flexion and extension of both wrist and fingers occurred. For A > 5.08 cm, the forearm and upper arm were involved in the movements. With this method of allocating actuation to different muscle groups by controlling the range of movement, Langolf and colleagues concluded that the information processing rates (1/b) for the fingers, wrist, and arm were 38 bits/sec, 23 bits/sec and 10 bits/sec respectively (see Figure 6 in Langolf, et al., 1976). This study has been widely cited in the literature (e.g. Boff and Lincoln, 1988; Keele, 1986; Card, Mackinlay, and Robertson, 1991) as evidence that fingers are among the most dextrous organs.

Card et al. (1991) recently reviewed Fitts' law studies with various body parts (finger, wrist, arm, neck) and pointed out the limitations of the widely used computer input device - the mouse. They suggested "a promising direction for developing a device to beat the mouse by using the bandwidth of the fingers". Experimental work has not yet been produced to support this prediction, however.

In summary, both neurophysiological studies (the homunculus model) and Fitts' law studies suggest that use of the small muscle groups (fingers and thumbs) should result in better performance than the large muscle groups (arm and shoulder). However some studies in manual control (e.g. Gibbs, 1962; and Hammerton and Tickner, 1966) are not completely consistent with such a prediction.

Due to their theoretical motivation, most studies in the literature tend to compare performance of different muscle groups *against* each other. From a practical and ecological point of view, such a contrast is not necessary for the design of a 6 DOF input device. The human upper limb as a whole (from shoulder to finger tips) has evolved to be a highly dextrous and yet powerful device. Every part of it has its purpose and function. What is needed in input device design is to make use of all the parts according to their respective advantages. The larger muscle groups that operate the wrist, elbow, and shoulder have more power and a larger range of movement. The smaller muscle groups that operate the fingers and thumb have more dexterity. When all the parts work in synergy, movement range and dexterity can both be maximised.

4.3 Design of the FBALL

The preceding proposal suggests that improvement over the glove design for a 6 DOF isotonic device does not necessarily lie in moving operations from the large muscle groups to the smaller ones, but rather in using the small muscle groups *in addition to* the large ones. Motivated by this hypothesis, an isotonic position control alternative to the glove design, as shown in Figure 4.3, has been designed and implemented. This device has been dubbed the Fball, to reflect its nature of **f**ree-moving (isotonic) in 3D space ("**f**lying"), as well as the intention of operation with arm and **f**ingers.

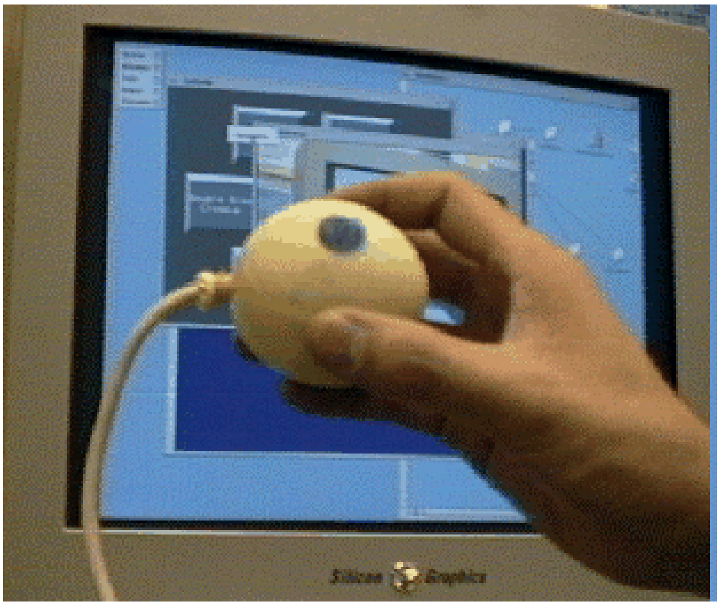


Figure 4.3 The Fball

The ball shape was chosen because a symmetrical ball shape can be easily grasped and manipulated by the fingers in all directions. The Fball is designed to be held and moved (rolled) by the fingers, wrist, elbow and shoulder, in postures that have been classified as "precision grasp", as opposed to "power grasp" (Cutkosky and Howe, 1990; MacKenzie and Iberall, 1994) . Precision grasping, while holding objects with the finger tips, puts emphasis on dexterity and sensitivity. In contrast, power grasping, while holding objects against the palm, puts emphasis on security and power. The Fball is also a versatile shape that can be engaged with different types of object shape in a manipulation task.

To take maximum advantage of finger operations, two additional features are desirable. One is to make the ball tetherless, so that the user can roll it between her fingers without interference. The second desirable feature is that the ball be made of an elastic, conductive material, so that the entire ball functions as a button that can be squeezed from any direction. Enabling technology for wireless design is not easily available. The Fball currently uses the Ascension Bird™ mounted in the centre of an elastic ball 6 cm in diameter. The cord of the Bird is pointed away from the hand in the null position, so as to maximise the range of rotation without interference from the cord (Figure 4.3).

In the design of the glove (Figure 4.2), the clutch was an essential component. Since the glove requires rotation to be made with the wrist, the elbow and the shoulder, the range of rotation is limited in one movement. Whenever a limit is reached, the user needs the clutch to disengage the manipulated object and restore the hand to a more comfortable posture in order to recommence the manipulation. This is very similar to lifting a 2D mouse and starting from a new position on the mouse pad. We refer to this process as "re-clutching". It is also called "indexing" by some authors (Johnsen and Corliss, 1971).

Since the Fball can be rotated up to 180 degrees in any direction, however, the clutch becomes unnecessary and has therefore been eliminated from the following experiment. The 3Ball™, manufactured by Polhemus, is a commercial product similar to the Fball design. The limitation of the 3Ball is its fixed button location. In order to access this button, users can not easily roll the ball between their fingers.

Other existing designs of freely moving 6 DOF devices, such as the "Bat" (Ware, 1990) , the "Cricket" (DIDI, 1993) and the 3D mouse (Logitech, 1991) are similar to the glove design in assigning wrist, elbow and shoulder muscle groups for manipulating the six degrees of freedom, but not the fingers. The "Bat" and "Cricket" are shown in Figure 1.1 in Chapter 1.

4.4 Experiment 4

4.4.1 Experimental Set-up

4.4.1.1 Experimental Conditions

Two experimental conditions were used in this experiment: the glove and the Fball. A pilot study showed that the best performances with both conditions were achieved when the control display ratio (control gain) was 1. In such cases, subjects can take the advantage of the direct mapping nature of the 6 DOF isotonic position controls.

4.4.1.2 Experimental Task

A docking task was used for this experiment. This task was very similar to those of Experiments 1 and 2, except for the initial cursor and target positions. In Experiments 1 and 2, the target stayed in the centre of the 3D space while the cursor randomly appeared in one of the four pre-set arbitrary locations and orientations. In this experiment, at the beginning of each experimental trial the cursor appeared instead in the centre of the 3D space while the target randomly appeared in one of five pre-set arbitrary locations and orientations. During practice sessions, the target appeared in completely uncontrolled random locations and orientations. This exchange of the target and the cursor locations was designed to increase the level of task difficulty, an issue identified from Experiment 2 results. When the target was kept in the centre of the 3D display, the final fine positioning stage of the docking task was always carried out around in the same location. Subjects might bring the cursor to the same location (typically in front of the target) and then push it to the target. This means that regardless of the initial cursor locations, the final stage of the docking task remained essentially the same, making it very easy to learn. In contrast, when the target is randomly assigned to one of the multiple locations, subjects were forced to use a different set of control movements for each target location, hence facing an increased level of difficulty.

4.4.1.3 Experimental Design

A within-subjects design was used in this experiment in consideration of efficiency. Each subject was tested with both of the two conditions, the glove and the Fball, on the same day. According to the results in Experiment 1, subjects' performance with the isotonic position control started to stabilise after 20 minutes of practice. In this experiment, each condition was given about 25 minutes of exposure, which was composed of five tests and some practice trials between tests. Each test consisted of two identical blocks of trials. Each block had 5 trials with 5 distinctive initial target locations in random order. Test 1 started after a short demonstration and two warm-up trials. Test 2, Test 3, Test 4 and Test 5 started 5, 10, 15, and 20 minutes after the beginning of Test 1 respectively. Including the demonstration and warm-up trials, each condition of the experiment took approximately 25 minutes. Subjects were alternatively assigned to one of the two experiment orders: glove first (GB) and Fball first (BG). After completing the first condition, a short break was given to the subject before proceeding to the second condition.

4.4.1.4 Subjects

Twelve paid volunteers who had not participated in Experiments 1, 2 and 3 were recruited. Two of them failed to pass the screening task due to weak stereopsis (using the Baush and Lomb Orthorator). The remaining 10 participated in the complete experiment. Their ages ranged from 22 to 33, with median 29. Eight of the subjects were right handed and two were left handed. Subjects were asked to use their dominant hand in using both input devices (Fball or glove).

4.4.2 Within-Subjects Analysis of the Overall Results

As in the analyses of the earlier experiments, log transformation was applied to the completion time data to meet the residual distribution requirement in ANOVA for the following statistical analysis.

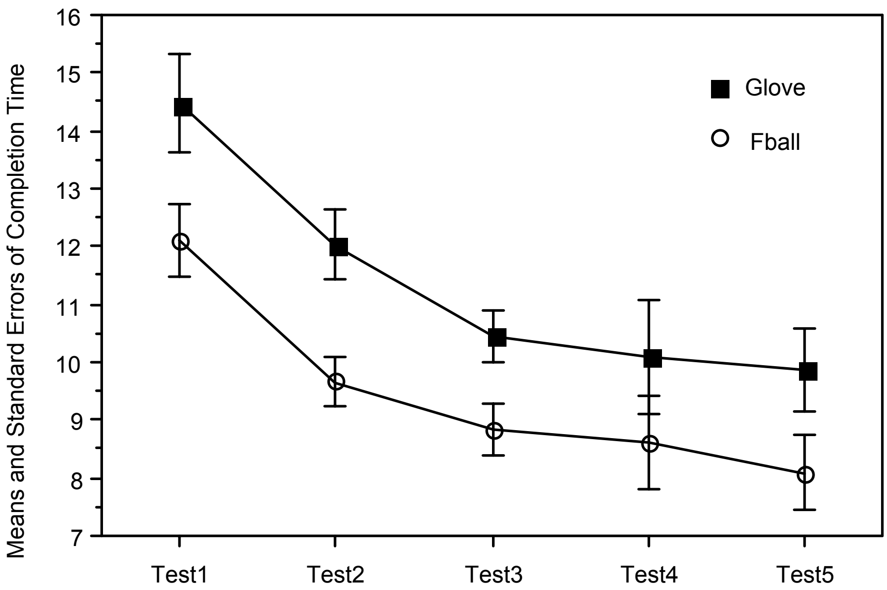


Figure 4.4 Task completion times with Fball and Glove

Figure 4.4 shows the subjects' mean trial completion times in each of the five tests. On average, task completion times were shorter for the Fball than for the glove in each of the five tests. This performance difference remained consistent over different learning phases. Repeated measures analysis (Table A3.4.1, Appendix 3) showed that overall performance with the two devices was significantly different: $F(1, 8) = 26.554$, $p < 0.005$.

With both modes, subjects significantly improved their performance over the five learning phases: $F(4, 32) = 34.04$, $p < 0.0001$. The performance difference between the two modes was independent of learning phase, as indicated by the absence of a significant interaction: Device x Phase: $F(4, 32) < 1$, $p > 0.5$. Other significant factors included Block:

F(1,8) = 26.44, p < 0.001. As said earlier, each test consisted of two blocks of trials. Completion times in the second block were significantly shorter than for the first block, due to the learning effect.

The presentation order of the two modes was not significant: F(1,8) = 2.2, p > 0.1 but Order x Device interaction was significant: F(1,8) = 22.587, p < 0.005. This could imply an asymmetrical skill transfer due to within-subjects design (Poulton, 1969, 1974). Note that the Order x Device x Phase interaction is also significant, indicating that the transfer effect varies with learning phase. Two approaches were taken to test if possible asymmetrical skill transfer has caused the performance difference between the Fball and the glove. First, a between-subjects analysis (4.4.3) has been carried out. Second, as we have seen, the performance difference between conditions in test 5 is very similar to early tests but asymmetrical skill transfer is least likely to be still in effect after 4 tests and 20 minutes of practice with the second device. A within subject analysis (4.4.4) was therefore conducted with data collected from the last test.

4.4.3 Between-Subjects Analysis

In order to remove the possibility that the results were due to asymmetrical skill transfer, a between subjects analysis was carried out with only the data for the first device used by each subject. Subjects were divided into two groups. Members of the Fball group were the subjects who were tested with the Fball first and the glove later. Their data with the glove were discarded for the between subject analysis. Similarly, the Fball data were discarded for the group who tested the glove first. This approach is expected to be much less sensitive than the within subject analysis in last sub-section, given the small number of subjects in each group. Figure 4.5 shows the results after discarding half of data. Table A3.4.2 shows

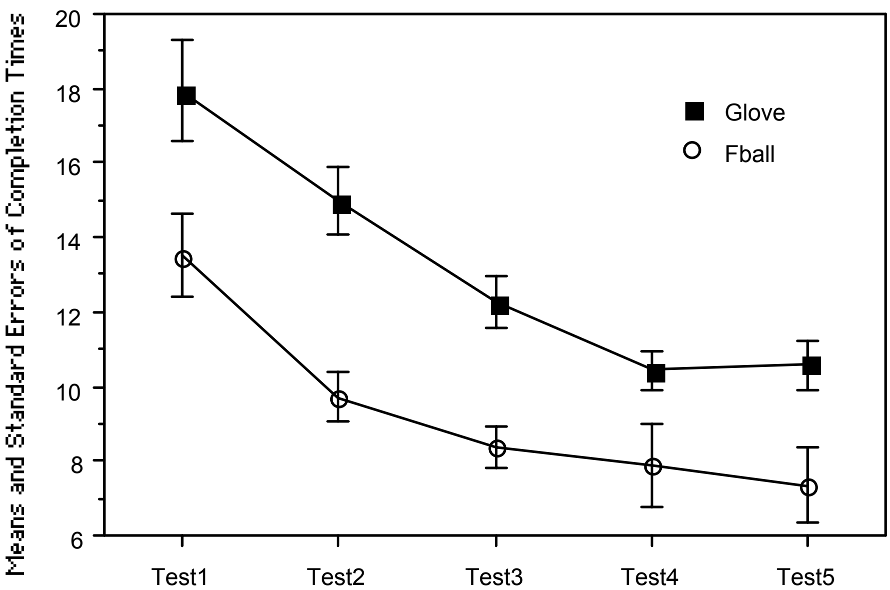


Figure 4.5 Between-subjects analysis of Fball versus Glove

the results of the repeated measure variance analysis of this between subject design. The major conclusions with regard to the Fball versus the glove were consistent with the early analysis, i.e., completion time with the Fball was significantly shorter than the glove: $F(1,8) = 3.6$, $p < 0.05$. Learning did not reduce this difference, as the Phase x Device interaction was insignificant: $F(4, 32) < 1$, $p > 0.5$.

In conclusion, the between-subjects analysis performed by dropping half of the experimental data still reached the conclusion that the Fball outperformed the glove.

4.4.4 Performance Analysis of the Final Test

This subsection analyses the performance in the last test in each condition, using the within-subject, repeated measure method. Table A3.4.3 in Appendix 3 summarises the results of this analysis which again confirmed the conclusions drawn from previous two approaches: completion time was significantly shorter with the Fball than with the glove: $F(1, 8) = 15.8$, $p < 0.005$. Furthermore, neither Order of presentation, nor Order x Device interaction was significant, meaning that any possible skill transfer effect between conditions did not significantly affect performance in the last test.

On the basis of all the above three methods of analysis, we can therefore confidently conclude that the Fball outperformed the glove in the experiment.

4.4.5 The Effect of Clutching vs. Muscle Groups

From a practical point of view, the above analyses have concluded that the Fball is a more efficient device than the Glove. However, from a more theoretical point of view, the cause of the performance differences is still not clear. As discussed earlier in this chapter, the Fball differs from the glove in two major aspects: the use of finger joints and the absence of a clutch. With the glove, when the subject reaches an awkward posture, he/she has to disengage the glove (by releasing the button under the fingers), restore the hand/arm to a more comfortable posture and re-engage (by closing the fingers around) the manipulated object. This re-clutching process takes time to complete (from the moment of disengaging to the moment of re-engaging). Subject usually make 1 to 3 clutches/declutches in each trial. This could be the sole cause of the performance difference in above analyses, leaving the effect of using finger joints/muscle groups unknown.

This issue had been considered during the design stage of the experiment, however. The accumulated re-clutching time was recorded during the experiment. In the following analysis, the re-clutching times are subtracted from the trial completion times for the glove condition. The net score is labelled as C-R Time. Note that the C-R Times is a biased measure against the Fball condition for two reasons. First, with the Fball, the re-clutching process still exists, although not as explicitly. From time to time subjects had to move the fingers to different parts of the ball surface to make further rotation. This effort (and time) was not taken into account by the C-R time, since no explicit re-clutching time could be measured. Second, during the re-clutching time with the glove, subjects were not necessarily idle but probably instead engaged in mentally making decisions about what to do next. It is known that mental rotation takes up a certain amount of time (Shepard and Metzler, 1971) . This time may overlap with the re-clutching time in the glove condition and is therefore reduced in the C-R Time measure. Nonetheless, C-R Time serves as a conservative measure to test if the use of fingers was really advantageous. If the Fball still outperformed the glove as measured by C-R Time, the advantage of using fine joints must exist. However the converse may not be true.

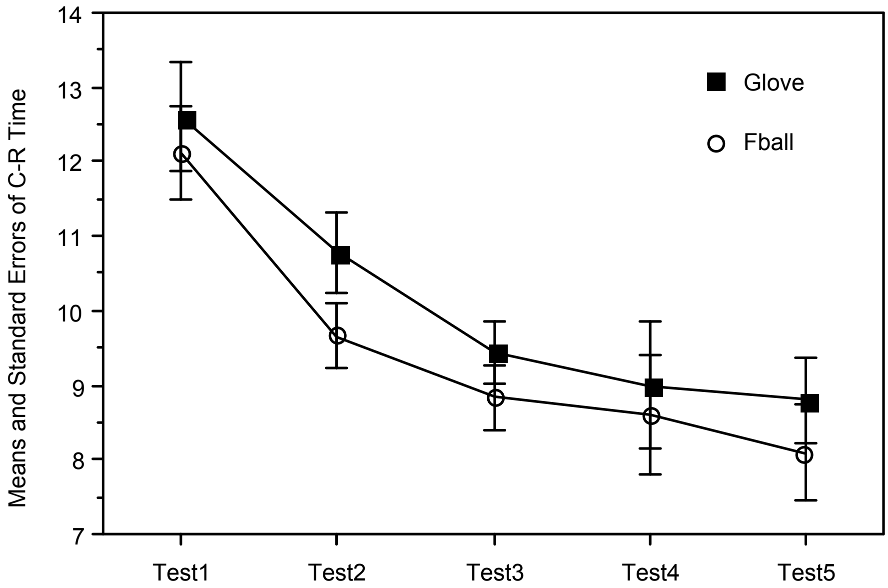


Figure 4.6 Comparison between the Fball and the glove after discounting re-clutching time with the glove

Figure 4.6 shows the performance differences between the Fball and the glove as measured by C-R Time. As can be seen, the mean completion times with the Fball were still shorter than the mean C-R Times with the glove. Table A3.4.4 in Appendix 3 shows the results of repeated measure variance analysis of C-R Times collected in Test 5 (Last phase of experiment). The difference between completion time with the Fball and the C-R time with the glove is still significant: $F(1,8) = 5.324$, $p < 0.05$. Neither the order of presentation nor its interaction with device was statistically significant, suggesting that this difference was not caused by asymmetrical skill transfer.

The analysis with C-R Time, which exclude the effects of the clutch, therefore further supports the conclusion that the use of different muscle groups is indeed one cause of the superior performance of the Fball as compared to the glove.

4.4.6 Subjective Evaluation

Upon completing the experimental trials, subjects rated each of the devices on a continuous scale ranging from -2 to +2 (-2: very low, -1: low, 0: OK, 1: high, 2: very high). Of the 10 subjects, 6 rated the Fball higher than the glove. The other 4 subjects rated the glove higher than the Fball. Subjects were encouraged to jot down comments on features about which they felt strongly. Seven subjects felt that the cord with the Fball got in the way. Three subjects did not like the wrist rotations imposed by the glove. Two subjects wrote that the

Fball was less natural than the glove. One subject particularly liked the clutch function with the glove. One subject reported fatigue with both devices.

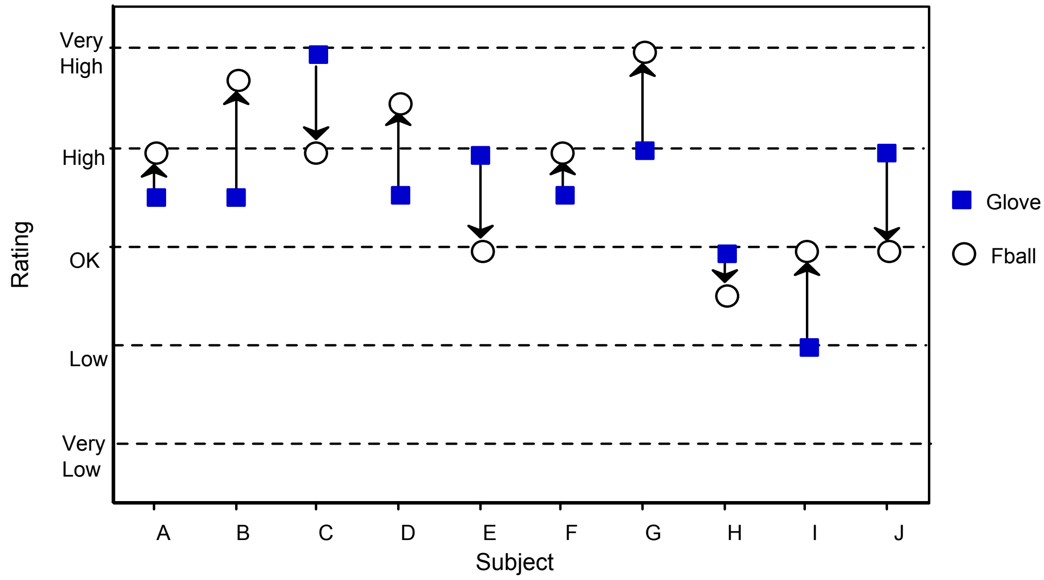


Figure 4.7 Subjective Ratings of Fball vs. Glove;, Upward arrows indicate that the Fball was preferred

Figure 4.7 shows the ratings each subject gave to the Fball and the glove. On average, the Fball received higher ratings than the glove (mean value: 0.78 vs. 0.60, 0 is OK, 1 is high), but this difference was not statistically significant: $F < 1$, $p > 0.5$.

The ambiguous subjective ratings are in obvious contrast with task performance measures. In the last test, all subjects, except subject A, had a shorter task completion time with the Fball than with the glove (Figure 4.8). Subject A reported fatigue during his last Fball test. (This was also the last test in his entire session). His second last test with the Fball had a much shorter mean completion time (6.98 second).

One possible reason for the disparity between the performance measures and the subjective evaluations could be that the subjective preferences were strongly affected by some salient features of the devices. In this experiment, the Fball cord could be such a feature. Although most of the subjects were able to overcome the inconvenience caused by the cord and indeed performed better with the Fball than with the glove, 4 of them still rated the Fball lower than the glove, possibly due to the interference of the Fball cord. One other reason could be that some subjects felt more "natural" with the glove. This is discussed further in next subsection.

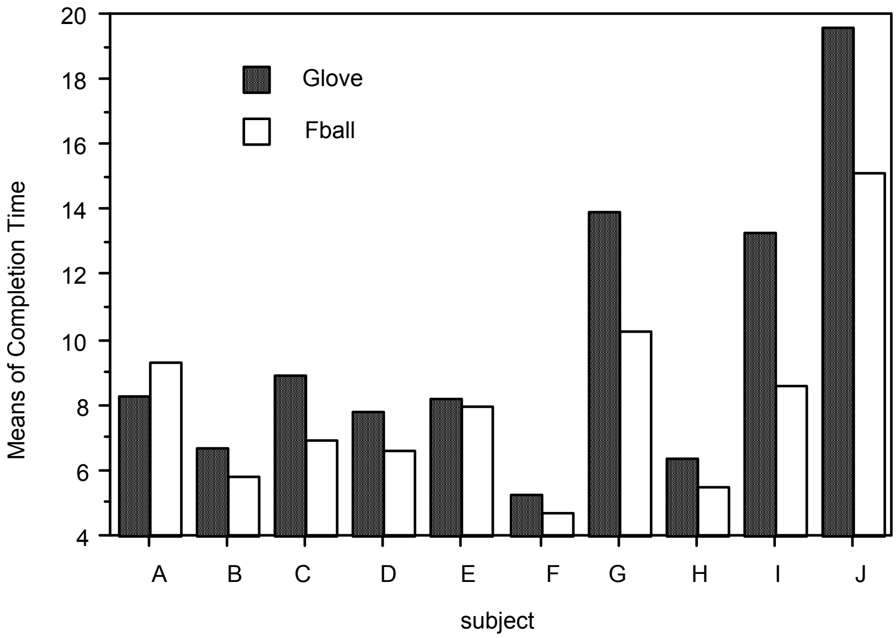


Figure 4.8 Mean completion time in test 5 of Experiment 4 for each subject

4.5 Discussion and Conclusions

As measured by task completion time in a 6 DOF docking task, the experiment has conclusively shown that the Fball is a more efficient isotonic position control device than the glove for this class of manipulation tasks, although this performance advantage was not unanimously supported by subjective ratings.

Theoretically, there are two major differences between the Fball and the glove. The Fball allows the use of finger joints in addition to the shoulder, elbow and wrist, while the glove uses the shoulder, elbow and wrist only. The second difference is that the glove utilises a clutch to resolve the limited range of rotation by the wrist and the arm, by allowing the user to release the object and reset the hand position (re-clutching). The re-clutching process takes a certain amount of time. Figure 4.9 shows the mean completion time with the Fball, the mean completion time with the glove, and the re-clutching time with the glove, all from test 5. The mean re-clutching time in test 5 was 1.056 second, accounting for 10.7 % of the mean completion time with the glove. Statistical results demonstrated that the use of finger joints for the Fball operation must be beneficial, since the Fball outperforms the glove even if the re-clutching times with the glove are subtracted from the total completion times.

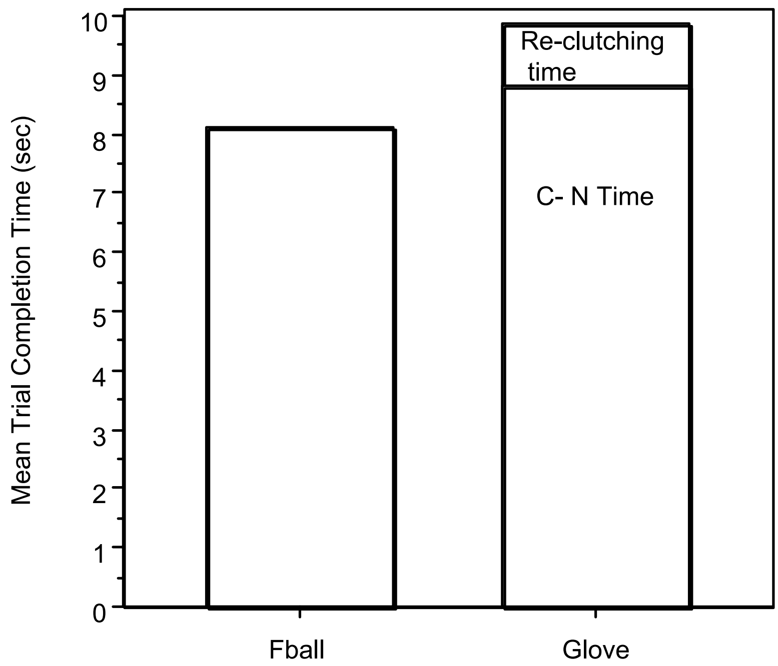


Figure 4.9 Mean completion time in Test 5 of Experiment 4

Chapter 5

Displaying User's Input: Utilising Semi-transparency in 3D Interaction

5.1 Introduction

An important part of the input control process is displaying the user's control actions in relation to the target location (see Figure 1.1). How this display is designed can have a significant impact on input control performance. In the history of manual control research, the configuration of displays has been an inseparable part of the literature. The various studies on compensatory displays versus pursuit displays are such an example (See Poulton, 1974 for a review).

A unique challenge in designing interaction systems with 6 degrees of freedom is to effectively reveal the user's actions in relation to the target location in the depth dimension. If this relationship is not readily perceived by the user, effective input control can not be achieved, regardless of how well other parts of the interaction system are designed. In fact, much effort has been put into the design of displays used in the preceding experiments. None of those experiments could have been carried out without implementing proper 3D displays. For example, without stereoscopic displays, subjects simply could not perform the docking task, because the subject could not determine where the tetrahedron cursor (or target) was pointing and thus he/she could not decide in which direction to rotate the cursor.

Visual perception research has identified many depth cues that allow humans to readily perceive natural 3D world. Correspondingly many techniques, such as stereoscopic viewing, have been invented to produce these cues in artificial ways. This chapter focuses on a novel 3D mechanism, the partial occlusion effect, which is implemented by the use of semi-transparent surfaces in 3D graphic displays. The chapter starts with a brief review of various depth cues in human perception and their exploitation in corresponding 3D display techniques. It then proceeds to an experiment to evaluate the use of the semi-transparency effect in a 3D target acquisition task. The experimental results are then discussed, with particular emphasis on the semi-transparency cue characteristics for 3D interaction and the modelling of multiple depth cues. Finally, some existing and future potential applications of semi-transparency in 3D interaction are presented.

5.2 Presenting Depth Information

A variety of techniques are commonly used in computer interfaces for presenting 3D information. Almost all of these techniques can be linked to the depth cues identified in psychological research on human perception in the natural environment (See Haber and Hershenson, 1973; Kaufman, 1974; Wickens, Todd, and Seidler, 1989; McAllister, 1993 for reviews of depth cue theory). The most commonly exploited depth cues include occlusion, binocular disparity, perspective, shadows, texture, motion parallax and active movement. To put the study of semi-transparency into perspective, this section briefly reviews these depth cues and their applications to 3D interaction systems.

Occlusion is one of the most dominant cues in depth perception (Schriever, 1925) . Objects appearing closer to the viewer occlude other objects which are further away from the viewer. In 3D computer graphics, the importance of occlusion has long been recognised, most commonly through the use of hidden line/surface removal techniques.

Stereopsis, produced from binocular disparity when viewing 3D objects in natural environments, is a strong depth cue, particularly when the perceived objects are relatively close to the viewer (Yeh, 1993) . Various techniques have been devised to create stereopsis on a 2D screen (Arditi, 1986; McAllister, 1993) . The currently most common method uses liquid-crystal time-multiplexed shuttering glasses. The effectiveness of stereoscopic displays strongly depends on the particular experimental task to which they are applied and on technical implementation variables such as shutter frequency and equivalent binocular perspective.

Perspective and relative size cues, which account for objects further away producing smaller retinal images than closer objects, are commonly exploited in 3D graphics (Foley, van Dam, Feiner, and Hughes, 1990) . Perspective cues are particularly effective when the displayed scene has parallel lines, as noted by Brooks (1988) .

Operating on the same principle as for perspective and size cues, the densities of surface features *(texture)* increase for more distant surface elements. *Texture* cues are therefore also described as detail perspective (Kaufman, 1974) .

The *shadow* of a 3D object is also often an effective depth cue. Herndon, Zeleznik, Robbins, Conner, Snibbe, and van Dam (1992) , for example, explicitly exploit shadows for 3D interaction. In their design, shadows are projected on walls and floors of a 3D environment so that the user can control object movement in each dimension selectively by choosing and moving the shadows. The use of shadows is also an important element of the information visualisation display proposed by Robertson, Mackinlay, and Card (1991) .

Motion parallax . When an *object* moves in space relative to an observer, the resulting motion parallax produces a sensation of depth. This effect is also frequently exploited in graphical displays. For example, Sollenberger and Milgram (1993) showed the usefulness of the kinetic depth effect in graphically visualising the connectivity of complex structures such as blood vessels in the brain.

Active movement. Depth information obtained by actively altering a viewer's *own* viewpoint is often referred to as movement cue. Motivated by the Gibsonian ecological approach, Smets and colleagues (Smets, 1992; Overbeeke and Stratmann, 1988) demonstrated the advantages of the active observer, for whom images on a screen were drawn according to tracked head movements, in comparison with a passive subject, whose head movements were not coupled to the displayed image. In a path-tracing experiment, Arthur, Booth, and Ware (1993, also Ware and Arthur, 1993) found that while subjects' task completion times with an active head-tracking display and a stereoscopic set-up were similar, their error rates were significantly lower with the head tracking condition.

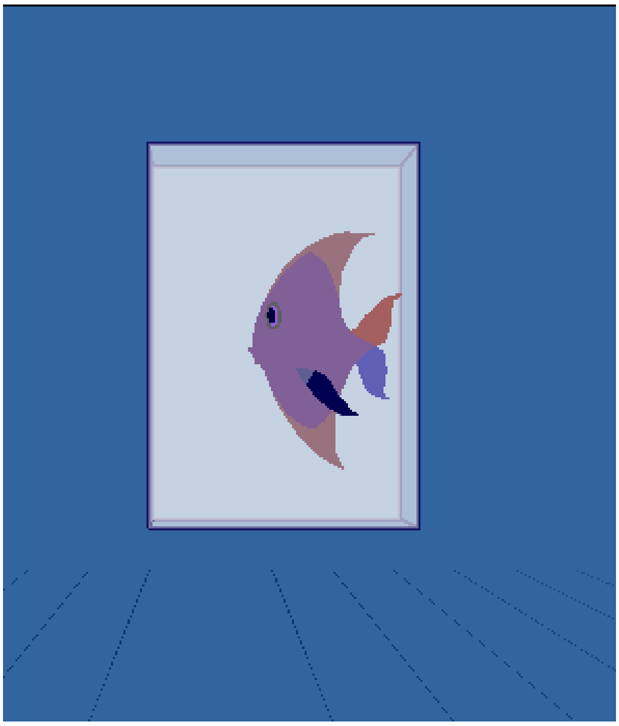


Figure 5.1 The Partial occlusion effect; Portions of an object appearing in front of or behind the semi-transparent "silk" surface are perceived as such according to different levels of contrast.

As we can see, many of these depth cues have been carefully investigated and consciously applied to graphical displays. There is yet another phenomenon, produced by *semi-transparent* surfaces, which can be a strong depth cue. Whenever a semi-transparent surface overlaps another object, the viewer will see not only the proximal occluding object, but also the overlapped or *partially occluded* object, or portions of that object, in lower contrast (Figure 5.1). One example of this phenomenon in everyday life is the silk stocking; hence the semi-transparency* cue is referred as the "silk" effect in this chapter.

The effectiveness of semi-transparency as a depth cue has not been the subject of the same extensive research as other depth cues, possibly because semi-transparency is not

* A related term, "translucent", could conceivably have been used here; however, that term has been avoided in this thesis due to the concern that it could also have been construed as meaning "transmitting and diffusing light so that objects beyond cannot be seen clearly" (Webster's Ninth New Collegiate Dictionary).

experienced very commonly in the natural environment. There are many reasons to hypothesise that the partial-occlusion effect introduced through semi-transparency would be no less powerful than some of the more common depth cues used in 3D interactive systems. First, the literature has well concluded that interposition is one of the strongest depth cues. However, it is difficult to utilise the total interposition cue in 3D interaction systems, since objects further away are completely obscured. A semi-transparent surface, on the other hand, does not completely occlude distal objects. Such partially occluded objects only appear with lowered contrast, which should assist the viewer in perceiving the relative location of the distal object relative to the semi-transparent surface. Second, in a graphical environment, the partial occlusion effect can be enhanced *interactively*. When a "silk" surface is gradually moved *through* an object, the resulting immediate changes in the object's appearance (see Figure 5.1) are continuous. This suggests a potentially powerful mechanism for displaying users' input actions in relation to targets in 3D space.

5.3 Experiment 5*

5.3.1 Experimental Set-up

5.3.1.1 Experimental Platform

MITS, the same experimental platform as in the previous experiments, was used in this experiment. Due to the more complex graphics rendering, the experiment was carried out on a more powerful computer, a SGI IRIS 4D Crimson/VGX graphics workstation, in order to maintain a 15 Hz update rate.

5.3.1.2 Experimental Task

Since depth display is the primary concern in this chapter, a 3 DOF (instead of 6 DOF) positioning task, comprising both perception and manipulation in 3-space, was carried out both with and without the semi-transparency effect. The task is a modification of the tracking task in Experiment 3.

In each trial of the experiment, a graphically rendered angel fish "swam" around (moved in X, Y Z translations) randomly within a 3D virtual environment (Figure 5.2). Subjects were asked to control a 3D *volume cursor* (Figure 5.3) to chase the fish, envelop it, and "grasp" it when the fish was perceived to be completely inside the cursor. Subjects

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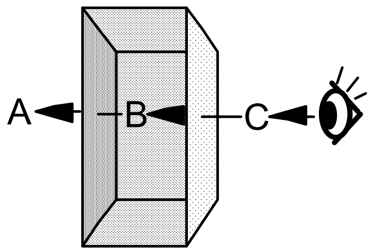
* A preliminary analysis of this experiment was published in (Zhai, Buxton, and Milgram, 1994). A revised version of this chapter will be published in (Zhai, Buxton, and Milgram, in press).

wore the glove (Figure 2.5) designed in Experiment 1, working in isotonic position control mode with a Control/Display ratio of 1:1. Grasping was done simply by closing the hand naturally. If the fish was entirely inside the cursor volume, the trial was successful and the fish stayed "caught" within. The time score of each trial was displayed to the subjects, along with a short beep. If the fish was not *completely* inside the cursor when grasped, the fish disappeared. In this case, which was considered a "miss", a long beep was sounded and error magnitudes in each of the x, y, and z dimensions were displayed, along with the message "Missed!". Each new trial was activated when the subjects pressed the spacebar on the keyboard.

Figure 5.2 Experiment 5 set-up

Figure 5.3 The volume silk cursor: Use of a "silk" covering over a rectangular volume cursor in order to obtain occlusion-based depth cues. An object at point A is seen through two layers of "silk", and thus is perceived to be *behind* the volume cursor. An object at point B is seen through one layer, and thus is perceived as *inside* the cursor's volume. An object at point C is not occluded by the silk at all, and so is seen to be *in front of* the volume cursor.



Although presented as a game (which incidentally was greatly enjoyed by the subjects), the “virtual fishing” task is essentially a 3D dynamic target acquisition task. Note that simply to select, or designate, a target in a 3D space does not necessarily require much depth information. That is, using a conventional 2D mouse cursor, any target, be it 2D or 3D, can be easily *selected* by clicking on its projection on the 2D screen plane. The purpose of the fishing task was to require the subject precisely to *locate* the target in 3-space, a capability essential for many 3D interaction tasks.

5.3.1.2. The Targets and Their Motion

Each of the targets ("angel fish") used in this experiment had a flat body, except for two fins and two eyes protruding from the body (see Figure 5.1, and Figure 5.4 - 5.7). The angle between any fin and the body was 30 degrees. The size and colour of the fish changed from trial to trial, in order to eliminate size constancy cues in the experiment. The x (from lips to tail), y (vertical) and z (from left fin tip to right fin tip) dimensions of the largest ("adult") fish were 10 cm, 15 cm and 1.3 cm respectively. The smallest ("baby") fish was 30 percent of the size of the largest adult fish.

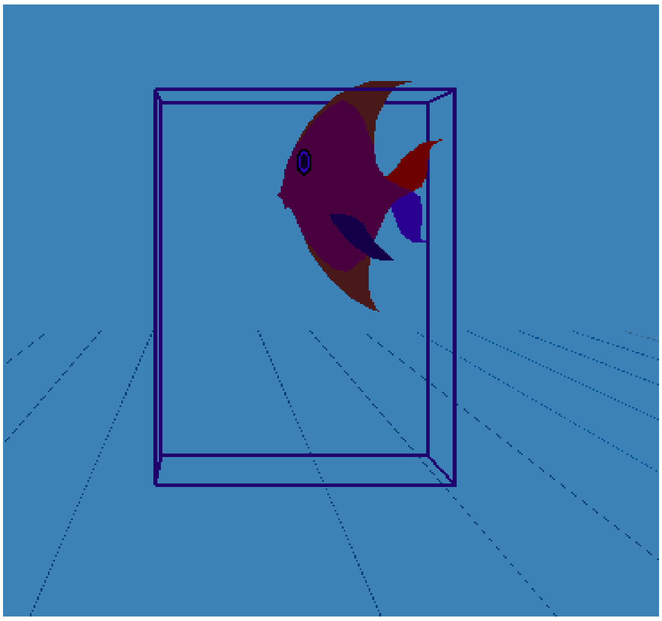


Figure 5.4

A fish and the wireframe cursor

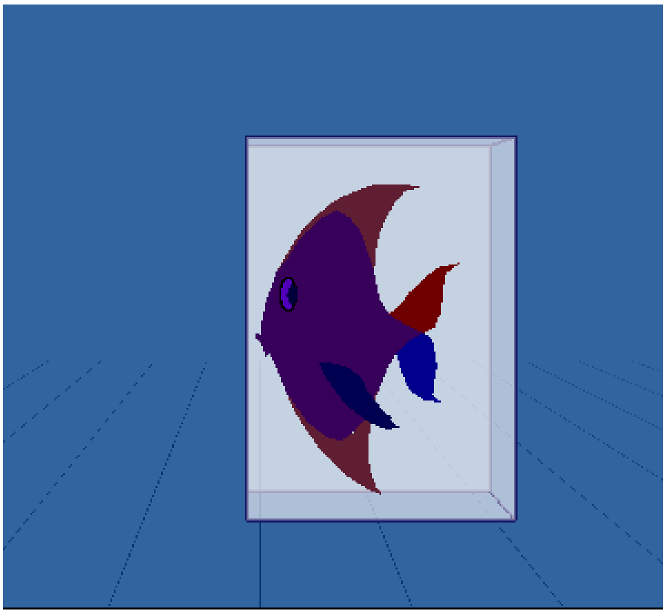


Figure 5.5

A fish *in front of* the silk cursor

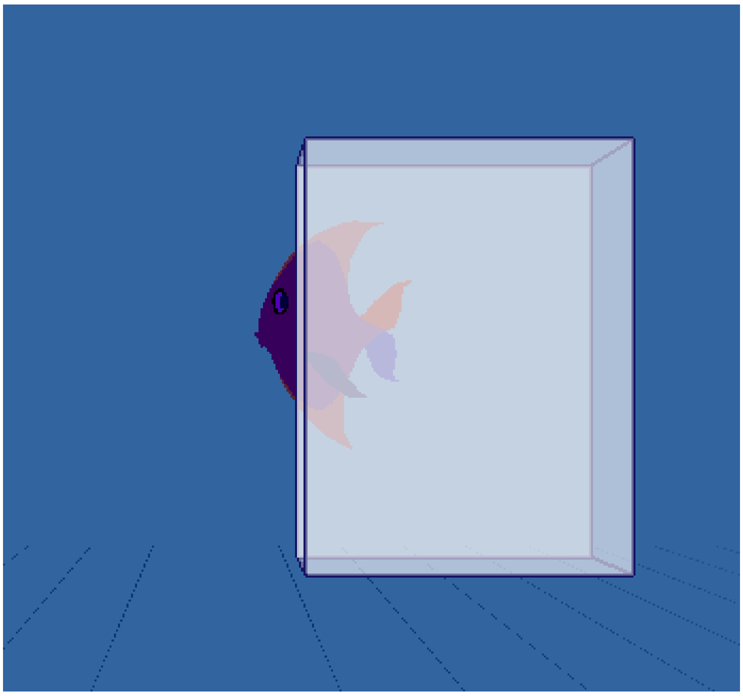


Figure 5.6

A fish *behind* the silk cursor

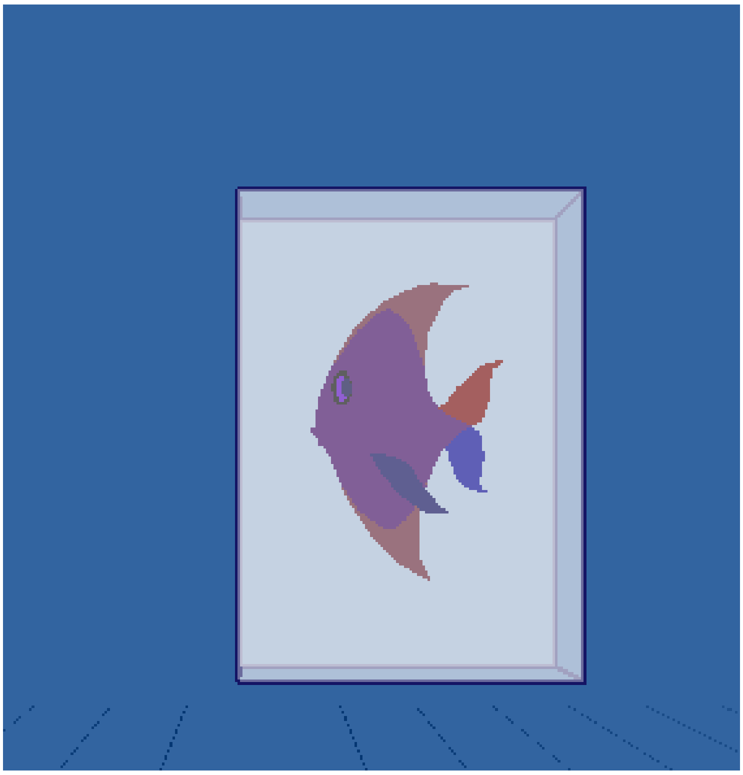


Figure 5.7

A fish completely *inside of* the cursor

The fish movements were driven by independent forcing functions in the x, y and z dimensions. In this experiment, the particular forcing functions applied to the fish motions were:

$$x(t) = \sum_{i=0}^{5} Ap^{-i}\sin(2\pi f_0 p^i t + \phi_x(i))$$
$$y(t) = \sum_{i=0}^{5} Ap^{-i}\sin(2\pi f_0 p^i t + \phi_y(i)) \quad ,$$
$$z(t) = -7.8 + \sum_{i=0}^{5} Ap^{-i}\sin(2\pi f_0 p^i t + \phi_z(i))$$

where t was the time from the beginning of each test (see section 5.3.3 on experimental design and procedure for the definition of a test), A = 4.55 cm, p = 2, and f_0 = 0.02 Hz. The phase terms, $\phi_x(i)$ $\phi_y(i)$ and $\phi_z(i)$ (i = 0, 1, ..., 5), were pseudo-random numbers, ranging uniformly between 0 and 2π. This design resulted in fish motions which were sufficiently unpredictable to the subjects and different from trial to trial, but repeatable for each test and between experimental conditions.

5.3.1.3 The Cursor and the Input

The cursor used to capture the fish was a rectangular box of size 11.3 cm, 16.3 cm and 2.6 cm in x, y and z dimensions respectively (Figure 5.3). Two versions of the cursor were used in the experiment. One was a *wireframe cursor*, as shown in Figure 5.4. In order to test the semi-transparent effect, the second version of the cursor was designed to be a *silk cursor* (Figure 5.1, 5.5 - 5.7). The silk cursor had exactly the same geometry as the wireframe cursor but its surfaces were semi-transparent. The intensity, I, of the semi-transparent surface was rendered by interpolating the cursor colour (source) intensity, I_s, with the destination colour intensity, I_d, according to (Foley, et al., 1990):

$$I = \alpha I_s + (1 - \alpha) I_d$$

Although I_s was chosen to be white (RGB values were set to 255, 255, 255) in this experiment, different colour compositions may be more suitable for other particular applications.

If $\alpha = 1$, the cursor is totally opaque and therefore completely occludes objects behind it. If $\alpha = 0$, the cursor is totally transparent and no partial occlusion cues are available. The wireframe cursor (Figure 5.4) therefore effectively corresponds to a silk cursor with $\alpha = 0$. On the basis of pilot experiments, we determined a suitable coefficient of $\alpha = 0.38$ for all surfaces of the cursor, except for the back surface, which was set at $\alpha = 0.6$. These values resulted in partial occlusion states (i.e., in front of and between two layers of the silk surface) which were judged to be satisfactorily distinguishable.

The transparency interpolation was realised by means of blendfunction(sfactr, dfactr) in the GL library. Note that the actual sequencing of rendering commands is critical to the transparency effect. Polygons further away from the user's viewpoint must be drawn before polygons closer to the user.

In the experiment, the "home" position of the glove corresponded to a cursor location of (0, 0, 0) and was calibrated to make the subject most comfortable when using the glove. Since only translations were needed in the fishing task, rotational signals from the glove were disabled for this experiment.

5.3.1.4 The Display

Two modes of display were used in the experiment: stereoscopic and monoscopic. In the stereoscopic case, subjects wore 120 Hz flicker-free stereoscopic CrystalEyes™ viewing glasses (Model No. CE-1), manufactured by StereoGraphics Inc.

5.3.2 Experimental Conditions and Hypotheses

The primary goal of this experiment was to evaluate the effectiveness of semi-transparent surfaces as an interactive medium for displaying users' input actions in depth. Since stereoscopic viewing is widely recognised as one of the most effective 3D interface techniques (Wickens, et al. 1989; Yeh and Silverstein 1992; McAllister 1993), the stereo display condition was used as the standard of comparison for the semi-transparency effect. Two display modes (monoscopic versus stereoscopic) and two types of cursor (silk cursor versus wire frame cursor) were included in the experiment. Thus, the experiment had four conditions: silk cursor with stereo display (SilkStereo); wire frame cursor with stereo display (WireframeStereo); silk cursor with mono display (SilkMono); and wire frame cursor with mono display (WireframeMono).

The reason for including the WireframeMono case was to provide a baseline standard of comparison for judging potential interactions between the stereoscopic and semi-transparency cues (e.g. Sollenberger and Milgram 1993). In the WireframeMono case the subjects had to rely on occlusions between the edge of the cursor and the fish. They tended to move the cursor so that the fish first was apparently located between the edges of the cursor in the z dimension (Figure 5.4) and then slightly adjust the cursor in the x and y dimensions to bring the fish into the centre of the cursor before grasping.

In the WireframeStereo case, subjects no longer had to depend on edge occlusion. Because the stereoscopic cue gave them a strong 3D sensation, they could judge the depth dimension directly and simultaneously with their judgement along the x and y dimensions.

In the SilkMono case, portions of the target appeared with different contrast ratios when located in front of (Figure 5.5), behind (Figure 5.6) or inside the cursor (Figure 5.7). The subjects tended to use the semi-transparency cue interactively, by moving the silk cursor first through the target to observe the continuous change of target appearance (Figure 5.1) and then grasping immediately after the front surface of the silk cursor moved in front of the fish fin.

In the SilkStereo case, subjects had the advantage of both the stereo cue and the semi-transparency cue. SilkStereo was expected to be the most efficient case and WireframeMono to be the least efficient. What was of particular interest to us, however, was whether the SilkMono case (semi-transparency cue alone) would generate superior, or in any case comparable, performance scores relative to the case of WireframeStereo (stereo cue alone), which would confirm the potentially powerful advantages of the semi-transparency cue on its own.

Stated formally, the hypotheses for this particular class of tasks were:

1. Semi-transparent surfaces improve performance over simple wireframes;

2. Stereoscopic displays improve performance over monoscopic displays;

3. The effect of the semi-transparency cue is superior to, or in any case comparable with, the stereo cue.

4. The use of semi-transparency will further improve users' interaction performance in addition to the benefit of stereoscopic displays and therefore performance is best when both cues are present.

5.3.3 Experimental Design and Procedure

Eleven males and one female paid volunteers served as subjects in this experiment. The subjects were screened using the Bausch and Lomb Orthorator visual acuity and stereopsis tests. Subjects' ages ranged from 18 to 36, with the majority in their early and mid-20's. One of the 12 subjects was left handed and the rest were right handed, as determined by the

Edinburgh inventory (Oldfield 1971) . Subjects were asked to wear the input glove on their dominant hand.

A balanced within-subjects design was used. The 12 subjects were randomly assigned to a unique order of the four conditions (SilkStereo, WireframeStereo, SilkMono, WireframeMono) using a hyper-Graeco-Latin square pattern, which resulted in every condition being presented an equal number of times as first, second, third and final condition.

Following a 2 minute demonstration of all four experimental conditions, the experiments with each subject were divided into four *sessions*, with one experimental condition in each session. There was a 1 minute rest period between every two sessions. Each session comprised 5 *tests*. Each test consisted of 15 *trials* of fish catching. Test 1 started when the subject had no experience with the particular experimental condition. Test 2, 3, 4, and 5 started after the subjects had 3, 6, 9 and 12 minutes worth of experience respectively. Practice trials filled the gap following a test and before the next test began, so that each test (e.g. Test 3) always started when the subject had a fixed amount of practice with the particular experimental condition (e.g. 9 minutes for Test 3). At the end of each test, the number of fish caught and missed (as both an absolute number and a relative percentage) and mean trial completion time were displayed to the subject.

At the end of the experiment, a short questionnaire was administered to assess users' subjective preferences for all experimental conditions.

5.3.4 Performance Measures

Task performance was measured by trial completion time, error rate and error magnitude. Trial completion time was defined as the time duration from the beginning of the trial to the moment when the subject grasped the target. Error rate was defined as the percentage of fish missed in a *test* (15 trials). Whenever a fish was missed, the error magnitude was defined as the Euclidean summation of errors (portions of the body outside of the cursor) in the x, y, z dimensions:

$$\text{Error Magnitude} = \sqrt{e_x^2 + e_y^2 + e_z^2}$$

Note that the error magnitude is not a primary measure for two reasons. First, the subjects' task was to capture the fish as quickly as possible. Error magnitude was not an explicit requirement. Second, error magnitude is relevant only when the subject missed the fish. It was included, however, to gather a complete set of performance measures.

5.3.5 Experimental Results

3600 experimental trials (i.e., 12 (subjects) x 2 (cursor types) x 2 (display modes) x 5 (tests) x 15 (trials per test)) of data were collected during the experiment. Repeated measure analyses of variance were conducted through the multivariate approach to test the statistical significance of the individual effects and their interactions under each of the three performance measures. As in earlier experiments, the data on trial completion times, error rates and error magnitudes collected here were not normally distributed, but rather skewed towards lower values. In order to increase the validity of the statistical analysis (Howell 1992), logarithmic transformations were applied to the trial completion time and error magnitude data and a square root transformation was applied to the error rate data. These transformations made the data meet the variance analysis assumptions of normality and homogeneity of variance. The following are the primary results of the statistical analysis.

5.3.5.1 Trial Completion Time

Variance analysis (Table A3.5.1, Appendix 3) indicated that cursor type (silk vs. wireframe cursor: $F(1,11) = 66.47$, $p<.0001$), display mode (stereo vs. mono display: $F(1,11) = 15.0$, $p < .005$), experimental phase ($F(4,44) = 21.59$, $p<.0001$), trial number (different fish size and 3D location: $F(14,154) = 12.55$, $p<.0001$), cursor x display interaction ($F(1,11) = 6.68$, $p < .05$), and cursor x display x phase interaction ($F(4, 44) = 4.0$, $p <.01$) all significantly affected trial completion time.

Figure 5.8 illustrates the effect of cursor type and display mode on trial completion time. Multiple contrast tests (Table A3.5.2, Appendix 3) showed that the silk cursor produced significantly shorter completion times than the wireframe cursor, for both monoscopic and stereoscopic displays. With regards to the magnitude of the differences, the mean completion time with the silk cursor was 48.4% shorter than that of the wireframe cursor in monoscopic display mode and 28.1% shorter in stereoscopic display mode. Finally, the mean completion time for SilkMono (semi-transparency cue alone) was 18.1% shorter than for WireframeStereo (stereo cue alone), even though this difference was not statistically significant ($p = .28$), due to the limited power of the test. These results suggest that, for tasks like the one presented here, semi-transparency is indeed a more effective cue than stereopsis.

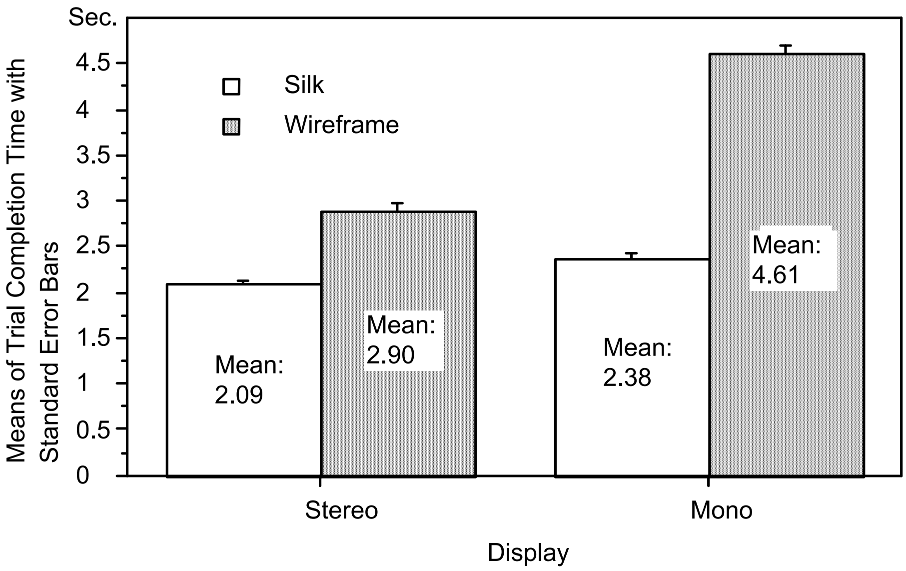


Figure 5.8 Trial completion times as a function of cursor type and display mode

5.3.5.2 Error Rate

As illustrated in Figure 5.9, the pattern of the error rate data as a function of cursor type and display mode is very similar to that of the trial completion time data. Repeated measure ANOVA (Table A3.5.3, Appendix 3) showed that the statistically significant factors affecting error rate were cursor type ($F(1,11) = 92.16$, $p<.0001$), display mode ($F(1,11) = 14.48$, $p < .005$), and cursor type x display mode interaction ($F(1,11) = 7.47$, $p < .05$). Neither experimental phase nor any interactions between experimental phase and other factors were significant.

Multiple contrast tests (Table A3.5.4, Appendix 3) showed that the silk cursor produced significantly fewer errors than the wireframe cursor, both for monoscopic displays and for stereoscopic displays. Regarding the actual differences in magnitude, for monoscopic displays the mean error rate of the silk cursor was 59% less than that of the wireframe cursor. For stereoscopic displays the mean error rate with the silk cursor condition was 36.7% less than for the wireframe cursor. For the semi-transparency cue alone (SilkMono) the mean error rate was 19.5% lower than for the stereo cue alone (WireframeStereo), although this difference was not statistically significant ($p = .21$), once again due to the low power of the test. As with the trial completion time data, therefore, the error rate data also suggested that the semi-transparency cue was more effective than the stereo cue.

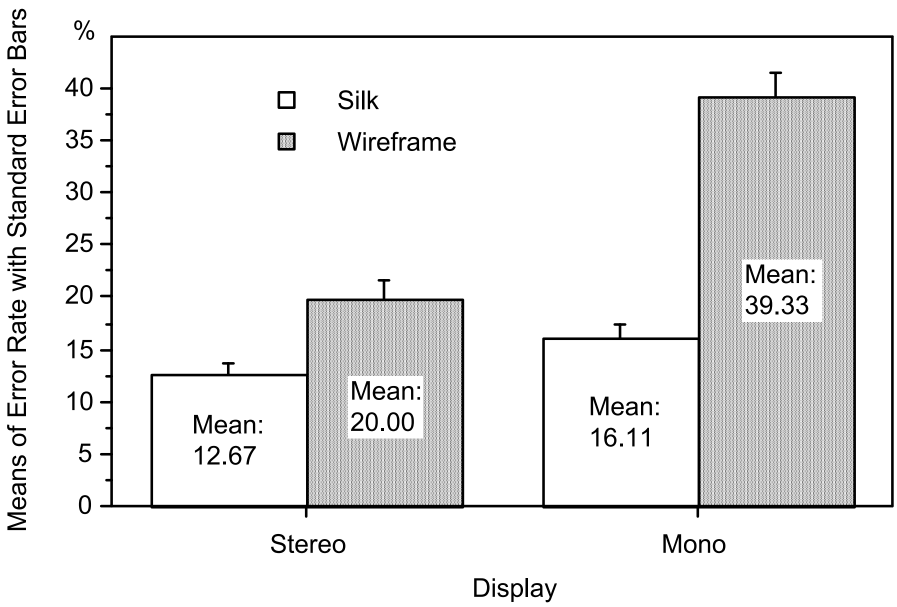


Figure 5.9 Error rate as a function of cursor type and display mode

5.3.5.3 Error Magnitude

The effects of cursor type and display mode on error magnitude are shown in Figure 5.10. When examining the error magnitude data, it should be noted that error magnitude was defined only when an error was made (i.e., a target was missed), and that fewer errors occurred in some conditions than for others. The variance analysis (Table A3.5.5, Appendix 3) showed that error magnitude was significantly affected by cursor type ($F(1,11) = 11.37$, $p < .01$), display mode ($F(1,11) = 18.19$, $p < .005$), and experimental phase ($F(4,44) = 3.97$, $p < 0.01$). No significant between factors interactions of any order were found.

Multiple contrast tests (Table A3.5.6) showed that the silk cursor produced significantly lower error magnitudes than the wireframe cursor, both for the monoscopic displays and for the stereoscopic displays. For the monoscopic displays the mean error magnitude of the silk cursor was 15.1% lower than that of the wireframe cursor. For the stereoscopic displays the mean error magnitude of the silk cursor condition was 41.5% smaller than that of the wireframe cursor.

In conclusion, therefore, in contrast to the trial completion times and error rate data, it appears that when an error did occur, the stereo cue was more effective than the semi-transparency cue in reducing the error magnitude. The SilkMono mode (semi-transparency cue alone) produced a larger mean error magnitude than the WireframeStereo mode (stereo cue alone); however, this difference was not statistically significant ($p > 0.5$).

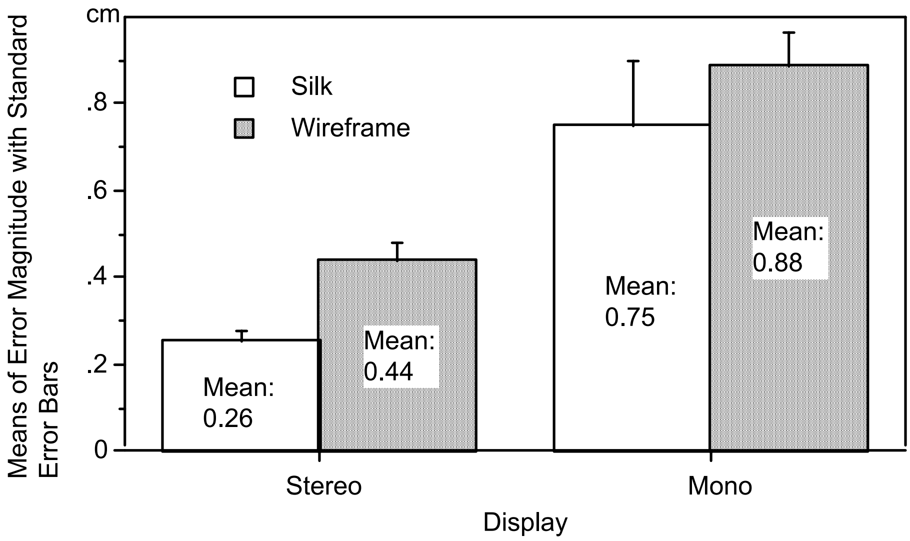


Figure 5.10 Error magnitude as a function of cursor type and display mode.

5.3.5.4 Temporal Effects and Results in Final Phase

As indicated in the variance analyses above, experimental phase was a significant factor for trial completion time and error magnitude, but not error rate. It also interacted significantly with cursor display combinations, as measured by trial completion time. This subsection describes the performance changes as learning apparently progressed, and the results in the final phase of the experiment are examined.

Figure 5.11 shows the trial completion time data for each technique as a function of the experimental phase. It shows clearly that the relative scores between the different conditions were ordinally consistent over all experimental phases. Subjects improved their time scores for the SilkStereo, SilkMono and WireframeStereo modes as they gained more experience, and presumably more confidence. Little improvement in completion time was evident with the WireframeMono condition however.

Variance analysis (Table A3.5.7, Appendix 3) was conducted on the trial completion time data in the final experimental phase (Test 5 in Figure 5.11). The statistical conclusions were the same as those drawn from the overall data above (section 5.3.5.1): cursor type ($F(1,11) = 90.8$, $p < .0001$), display mode ($F(1,11) = 21.5$, $p < .001$), cursor type and display mode interaction ($F(1,11) = 17.3$, $p < .005$), trial number ($F(14, 154) = 6.4$, $p < .0001$) all significantly affected trial completion times. Results of the multiple contrast comparisons for the final phase completion time data also agreed with the results from the overall data: SilkStereo vs. SilkMono ($p = .27$) and SilkMono vs. WireframeStereo ($p = .32$) were not significantly different. All other pair comparisons were significant ($p < 0.05$). Mean trial completion time reductions due to the semi-transparent effect in the final phase are as follows. For the mono displays, SilkMono (mean 2.064 sec.) was 52.8 % less than

WireframeMono (mean 4.376 sec.). For the stereo displays, SilkStereo (mean 1.850 sec.) was 20.6% less than WireframeStereo (mean 2.329 sec.).

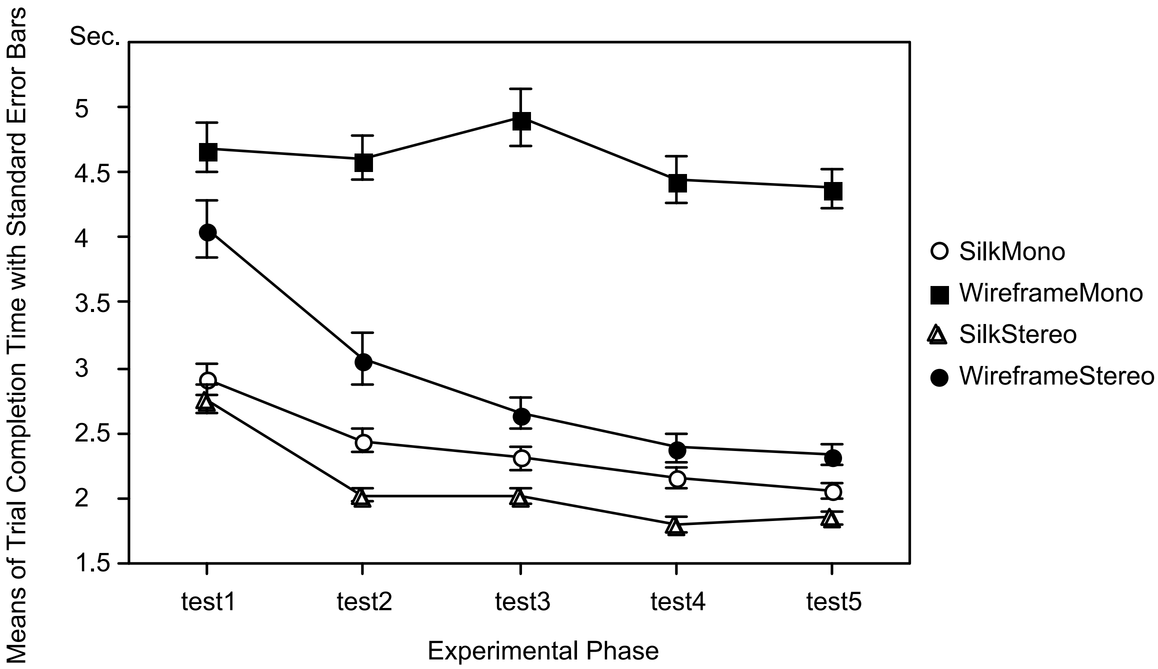


Figure 5.11 Time performance for each of four conditions at each phase of Experiment 5

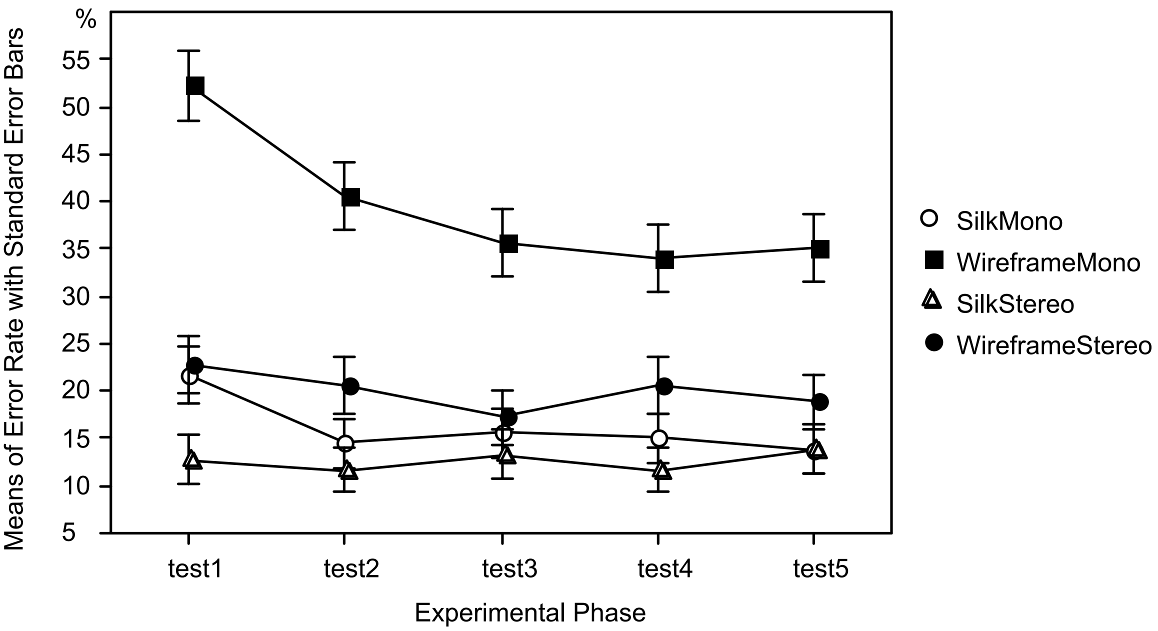


Figure 5.12 Error rate for each of four conditions at each phase of Experiment 5

Figure 5.12 presents the error rate data as a function of experimental phase. Again, the relative rank of each mode was consistent across all five phases of the experiment. Interestingly however, in contrast to the completion time data (Figure 5.11), the error rates for the WireframeMono condition showed the most obvious improvement over the experiment. A small amount of improvement was also found in the SilkMono condition, but essentially none in the SilkStereo and WireframeStereo modes. Variance analysis (Table A3.5.8, Appendix 3) for the final (test 5) phase error rate data showed that cursor type ($F(1,11) = 26.6$, $p < .0005$) and display mode ($F(1,11) = 6.05$, $p < .05$) were both significant factors, but the cursor type x display mode interaction ($F(1, 11) = 1.53$, $p = .24$) was not significant. Multiple contrast comparisons showed that final phase error rate with WireframeMono was significantly higher than the other three cases ($p < 0.05$). Other contrasts were not significant, however. Mean error rate reductions resulting from the semi-transparent effect in the final phase are as follows. For the mono display, error rate with SilkMono (mean 13.9%) was 60.8% lower than WireframeMono (mean 35.0%). For the stereo display, SilkStereo (mean 13.9%) was 26.5% lower than WireframeStereo (mean 18.9%).

Comparing Figure 5.11 with Figure 5.12 reveals important information about speed accuracy trade-off patterns with respect to learning. For the WireframeMono mode, subjects had more than a 50% error rate at the beginning of the experiment, which apparently caused them to focus on improving the accuracy aspect of the task at the expense of completion time performance. In the other three cases (SilkStereo, SilkMono, and WireframeStereo), subjects already had less than a 25% error rate and it appears that they were relatively satisfied with this level of accuracy, and thus decided to devote more effort to reducing their trial completion times.

The error magnitude data were not suitable for statistical analysis as a function of each experimental phase, since very few errors occurred for some of the phase and technique combinations.

5.3.5.5 Subjective Preferences

Figure 5.13 shows the mean scores for the subjective evaluation data collected after the experiment. On average, the SilkStereo condition was the most preferred and WireframeMono was least preferred, with SilkMono ranked higher than WireframeStereo. Statistically, significantly different preference scores were found across conditions through repeated measure variance analysis ($F(3,33) = 54.36$, $p<0.0001$, see Table A3.5.9 in Appendix 3 for detail). Multiple contrast tests (Table A3.5.10, Appendix 3) show that subjects' preferences between every pair of techniques were significantly different (including WireframeStereo vs. SilkMono). The subjective evaluation data in this experiment were consistent with the acquired performance measures (completion time and error rate) in terms of ordinal rankings but were more sensitive in detecting differences between conditions.

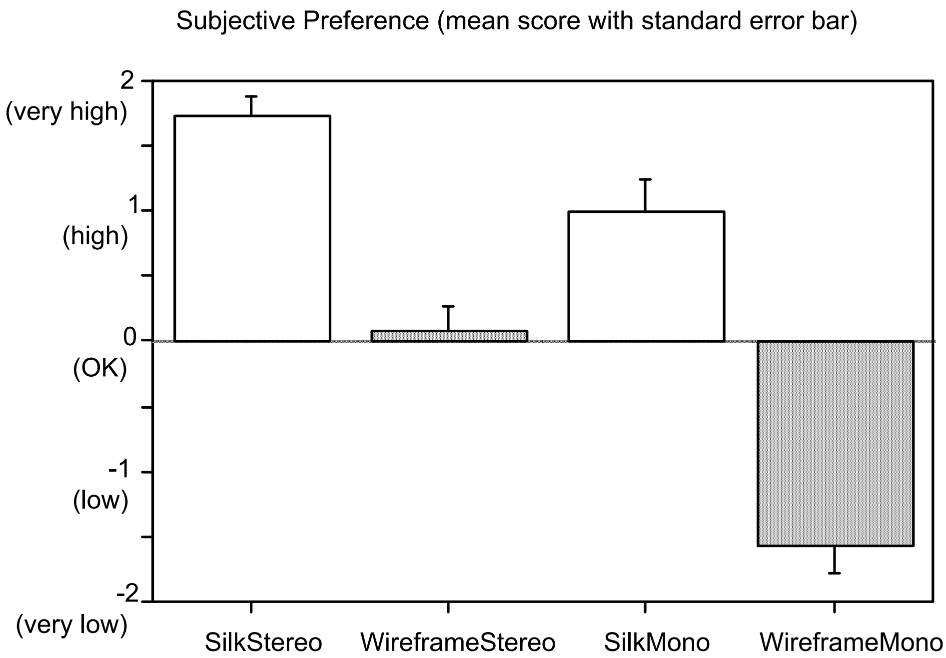


Figure 5.13 Mean scores for subjective evaluation of Experiment 5

5.3.5.6 Summary of Results

The experiment largely confirmed the initial hypotheses. In terms of all three measures of performance, trial completion time, error rate and error magnitude, both stereopsis through binocular disparity and partial occlusion through semi-transparency were significantly beneficial to the manual 3D localisation task. The semi-transparency cue was effectively utilised by the subjects in both monoscopic and stereoscopic displays. Comparing the two cues, semi-transparency appeared to be slightly more effective than binocular disparity for successful 3D target acquisition. Subjects' performance with each of the techniques improved with learning but the relative rank of the techniques remained unchanged throughout. Subjective evaluations supported the conclusions drawn from performance measures.

5.4 Discussion

Comparatively little perceptual research has been carried out on the relative strengths of various depth cues, and only a small portion of that research has addressed issues specifically related to computer interfaces. In one early cue conflict study, Schriever (1925) compared the relative influences of binocular disparity (i.e., stereoscopic displays), perspective, shading and occlusion, and showed, among other things, the dominance of occlusion over disparity information. More recently, Braunstein, Anderson, Rouse, and

Tittle (1986) showed that edge-occlusion dominates disparity when the two conflict, a result which has important implications for planning the placement of objects in depth in stereoscopic display design (McAllister, 1993). Even more recently, Wickens et al. (1989) , in a review of the depth combination literature, concluded that motion, disparity and occlusion are the most powerful depth cues for computer displays. The results presented here clearly contribute to that literature by illustrating some of the powerful advantages that can be afforded by augmenting visual feedback through both semi-transparency and binocular disparity.

5.4.1 Properties of Semi-transparency: Discrete, Relational Depth Cueing

Two particular properties of semi-transparency are especially relevant to 3D interaction systems. One of these is the fact that a semi-transparent surface does not completely block out the view of any object which it (partially) occludes. This eliminates one of the *dis*advantages of the powerful total occlusion cue and permits the user to maintain awareness of the background information.

The second property relates to the fact that the semi-transparency cue provides primarily *relational or discrete* depth information about the position of a semi-transparent surface relative to other objects. This information is discrete in the sense that it can take on only one of three possible values: in front of, within and behind. This is in contrast to stereoscopic displays, which provide continuous quantitative depth information. As illustrated in Figure 5.1 and Figures 5.5 to 5.7, we see how the silk covering on the volume cursor directly reveals *whether* an object is in front of the cursor volume, within it, or behind it. When an object is behind a semi-transparent surface, however, the user is not able to tell by *how much* the object is separated from the surface in depth. For some tasks, such as making an absolute judgement of distance, the discrete nature of the silk surface may represent a shortcoming, whereas for others it will be a distinct advantage, since the user does not have to use such continuous information for making discrete decisions. This was precisely the case in the experiment presented here, where the objective was to manipulate the cursor such that it totally enveloped the fish being chased. This is clearly a discrete task, as the subjects were instructed simply to capture the fish and not necessarily to centre the cursor on it as accurately as possible. This contention is supported by evidence from the experiment, where in Figures 5.8 and 5.9 we see clearly that semi-transparency was a more effective cue than binocular disparity for successful target acquisition. However, upon examining Figure 5.10, we note that the mean error magnitude of the SilkMono case was larger than that of the WireframeStereo case. The implication of this is that, although fewer errors were made under the SilkMono condition relative to the WireframeStereo condition, the *magnitude* of those fewer errors must have been relatively larger than with the WireframeStereo case, thus supporting the distinction between discrete versus continuous depth information.

Although static semi-transparent surfaces provide primarily discrete cues, continuous depth information can nevertheless be acquired when semi-transparent surfaces are used as a *dynamic* interaction tool. That is, when the silk cursor is being actively moved *through* another 3D object, the user can potentially estimate the object's depth by estimating the distance travelled in passing through the object, through timing and kinaesthesia.

5.4.2 Interactions among depth cues: Modelling of 3D performance

The manipulation of two sources of depth information in this experiment, occlusion and binocular disparity, brings to the fore an important theoretical question: When multiple sources of depth information are provided, how does the visual system judge actual depth information and how does performance change accordingly? Our visual system could either select one of the multiple sources or integrate them to form a decision. Two classes of models have been applied to address this issue, additive models and multiplicative models (Bruno and Cutting, 1988; Sollenberger, 1993). An additive model represents the fact that either depth cue can improve performance on its own and when both sources of information are present simultaneously the resulting performance improvement is a simple summation of the benefits from the two sources individually. A multiplicative model describes the fact that the two sources of information can interact, causing a combined effect either greater or less than the additive effects. In their study of the combination of relative size, projection height, occlusion, and motion parallax, Bruno and Cutting (1988) concluded that additive models produced the best fit to their experimental data. In a series of experiments with motion parallax (kinetic depth) and binocular disparity, Sollenberger (1993) found some evidence for a multiplicative model with greater than additive effects for his path-tracing task.

In the present experiment, binocular disparity and partial occlusion, as measured by both trial completion time and error rate were also found to be compatible with a multiplicative model, but with less than additive effects. As shown in Figures 5.8 and 5.9, a strong interaction was found between display mode and cursor type for both trial completion time and error rate. That is, both stereo display alone (i.e. WireframeStereo) and silk cursor alone (i.e. SilkMono) greatly improved performance relative to WireframeMono, but further improvements from SilkMono to SilkStereo (i.e. with both cues present) was marginal.

For cases in which targets were missed, on the other hand, the pattern of error magnitudes (Figure 5.10) conformed with an additive model, since no interaction was found between display mode and cursor type ($F(1,11) = 0.0004$, $p = .97$).

5.5 Applications

In the experiment, a silk cursor in a box shape was used to demonstrate the effect that semi-transparency surfaces introduce an extra cue in revealing users actions in relation to targets in 3D space. A 3D cursor can have many other shapes. In fact, a silk cursor with a tetrahedral shape has been used in Experiment 3 (Figure 3.11). As can be seen in Figure 3.9, a silk cursor with such a shape reveals the relationship between the target and the cursor both in translation and in orientation.

Another more complex shape of 3D cursor is the hand metaphor often used in VR applications. Such a cursor can be drawn either in solid colour or in wireframe. However, given the various manipulative functions of the hand representation, many of which involve occlusion of underlying objects, rendering the hand in semi-transparency for such applications, as illustrated in Figure 5.14, is expected to be beneficial.

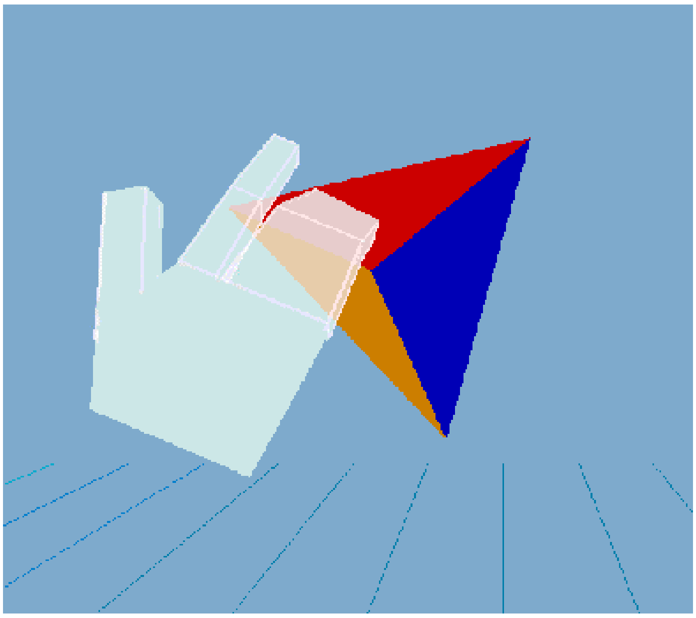


Figure 5.14

A proposed "silk hand" for VR applications

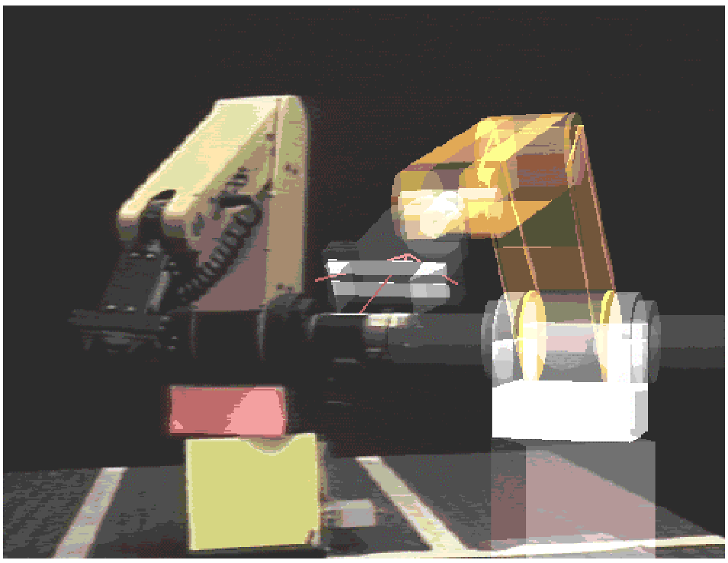


Figure 5.15 The "silk phantom robot" for telerobot control (Courtesy of Anu Rastogi)

An even more complex form of 3D cursor is a graphical robot (Figure 5.15). In order to off-load human operators from the task of continually having to control a telerobot in real time, some researchers have developed the technique of planning the slave robot movements by means of a graphical/virtual robot model (Bejczy, Kim, and Venema, 1990; Funda, Lindsay, and Paul, 1992; Zhai and Milgram, 1991, Milgram et al, 1995) . Such a "phantom robot" (Bejczy, et al. 1990) is usually drawn in a solid colour or wireframe. A "silk phantom robot" (Figure 5.15) drawn in semi-transparency could allow the operator to see objects behind the robot and better to visualise operations, particularly when the robot is in close proximity to obstacles and targets.

In conclusion, this chapter has investigated semi-transparency as a potentially powerful depth cue, to be used alongside such established 3D graphic techniques as perspective projection, stereoscopic displays, motion parallax and viewpoint tracking. Such a depth cue is particularly useful for displaying users' input actions in 3D space for manipulation of target objects.

Chapter 6

Conclusions, Contributions, Discussions and Future Research

6.1 Summary of Primary Conclusions and Contributions

Developments in virtual environments, telerobotics, computer aided design, scientific data visualisation, and many other technologies and applications demand human factors knowledge with regard to the design of interaction systems that allow 6 degree of freedom manipulation. Few answers have been readily available for addressing basic questions such as what the controller resistance should be and what kind of transfer function to provide for efficient human-machine system performance. This thesis is one attempt to provide both an empirical and a theoretical basis for the design and selection of 6 DOF interaction techniques, based upon surveying literature in many related domains, applying theories of human motor control, and conducting experiments with elemental manipulation tasks.

As discussed in Chapter 1, there are multiple components and stages involved when a human user exchanges spatial information with a computer (Figure 1.2, redrawn as Figure 6.1 for convenience). The user's motor actions act upon a physical device (manipulandum) which feeds a certain type of control feel (via proprioception) back to the human through resistance. The information output from the manipulandum can be transformed by various types of transfer functions. The result of the transformed input is then visually displayed. New motor control actions are generated through the interaction between exteroception, proprioception and central resources, including attention, pre-stored motor programs formed from past experience, and so on.

When designing any interactive system, the system characteristics should conform with human capabilities and limitations. On the basis of a review of a large body of literature and a series of experiments involving 6 DOF manipulation tasks, this thesis has advanced the knowledge base with respect to human performance as a function of the designing of each of the components in that interaction system as shown on the right hand side of Figure 6.1.

Experiment 1 revealed the compatibility principle between the transfer function of the controller dynamics (Block 2 in Figure 6.1) and the mechanical properties of the physical device (Block 1 in Figure 6.1). Two 6 DOF devices with different resistance, one isometric and one isotonic, and two types of transfer functions, position control and rate control, were examined in a 6 DOF docking task. A strong interaction was found between the resistance mode and the transfer function mode. In the position control mode, the subjects had shorter mean completion times with the isotonic device than with the isometric device. In the rate control mode, the completion time scores for the isotonic and isometric devices were reversed. Analysis showed that the strong self-centring effect of isometric devices is the key in understanding this interaction pattern.

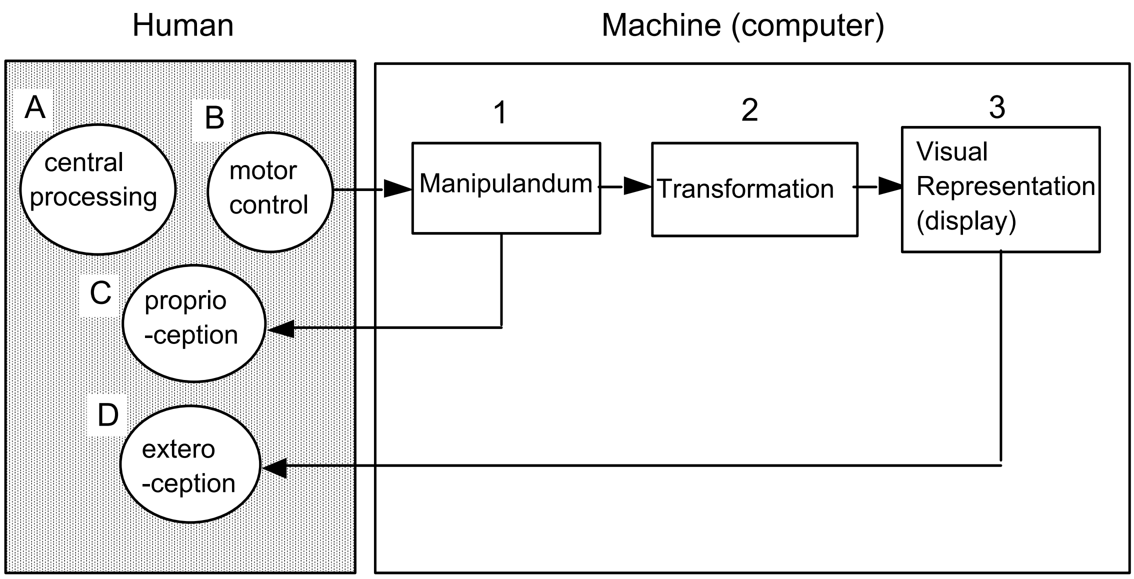


Figure 6.1 The human-machine interaction system

Between the two compatible modes, namely the isotonic position control and the isometric rate control, the former appears to be more natural and easier to learn but the latter is less fatiguing and generates smoother trajectories when the subject is well practised, due to the low pass filtering effect in rate control. In comparison to position control, rate control has both advantages and disadvantages. On the one hand, it is less direct than position control, therefore imposing a possibly higher cognitive load on the user (circle A in Figure 6.1). On the other hand it compensates for the physical limitations of the hand by enabling an essentially infinite operating range.

Experiment 2 focused on isometric versus elastic rate control. The major disadvantage with the isometric device is the insufficiency of kinaesthetic feedback (Circle C in Figure 6.1) to the user. The user can not feel the effect of her control actions very well on the basis of just the force cue alone involved in the isometric control. The major advantage of the isometric device, on the other hand, is its strong self-centring effect which Experiment 1 showed to be necessary for rate control. An elastic device, which provides movement proprioceptive cues in addition to force cues, is also self-centred. As the stiffness of the self-centring elasticity increases, the self-centring effect increases accordingly, hence enhancing compatibility with rate control. On the other hand, stiff elastic controllers allow less movement, hence reducing movement proprioceptive feedback. These two factors, compatibility (between Block 1 and Block 2 in Figure 6.1) and proprioception (circle C in Figure 6.1), therefore act in opposition in determining the magnitude of the elastic resistance. The optimal elasticity is thus a result of the trade-off between these two factors. Experiment 2 investigated the performance differences between an elastic rate control device and an isometric rate control device and found that the difference was related primarily to the experience subjects had acquired with each device. Slight advantages of the elastic device were found in early, but not later, learning stages of the experiment.

Experiment 3 pursued the same issue as in Experiment 2, but with a more demanding task, 6 DOF dynamic tracking. A more substantial difference was found between the elastic rate control and the isometric rate control, but the general trend was the same as in Experiment 2: the elastic device was easier to learn than the isometric device. Consistent with many existing human motor control theories, the results of Experiment 2 and Experiment 3 imply that the basis of human motor skills shifts from closed-loop feedback driven behaviour to open-loop motor-program driven behaviours. When richer proprioceptive feedback is available, users (of elastic devices) may more easily acquire the skills related to performing the task.

A detailed analysis of subjects' tracking performance was done through dimensional decomposition (Appendix 2), which revealed a number of interesting phenomena about 6 DOF tracking. First, a satisfactory level of performance in the depth dimension (relative to results reported in the literature) was found when interposition, perspective, stereoscopic disparity and partial occlusion cues were all incorporated into a 3D display system. Subjects' tracking errors in the depth dimension were only about 35% to 45% larger than those in the horizontal and vertical dimensions, much less than previously reported in the literature. Second, it was also found that the subjects had larger tracking errors in the vertical dimension than in the horizontal dimension in the early stages of the experiment, most likely due to their attention allocation strategy. Third, the issue of controllability of 6 degrees of freedom with one hand was addressed. With a certain priority order, subjects tended to concentrate on fewer degrees of freedom in early stages of the experiment and progressed to co-ordinate with more degrees of freedom in later stages of the experiment. Between the translational and rotational aspects, translation took higher priority. Between the horizontal, vertical, and depth dimensions, the horizontal dimension took priority. It was found that after 40 minutes of practice more than 80% percent of the subjects were able to control all 6 degrees of freedom simultaneously.

The issue of which muscle groups (Circle B and Block 1 in Figure 6.1) ought to be involved in 6 DOF manipulation was studied in Experiment 4. Two isotonic position control techniques were tested in a 6 DOF docking task. One technique, the glove, was operated with the user's wrist, elbow and shoulder. The other technique, the Fball, was operated additionally by the user’s fingers. The results showed that the Fball outperformed the glove, even if the effects of a confounding factor, the use of a clutch with the glove, was removed from the analysis.

An important part of input control is the visual representation (Block 3 and Circle D in Figure 6.1) of the task. The user needs timely and revealing exteroceptive feedback about her control actions in relation to target objects. When interacting with 3D environments, a key issue is displaying a user's actions in the depth dimension. Experiment 5 investigated the use of semi-transparent surfaces in exhibiting the relationship between the user's input and the target location. The interposition cue, i.e., the fact that closer objects obscure farther objects, is known to be one of the most powerful sources of depth information in human perception. However, it is difficult to use the interposition cue in interactive computer graphics because foreground images completely block the view of the background. Experiment 5 showed that the partial occlusion cue, introduced by semi-transparent surfaces, does not have the disadvantage of the total interposition effect but is still very effective in revealing the states of the user's input in relation to target objects.

Collectively the series of experimental and analytical studies in this thesis make a significant contribution to the understanding of human factors in 6 DOF manipulation. Prior to this research, it was realised that there are many dimensions in the 6 DOF input design space that influence user behaviour, but little was known about the performance implications of many of these dimensions. This thesis provides a basis for understanding some of those performance implications. The highlights of the results can be summarised very briefly as follows (see Figure 6.1).

(1) The physical property of a 6 DOF input device should provide rich proprioceptive feedback so that the user can easily feel her control actions so as to learn the task quickly.

(2) The controller transfer function used in any interaction technique should be compatible with the characteristics of the physical device.

(3) Fine, small muscle groups and joints (i.e. fingers) should be included in the operation of input devices when possible.

(4) Visual display of user actions in relation to target objects should be designed to allow immediate exteroceptive feedback, and the inclusion of semi-transparency well serves this purpose by revealing the depth relationship between a cursor and target objects.

The studies in the thesis also have significance beyond the explicit empirical findings with respect to users' performance in 6 DOF manipulation techniques. First, many of the user interface designs, such as the MITS glove, the EGG, the Fball and the "Silk Cursor", all have novel features with practical values. Second, the experimental paradigms, including 6 DOF docking, 6 DOF tracking, "virtual fishing" and their performance measurements, as well as the large software system developed in the course of this research, make methodological contributions to research in 6 DOF input and 3D human machine interaction. Third, some of the results, such as the role of proprioceptive feedback, also contribute to the understanding of human motor skills.

6.2 Isomorphic manipulation versus tool operation as input control

In light of the results in the thesis, we can also begin to gain insights into issues such as isomorphism (direct manipulation) versus tool-using in 6 DOF manipulation. As discussed in Chapter 1, there is a continuum between ideal isomorphism and indirect tools. This concept is illustrated in Figure 6.2. Although many attributes of an input device may influence its directness (its location on the isomorphism - tool continuum), the most dominating factor is the transformation from the *control space* to *display space.* The more mathematically complex this transformation is, the more indirect the input technique is. As shown in Figure 6.2, input techniques with first order (rate control) or higher order control dynamics are indirect tools. With these techniques, one or more integrals are involved in the mathematical mapping from the control space (user's control actions) to the display space (cursor movements). The elastic (EGG) and the isometric (Spaceball) devices used in Experiment 1, 2 and 3 in rate control mode are examples of indirect tools.

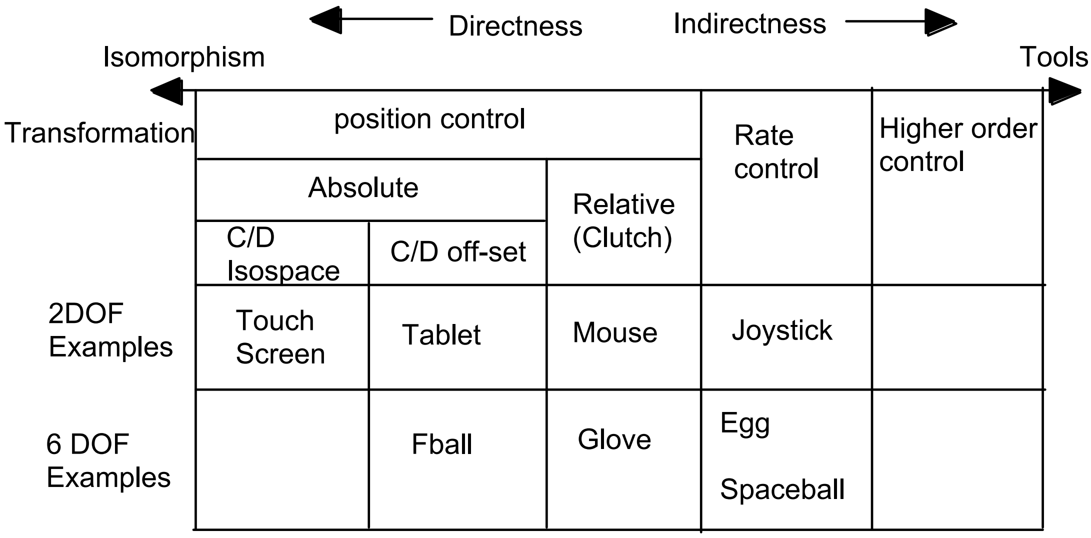


Figure 6.2 Isomorphism - tool continuum: A taxonomy of classifying input devices according to directness of transformation from control space to display space

Moving to the left of Figure 6.2, input devices become more direct. For position control techniques, the mathematical transformation from the control space to the display space is a multiplication, which is simpler than integration. Among position control techniques, *absolute* devices, such as a 2 DOF digitising tablet or the 6DOF Fball in Experiment 4 are more direct than *relative* devices, such as a 2 DOF mouse and the 6 DOF glove used in Experiments 1 and 4. Relative devices require a clutch mechanism to engage and disengage the link between control actions and cursor movements. For a mouse, for example, lifting it from mouse pad will disengage the linkage between control and display.

Another factor that affects the directness of position control techniques is the control-display (C-D) ratio. When the C-D ratio is 1, the multiplication operation is reduced to an assignment (copying) operation, which makes the input control more direct than when the C-D ratio is not 1.

There is still another factor that makes some absolute position input techniques more direct than the others: the orientation or location *offset* between the control space and the display space. Both a touch-screen and a tablet are absolute position control devices but the latter has an offset between the display and the control space in orientation (about 90° in pitch) and in location (about 20 - 40 cm in the vertical and/or in the horizontal axes). A touch screen interface is therefore more direct than a tablet interface. In the experiments presented in this thesis, all input techniques had a translation offset between the control space and the display space, but no orientation offset. 6DOF techniques without offset can conceivably be implemented, particularly in immersive virtual environments in which the display space (where the user looks) and the control space (where the user moves her limbs) can completely overlap with each other.

It should be noted that to the left of Figure 6.2 there are input devices that are even more direct. These are the position control devices with force-reflecting capabilities. The ultimate isomorphic input controller is one that allows force feedback in all directions, to recreate what we would feel when manipulating real 3D objects directly with our bare hands. In other words, the ultimate isomorphic interfaces are completely "transparent" to the user.

It is important to note that there are both advantages and disadvantages to techniques on each end of the isomorphism - tool continuum. In daily life, we prefer to perform many tasks with our bare hands. Even with a glove, the small "transformation" between the hand and the actual manipulation may be undesirable on some occasions. On the other hand, we do frequently use various tools, sometimes as simple as rulers, wrenches, screwdrivers, etc., for precision, for power and for overcoming some of our other physical limitations. In general, more isomorphic (more direct) designs are more intuitive and require less learning. Such devices are needed for applications where an explicit learning period is perhaps not available, such as commercial video games where users should be able to walk-up and play immediately. The disadvantages with such isomorphic designs lie in possible fatigue, coarseness of the control action and anatomical limitations of the human limb. In contrast, less direct, tool-like devices may take more time to learn but may be more efficient in terms of reduced fatigue, smoother motions and fewer physical limitations of the human limb. Such designs are clearly more suitable for tasks of long duration, such as in teleoperation.

6.3 Limitations and Future Research

Studies in human factors research often have limitations in their generalisability. This thesis is no exception in this respect. Caution has to be exercised in considering the strength of the findings in the experiments for a number of reasons. First, the experimental conditions were implemented using available technologies. None of the technical products used in the experiment were ideal. For instance, the 6 DOF position sensor used is known to have a significant amount (about 60 msec) of time delay (Adelstein, Johnston, and Ellis, 1992a 1992b). A tracker with much less delay may have improved the conditions implemented with the tracker (the Glove, EGG, and Fball); however, changes in the relative performance scores between the conditions is not expected. Second, these experiments were conducted with elemental tasks that do not cover the entire rich task space for practical 6 DOF interaction tasks. Third, the analyses of the experimental results were limited to integrated performance scores, even though Appendix 2 provides a dimensional decomposition analysis. It is believed that more insights into the nature of 6 DOF control with each device could have been gained through more trajectory based analysis, as discussed in the following section.

The work reported in this thesis is thus merely one earnest endeavour towards understanding human performance issues in input control. Many research questions that have been identified during this work are to be addressed in the future. The following are a few viable future research topics.

6.3.1. The interaction between device resistance and transfer function in low DOF input control

A very important finding of Experiment 1 is the interaction pattern between isometric versus isotonic resistance and position versus rate control transfer functions. The isotonic device worked better with position control than with rate control, whereas the isometric device worked better with rate control than with position control. The reason behind this interaction pattern appears to be rather straightforward: the self-centring effect in the isometric device helps the reversal actions required for rate control. Without the self-centring force (in the case of isotonic devices), a reversal action has to be made more expressly and effortfully, either by returning the manipulandum back to a null position or by releasing a clutch. Conversely, however, this self-centring force makes it more unstable and fatiguing to maintain a cursor location in position control mode, unless an explicit clutch is used to disengage the device frequently, which makes the control process less "seamless". Surprisingly, this seemingly rather obvious interaction pattern between resistance mode and transfer function had not been formally reported in the literature prior to Experiment 1 in this thesis. Instead, the literature extensively deals with the relative superiority of isometric versus isotonic devices without much attention paid to the effect of transfer function (see Chapter 2 for a review). In light of the interaction pattern found in Experiment 1, much of the controversy in the literature with respect to the relative performance between isometric and isotonic devices can be reduced to a simple explanation in these terms. However, Experiment 1 was conducted with a 6 DOF docking task while the classical studies were all done with lower DOF tasks. An experimental study with two modes of control resistance (isometric and isotonic) and two modes of transfer function (position control and rate control) with 1 or 2 DOF devices would therefore be a valuable contribution to the literature, even though the same interaction pattern found in Experiment 1 is expected to be found in low 2 DOF devices but perhaps to a less extent. In practice, isotonic devices, such as the computer mouse, are usually used in position control mode but some applications, such as some driving simulation games and some 3D graphics packages, do use the mouse in rate control mode. A user would probably find such a combination difficult to master. One the other hand, this might be ameliorated somewhat for cases such as an isotonic 2 DOF joystick, where even though the self-centring force that facilitates rate control is absent, the pivot of the joystick may still provide an anchor to the user for forming the reversal actions required in rate control.

6.3.2. Systematic examination of the effect of elastic resistance in rate control

In chapter 3, it was proposed that two factors, compatibility and proprioception, impose conflicting requirements for the setting of the level of elasticity in rate control. For the sake of compatibility with rate control, a stiff (therefore strongly self-centred) elasticity is desirable. However, a stiff (near isometric) elastic device provides less rich proprioception than a loose one that allows more movement within a range of non-fatiguing forces. How exactly input control behaviour and performance change as a function of elasticity levels ranging from isotonic to isometric is a question which deserves a more detailed examination. Such a study should be done, at least initially, with a 1 DOF positioning (step tracking) task for simplicity of experimental data analysis. Five levels of elasticity should be tested, including isotonic, weak elastic, medium elastic, strong elastic, and isometric. Both dynamic measures (overshoot, number of cursor movement reversals over the target, settling time, pure time delay etc.) and steady state performance (e.g. static accuracy) should be recorded. It is hypothesised that when the elasticity is on the weak side (isotonic or weakly elastic), poor compatibility with rate control will be manifested by large overshoots (due to less timely returning to the null position) or by a large number of reversals. On the strong elasticity side (isometric or strongly elastic), insufficient proprioception will be manifested by larger steady state errors.

One difficulty in conducting this experiment will be with the setting of control gains. One possible arrangement is to optimise control gain for every level of elasticity. A more rigorous arrangement, perhaps, would be to set the gain constant across all conditions. However, for a (finite) elastic controller, the overall control gain is actually a product of two gains, i.e., $K = K_1 K_2$ where K_1 is the gain between the force applied to the control handle and the displacement of the control handle (i.e., K_1 is the inverse of elastic stiffness) and K_2 is the gain between the control handle position and the cursor speed for rate control. In the pure isotonic condition, K_1 does not exist and $K = K_2$. In the pure isometric condition, K_2 does not exist and $K = K_1$ (from the force to the cursor speed). A reasonable arrangement would therefore be to test all levels of elasticity under two modes of gain arrangement. In Mode 1, a constant position-to-display gain is held for all levels of elasticity (i.e., keep K_2 constant and let K_1 float with different elasticity settings). In Mode 2, a constant force-to-display gain is held for all levels of elasticity (i.e., keeping $K = K_1 K_2$ constant and as K_1 increases with the level of elasticity, while decreasing K2 accordingly). This two mode design may provide some insights into the role of force, position and elasticity in input control. If subjects' performance were invariant in Mode 1, force and the level of elasticity would be proved to be ineffective factors in input control. If subjects' performance were invariant in Mode 2, position and the level of elasticity would be proved to be ineffective. Both of these two cases are expected to be false.

There is a problem in the extreme cases (isotonic and isometric) for the two mode gain arrangement. For Mode 1 (position-to-display constant), the isometric condition has undefined gain. One solution to this might be to assign the same value of force gain ($K = K_1 K_2$) for the next-to-isometric condition (i.e. strong elastic) to the isometric condition. Similarly, for Mode 2 (force-to-display constant), the isotonic condition has undefined gain. The position to display gain (K_2) value in the next-to-isotonic condition (i.e. loose elastic) could then be taken for the gain of the isotonic condition.

Such an experiment requires frequent adjustments to the level of elasticity and the level of control gain, making the experiment very difficult to conduct. One candidate apparatus for this experiment is the *pantograph*, described by Ramstein and Hayward (1994), which is a 2 DOF computer-controlled force reflecting device. Such a device can produce various levels of elasticity by programming the motor control algorithm. For the isometric condition, however, an alternative device has to be used.

6.3.3. Psychophysical study of motor accuracy with both force and displacement

Research on input control requires a deep level of understanding of human motor behaviour. As indicated in the motor control literature, it is still unclear what muscle variable(s) the nervous system actually controls in limb movements: force, length, velocity, stiffness, viscosity, more than one of the above, or none of the above (Stein, 1982). Some psychophysical experiments have investigated the just-noticeable difference (JND) for perceiving increments in force and for extent of movement (see 3.1.4 in Chapter 3 for a review) but JND for length combined with force is unknown. It is both theoretically and practically valuable to know the human motor accuracy when force and length are linearly linked, i.e., the human's ability to discriminate different kinaesthetic states when the hand is coupled to various spring loadings. Would the redundancy between force and length augmented each other or disturb each other? Is motor accuracy better with one of the variables alone or better when both are present? Such questions are obviously important for understanding the design of controller resistance.

The proposed experimental paradigm for addressing these issues is manual recall without visual feedback. The procedure would be approximately as follows. (a) S is presented with a fixed target (vertical bar) at the middle of a computer screen and a cursor (a cross hair) at one end of the screen. (b) S is asked to generate just amount of input (move/pull the controller) for the cursor to reach the target. (c) S is asked to remember the hand/arm state (a combination of force and displacement) corresponding to this input and then return to the rest position. (d) Without cursor display, S tries to move the controller to the same state as the trial in step (b). S pushes a key (to mark the end of the trial) when she feels that invisible cursor has reached the correct position. (e) Error is displayed. (f) Go back to (a), repeat for a few trials.

Five experimental conditions would be tested. All can be considered as a spring-loaded manipulandum with certain spring constant, that is:

$$D = K F$$

where D is displacement, K is the spring constant and F is the force applied to the spring. The five conditions would be:

K1 = 0 (isometric)

K2 = 2 cm/N (Stiff Spring)

K3 = 4 cm/N (Medium Spring)

K4 = 8 cm/N (Loose Spring)

K5 = infinity (Free)

Each of these 5 levels of spring loading can be represented as a thick line segment shown in Figure 6.3. Under each spring loading, two points would be tested. These testing points are labelled with X signs in Figure 6.3.

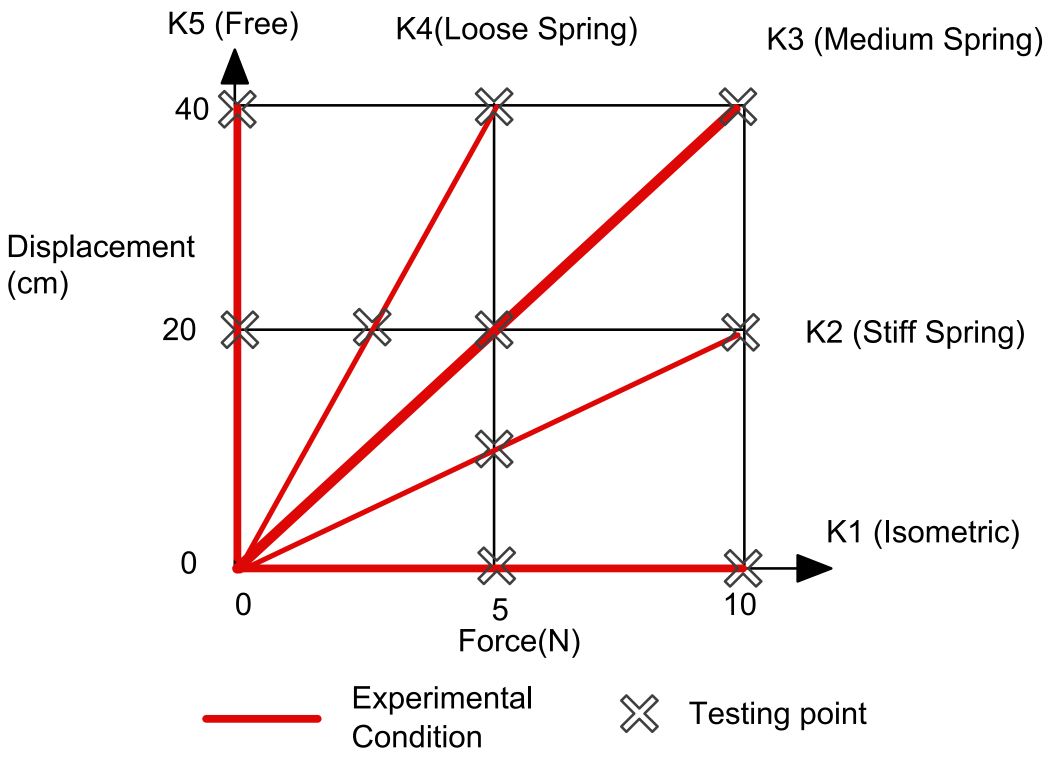


Figure 6.3 Proposed experimental design for testing motor accuracy as a function of spring loading

The arrangement in Figure 6.3 is designed to examine the interactive patterns of the two channels of cues contributing to motor performance. Testing points (X's) on each horizontal line in Figure 6.3 share the same displacement but differ in the level of force stimulation. If displacement is the dominant cue and force does not serve as an augmentation, testing points (X's) on the right side would not generate better performance than points on the left. If force serves as perturbation instead of augmentation to displacement perception, testing points (X's) on the right side would generate *worse* performance than points on the left. Similarly, testing points (X's) on each vertical line in Figure 6.3 share the same force stimulation but differ in displacement magnitude. Testing points (X's) on each of the thick lines would have the same elasticity but differ in amount of stimulation magnitude (both force and displacement). How subjects' accuracy changes as a function of force and movement cues and how these two variables interact would be clearly revealed in this experiment.

Note that the target is always located at the middle of the screen in this experiment. For different operating points, the control gain would be calibrated so that the cursor reaches the target with the designated amount of force/displacement input. This arrangement would eliminate the possible bias introduced by different display scales for each condition.

6.3.4. Investigating the quality and coordination in multiple DOF input control

Input control has been traditionally evaluated using "performance" or product oriented measures. These measures include speed (e.g., task completion time), accuracy (e.g., RMS error, error rate) or information processing rate (e.g., bandwidth in Fitts' law). As far as multiple degrees of freedom are concerned, however, these measures do not capture completely the quality of manipulation trials. Other than how quickly a trial is accomplished or how accurate the cursor position overlaps with the target position, it can also be useful to know what trajectory the control object moves through. In other words, we need to have "process" or trajectory based measures.

One important process oriented concern is how *co-ordinated* a controlled trajectory is. Can users control 6 degrees of freedom at the same time? Or do users actually control fewer degrees of freedom at a time? When an operator wants to move an object in translation only, can she do it without rotating it? When she needs to rotate an object, can she do it without introducing translational cross talk? In order words, can the user integrate and separate the 6 degrees of freedom at will? All of these questions are related to the coordination of multiple degrees of freedom.

The first problem in studying the coordination of multiple DOF input is to define and quantify the concept of coordination. For simplicity, let us examine trajectories on a 2D space, as illustrated in Figure 6.4. As we can see, in order to move from Point A to B in this space, two variables x and y have to be changed from x_A to x_B and y_A to y_B respectively. Supposing we had only a 1 DOF input device that time-multiplexed between the x and y axis, one possible trajectory would be AC-CB, as a result of moving in the x dimension first and in the y dimension later. In such a case, the two degrees of freedom are completely un-co-ordinated, because x and y are not moved at the same time, resulting in a longer trajectory than necessary and possibly a longer movement time. If we had a 2 DOF device such as a mouse that allows movement in the x and y directions simultaneously, we may produce a trajectory that is close to the straight line AB, which is optimal because it is shortest and is also most co-ordinated in the sense that x and y move simultaneously at the *same relative pace*. Any deviation from the path AB can be considered as a result of lack of coordination, which will result in a longer trajectory. In light of this analysis, we define the translation coordination coefficient as:

Translation Coordination Coefficient = Length of shortest path / Length of actual path

By this definition, trajectory l_1 in Figure 6.4 is better co-ordinated than trajectory l_2.

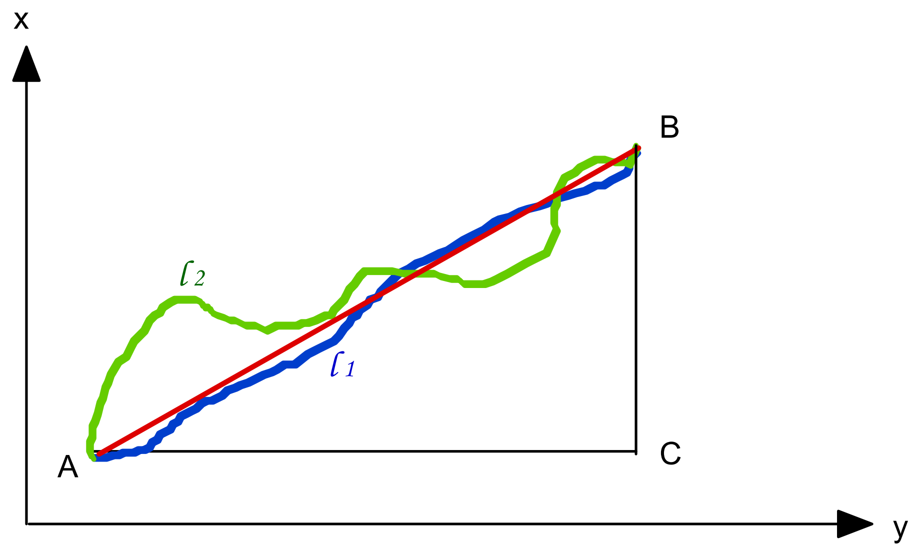


Figure 6.4 Measuring coordination: on a 2D plane, the shortest, most co-ordinated trajectory from A to B is the straight line AB, Trajectory AC-CB is completely uncoordinated (see text)

The same definition of coordination coefficient can be easily generalised to translations in 3D space simply by measuring 3D instead of 2D Euclidean distances. To generalise this concept to rotation in 3D space is less straightforward, however. Parameterisation of rotations is more complicated than it appears (Hughes, 1986, p.15) . The parameters commonly used in engineering, pitch, yaw, roll (Euler angles) are often misleading. A more valid metric is the *rotation vector* discussed in Appendix 2. Define the initial mismatch between a cursor and a target (both are 3D objects in 3D space) to be

$$\mathbf{Ø_A} = \phi_A \mathbf{n}_A = (\phi_{Ax}, \phi_{Ay}, \phi_{Az}),$$

where $\mathbf{Ø_A}$ is the rotation vector signifying an angle ϕ_A of rotation about $\mathbf{n}_A$, where $\mathbf{n}_A = (n_x, n_y, n_z,)$ is a unit vector defining the axis of the rotation in x, y, z frame of reference, then the *minimum* amount of rotation that the cursor has to go through to reach the target is ϕ_A. The ratio between ϕ_A and the actual amount of rotation of the cursor upon reaching the target is defined as the rotation coordination coefficient:

Rotation Coordination Coefficient = Initial rotation mismatch/Amount of actual rotation

When one can control all 3 rotation degrees of freedom with *perfect* coordination, the rotation mismatch between the cursor and the target will be reduced from $\phi_A \mathbf{n}_A$ to $0\ \mathbf{n}_A$, *without changing the direction of the mismatching rotation vector*. Otherwise, if the 3 rotational degrees of freedom cannot be controlled *simultaneously at the same relative pace*, at an instant of time t the mismatch will be $\phi_t \mathbf{n}_t$ ($\mathbf{n}_t \neq \mathbf{n}_A$), causing a larger amount of actual cursor rotation.

The two coordination coefficients defined above deal with translation and rotation separately but do not reveal the coordination aspect between translation and rotation taken together. In other words, a trial can be perfectly co-ordinated with respect to both its translation trajectory and rotation trajectory, but the rotation and the translation may not necessarily be performed at the same time. Hence, a third coordination factor is defined as:

Translation/Rotation Coefficient

= Ideal path in translation-rotation space / Actual path in translation-rotation space

This new translation-rotation space has two dimensions. One is the translation distance, d_t, between the cursor and the target centres of mass, and the other is the rotation mismatch ϕ_t (the magnitude of rotation vector) between the cursor and the target. Note that both d_t and ϕ_t are function of time, which define a 2D trajectory over the course of an experiment trial.

With the measurements of coordination thus formulated, we can now start to study the quality and coordination of 6 DOF manipulation as a function of different control input interfaces. Following the discussion of direct manipulation versus tool operation in the previous section, the EGG and the Fball are proposed here as two experimental input interfaces. The Fball (using position control), which is on the isomorphic side, is expected to outperform the EGG (using rate control), which is more tool-like as measured by task completion times. However, the EGG may produce better co-ordinated control trajectories, since it is not constrained by anatomical hand/arm limitations.

The proposed experimental task can be 6 DOF docking, similar to Experiment 4. Other than input interfaces, experimental phase should also be included as an independent variable, since subjects' ability to co-ordinate 6 degrees of freedom is expected to be strongly influenced by their experience.

This experiment should be conducted with a between subjects design so that follow-up experimental conditions can be added later. One follow-up condition, for example, could be an isometric rate controller. Both the EGG and the Spaceball are tools, but they offer different proprioceptive feedback to the user. One of the current theories in motor control is that proprioception plays an important role in *organising* human motor control movement (Hasan, 1992; Ghez, Gordon, Ghilardi, Christakos, and Cooper, 1990; Ghez and Sainburg, in press; Sainburg, Poizner, and Ghez 1993) . If so, the elastic device should produce more co-ordinated manipulation trials than the isometric device.

* * *

Many more interesting future studies could be proposed within the framework that this thesis has laid out. Some of these future studies will undoubtedly further generalise concepts, ideas, hypotheses and findings in this thesis and uncover new ones. Others may modify, correct or reject some of the conclusions in this thesis. What is certain is that the literature, which already has a long history, will continue to develop with this process and our understanding of human manipulation performance will continue to improve, thereby allowing us to design input control interfaces on a continuously more scientific basis.

Appendix 1

Formal Descriptions of Input Schemes in Experiments

Information on how each of the experimental conditions functions is critical for correctly interpreting the experimental results. A formal and concise method, based on a combination of mathematical models and the state-transition diagram of input devices (Buxton, Hill, and Rowley, 1985), will be applied in this section to describe the mechanism of each of the four input techniques in Experiment 1. The basis of the mathematical formulation used here can be found in numerous books in mathematics (e.g. Altmann 1986) (mathematically most rigorous), in aerospace engineering (e.g. Hughes 1986) (comprehensive and practical) and in computer graphics (e.g. Foley, van Dam, Feiner, and Hughes 1990) (introductory).

A1.1 Isotonic Position Control

While using the isotonic position control technique, the user operated in one of two interaction states (Figure A1.1). When the user's hand was open (State 1), the hand movement did not have any effect on the cursor. The user could re-position or re-orient the hand location in this state without affecting the cursor's position. When the user's hand was closed (by pressing the clutch down), the controller became engaged and the manipulated object would be slaved to the hand motion (State 2). In State 2, when the hand reached its limit (rotational or translational), the user had to release the clutch to enter state 1 and reset the hand gesture. This process might have to be repeated a few times when the object needed to be rotated, for example, 180 degrees around the vertical axis.

More formally, state 1 is a zero order hold. The cursor object remains unchanged, regardless of the hand gesture change, i.e.,

$$\mathbf{X}(k) = \mathbf{X}(k_1), \qquad \text{(A1.1)}$$

where $\mathbf{X}(k)$ is a 4 X 4 homogenous transformation matrix representing the location and orientation of the cursor; k is the sampling step

$$t = kS \qquad \text{(A1.2)}$$

t is the current time; S = 0.0667 (second) is the sampling period; k_1 is the step of entering state 1.

In State 2, the cursor movement will "copy" the hand's movement relative to the initial hand gesture at moment $t = k_2S$, i.e,

$$\mathbf{X}(k) = \mathbf{T}\,\mathbf{X}(k_2) \qquad \text{(A1.3)}$$

Where k_2 is the beginning step of state 2. $\mathbf{T}$ is the transition matrix from the hand state at time k_2S, represented by a 4 X 4 homogenous matrix $\mathbf{H}(k_2)$, to hand state at the current moment represented by $\mathbf{H}(k)$, i.e.,

$\mathbf{T} = \mathbf{H}(k)\mathbf{H}(k_2)^{-1}$ (A1.4)

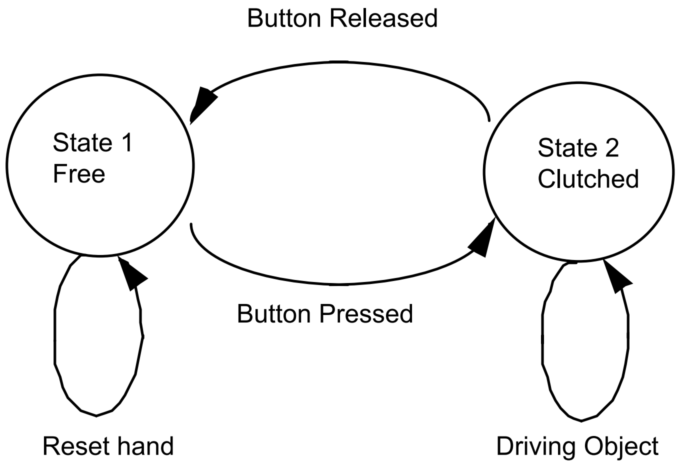


Figure A1.1 State transition model of the isotonic position control

Matrix **H**(k) is formulated according to the following equation* :

$$\begin{bmatrix} \cos(\beta_y)\cos(\beta_z) & \sin(\beta_x)\sin(\beta_y)\cos(\beta_z)-\cos(\beta_x)\sin(\beta_z) & \cos(\beta_x)\sin(\beta_y)\cos(\beta_z)+\sin(\beta_x)\sin(\beta_z) & x \\ \cos(\beta_y)\sin(\beta_z) & \sin(\beta_x)\sin(\beta_y)\sin(\beta_z)+\cos(\beta_x)\cos(\beta_z) & \cos(\beta_x)\sin(\beta_y)\sin(\beta_z)-\sin(\beta_x)\cos(\beta_z) & y \\ -\sin(\beta_y) & \sin(\beta_x)\cos(\beta_y) & \cos(\beta_x)\cos(\beta_y) & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(A1.5)

where $x, y, z, \beta_x, \beta_y, \beta_z$ are 6 DOF data (scaled by control gains) collected from the hand tracker at step k, representing positional and angular displacements of the tracker from the transmitter (signal source). x is the translation along the horizontal axis, y is along the vertical axis and z is along the depth axis. $\beta_x, \beta_y, \beta_z$ are rotations about x, y and z axes.

.c.A1.2 Isotonic Rate Control

Similar to the isotonic position control, the user operated in one of two interaction states with the isotonic rate control scheme (Figure A 1.2). When the user's hand was open (State 1), the hand movement did not have any effect on the cursor. When the user's hand was

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* Note that equations here are formulated in consideration of consistency and clarity. In actual programming, the equations vary with the algebra convention used in the graphics language, the definition of axes used in the hand tracker and the definition of axes used in the graphics language.

closed, the controller became engaged but the cursor velocity, rather than the cursor position, was proportional to the hand displacement (State 2).

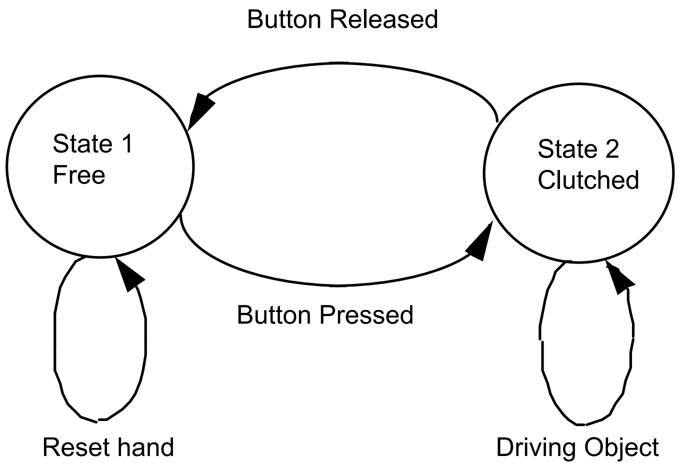

Figure A1.2 State-transition model of the isotonic rate control

More formally, in State 1:

$$\mathbf{X}(k) = \mathbf{X}(k_1), \qquad (A1.6)$$

Where k_1 is the beginning step of state 1 and k is the current step. Again, state 1 is a zero order hold.

State 2:

$$\mathbf{X}(k) = \mathbf{T}(k)\ \mathbf{X}(k_2) \qquad (A1.7)$$

Where k_2 is the beginning step of state 2. $\mathbf{T}(k)$ is the transition from hand status $\mathbf{H}(k_2)$ to current hand status $\mathbf{H}(k)$, i.e.,

$$\mathbf{T}(k) = \mathbf{H}(k)\mathbf{H}(k_2)^{-1} \qquad (A1.8)$$

$\mathbf{H}(k)$ is formulated in the same way as in equation (A1.5).

Note that equation (A1.8) is different from equation (A1.3). In equation (A1.3), hand movement is mapped to the amount of cursor movement. In equation (A1.8), hand movement is mapped to the velocity of cursor movement.

A1.3 Isometric Position Control

The 6 DOF isometric sensor used in the experiment was a Spaceball™. When used for isometric position control, the button on the Spaceball was employed to switch between two states of operation (Figure A1.3). When the button was pressed, the controller became engaged and the cursor's movement will be proportional to the force/torque that the user applied to the ball. Once the button was released, the cursor remained where it was. The user might have to switch between the two states several times in order to move the cursor over large distance without excessive force/torque.

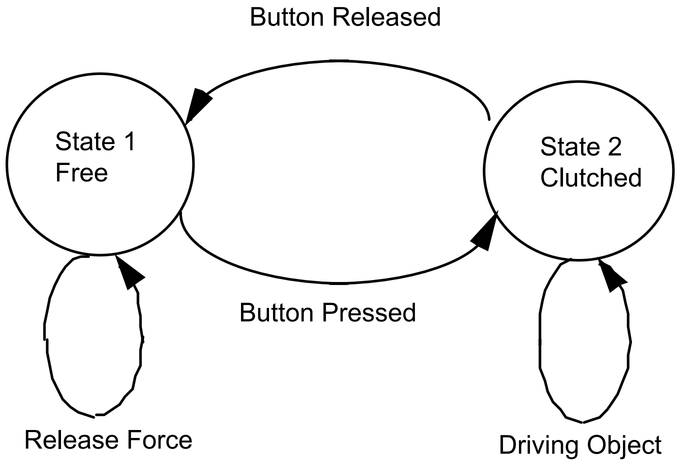

Figure A1.3 State-transition model of the isometric position control

More formally, in State 1:

$$\mathbf{X}(k) = \mathbf{X}(k_1), \qquad (A1.9)$$

Where k is the current step and k_1 is the beginning step of state 1.

In State 2:

$$\mathbf{X}(k) = \mathbf{T}(k)\,\mathbf{X}(k_2) \qquad (A1.10)$$

Where k_2 is the beginning of state 2. **T** is the transformation matrix based on the force vector $[x \quad y \quad z]^T$ and torque vector $[\beta_x \quad \beta_y \quad \beta_z]^T$ of the Spaceball at time t = kS, scaled by control gains.

T=

$$\begin{bmatrix} \cos(\beta_y)\cos(\beta_z) & \sin(\beta_x)\sin(\beta_y)\cos(\beta_z)-\cos(\beta_x)\sin(\beta_z) & \cos(\beta_x)\sin(\beta_y)\cos(\beta_z)+\sin(\beta_x)\sin(\beta_z) & x \\ \cos(\beta_y)\sin(\beta_z) & \sin(\beta_x)\sin(\beta_y)\sin(\beta_z)+\cos(\beta_x)\cos(\beta_z) & \cos(\beta_x)\sin(\beta_y)\sin(\beta_z)-\sin(\beta_x)\cos(\beta_z) & y \\ -\sin(\beta_y) & \sin(\beta_x)\cos(\beta_y) & \cos(\beta_x)\cos(\beta_y) & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(A1.11)

A1.4 Isometric Rate Control

The isometric rate control was a single state scheme (Figure A1.4). The object's velocity was proportional to the force/torque applied on the Spaceball.

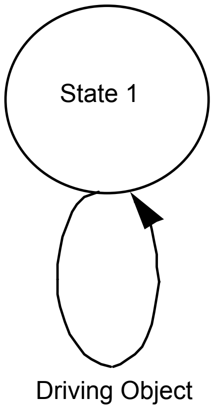

Figure A1.4 State-transition model of the isometric rate control

More formally, in State 1

$$\mathbf{X}(k) = \mathbf{T}(k)\ \mathbf{X}(k\text{-}1) \qquad \text{(A1.12)}$$

Where $\mathbf{T}(k)$ is defined in equation (A1.11).

Appendix 2
Asymmetries, Priorities, and Controllability of Multiple Degrees of Freedom: A Dimensional Analysis of 6 DOF Tracking

A2.1 Introduction

This chapter is a more detailed analysis of Experiment 3. Based on the measure of integrated RMS error, Chapter 3 has analysed the relative performance between the isometric controller and the elastic controller. This appendix takes the approach of decomposing subjects' 6 DOF tracking process into separate dimensions, so as to gain more insight into how users handle manipulation tasks with multiple degrees of freedom. Of particular interest to this chapter are differences between performance in different axes of 3D space and how well humans can handle all 6 degrees of freedom simultaneously.

With regards to human performance in X, Y, Z dimensions in 3D space, it can be expected that performance in the depth dimension will not be the same as that in the horizontal or vertical dimensions even with multiple sources of depth cues (see Chapter 5 for a review of depth cues and 3D display techniques). Unknown, however, is the magnitude of this difference: 10 percent, 50 percent, or order of magnitude? This appendix will evaluate subjects' performance in the Z dimension in comparison to the X and Y dimensions, with the presence of the depth cues that are easily available with today's technology.

As indicated in the human visual performance literature, performance differences between the horizontal and the vertical dimensions are also conceivable. For instance, in a task that required nursery school children to reproduce lines on a circular background, Berman, Cunningham, and Harkulich (1974) found that the reproductions of the vertical lines were significantly more accurate than the reproductions of the horizontal and the oblique lines, as measured by orientation differences. Gottsdanker and Tietz (1992) found that humans tend to be more sensitive in judging relative length in the horizontal dimension than in the vertical direction. It is therefore valuable not only to compare performance in the Z dimension with the X and Y dimensions but also to evaluate the performance difference between the X and the Y dimensions. In other words, the general objective here is to examine the (an)isotropies or asymmetries in X, Y, and Z dimensions.

The second goal of this chapter is to examine the simultaneous controllability of all 6 DOF. There have been some concerns in the teleoperation literature with regard to the controllability of all 6 degrees of freedom with one hand. Rice, Yorchak, and Hartley (1986) observed that controlling 6 DOF with one hand was difficult, due to unwanted cross coupling between axes. Some practical teleoperation systems, such as the Shuttle Remote

Manipulator, also known as the "CANADARM", require two-handed operation, one for rotation control and the other for translation control. On the other hand, O'Hara (1987) contradicted Rice et al's observation and found no difference between two 3 DOF controllers versus one 6 DOF control. McKinnon and King (1988) further argued that a one hand 6 DOF controller should be preferable to distributed control among separate controllers. Detailed empirical evidence has not been found on this issue, however.

A2.2 Method

A2.2.1 Review of Experiment 3

The analyses in this appendix are based on Experiment 3. In that experiment, subjects were asked to continuously control a 3D cursor and align it, as closely as possible in both location and orientation, with a 3D target which moved unpredictably in 6 DOF within a virtual environment. Both the tracking target and the controlled cursor were tetrahedral in shape. The target in the experiment was driven by six independent forcing functions for each degree of freedom. The cursor was controlled by the subjects through elastic or isometric rate controllers. Four types of depth cues were implemented in the experimental display: stereoscopic disparity, perspective, interposition (edge occlusion), and partial occlusion through semi-transparency (see Chapter 5).

A2.2.1 The Decomposed Performance Measures

At sampling step $t = i\Delta t$ (where i is the step number and Δt is the sampling period), the vector from the centre of the cursor to the centre of the target is defined as translation vector $\mathbf{T}i$. The translation error in 3D is the norm of $\mathbf{T}i$, i.e. the Euclidean distance from the centre of the cursor to the centre to the target. For each entire trial, the translation root-mean-square (RMS) error is:

$$T_{rms} = \sqrt{\frac{\sum_{i=0}^{N} |\mathbf{T}_i|^2}{N}} \qquad \text{(A2.1)}$$

where N is the last step.

$\mathbf{T}i$ consists of three components in the horizontal (xi), vertical (yi) and depth (zi) dimensions respectively, i.e.:

$$\mathbf{T}i = (xi, yi, zi) \qquad \text{(A2.2)}$$

For each trial the decomposed RMS tracking errors in X, Y and Z dimensions are:

$$X_{rms} = \sqrt{\frac{\sum_{i=0}^{N} x_i^2}{N}}, \qquad Y_{rms} = \sqrt{\frac{\sum_{i=0}^{N} y_i^2}{N}}, \qquad Z_{rms} = \sqrt{\frac{\sum_{i=0}^{N} z_i^2}{N}} \qquad \text{(A2.3)}$$

respectively. X_{rms}, Y_{rms}, Z_{rms} are the decomposed translation measures used later in the dimensional analysis of translation.

Rotational errors were measured in a similar way in the present work, although parameterisation of rotations in 3D space is a relatively complex subject (see Altmann, 1986; Hughes, 1986 for mathematical treatments of rotation parameterization). At $t = i\Delta t$, the angular displacement (rotation mismatch) between the cursor and the target can be expressed as (Altmann, 1986, p 70)

$$R(\phi_i \mathbf{n}_i) \qquad \text{(A2.4)}$$

$R(\phi_i \mathbf{n}_i)$ signifies that at tracking step i, the cursor and the target are angularly mismatched about axis $\mathbf{n}_i$ by scalar angle ϕ_i. $\mathbf{n}_i = (n_{xi}, n_{yi}, n_{zi})$ is a unit vector specifying the direction of the orientation mismatch and ϕ_i is the amount of mismatch. ϕ_i and $\mathbf{n}_i$ can be combined as a single rotation vector (Figure A2.1):

$$\text{Æ}_i = \phi_i \mathbf{n}_i = (\phi_i n_{xi}, \phi_i n_{yi}, \phi_i n_{zi}) = (\phi_{xi}, \phi_{yi}, \phi_{zi}) \qquad \text{(A2.5)}$$

Since $\mathbf{n}_i$ is a unit vector, the magnitude of $\boldsymbol{\O}_i$ is the amount of rotation mismatch between the cursor and the target. ϕ_{xi}, ϕ_{yi}, and ϕ_{zi} are the decomposed components of the rotation mismatch in the X, Y and Z dimensions. Note that ϕ_{xi}, ϕ_{yi}, and ϕ_{zi} are not pitch, yaw and roll angles. They are the projections of vector $\boldsymbol{\O}_i$ onto the X, Y and Z axes. The values of ϕ_{xi}, ϕ_{yi}, and ϕ_{zi} relative to each other reflect the inclination of $\boldsymbol{\O}_i$ towards the X, Y or Z axes. For instance, the greater ϕ_{xi} is (relative to ϕ_{yi} and ϕ_{zi}), the more biased the rotation vector $\boldsymbol{\O}_i$ is towards the horizontal axis X.

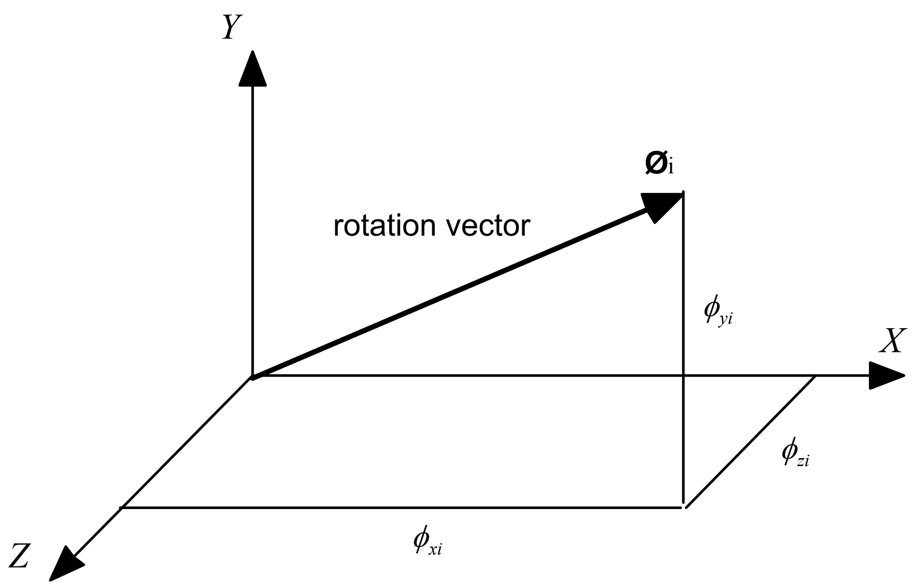

Figure A2.1 Rotation vector and its components in the X, Y and Z dimensions

For each entire trial, the RMS rotational error is:

$$R_{rms} = \sqrt{\frac{\sum_{i=0}^{N} |\phi_i|^2}{N}} \qquad \text{(A2.6)}$$

where N is the final step in the trial.

The RMS value of ϕ_{xi}, ϕ_{yi}, and ϕ_{zi} are:

$$R_{xrms} = \sqrt{\frac{\sum_{i=0}^{N} \phi_{xi}^2}{N}}, \qquad R_{yrms} = \sqrt{\frac{\sum_{i=0}^{N} \phi_{yi}^2}{N}}, \qquad R_{zrms} = \sqrt{\frac{\sum_{i=0}^{N} \phi_{zi}^2}{N}} \qquad \text{(A2.7)}$$

R_{xrms}, R_{yrms} and R_{zrms}, reflect the totals (from $i = 0$ to $i = N$) of the projections of rotation vector ϕ_i on X, Y and Z axes respectively. They serve as the decomposed rotation measures in the following analysis.

A2.3 Results and Discussions

RMS tracking error scores, as defined earlier in equations (7), (8), (12) and (13) were analysed for 2 (controls) x 13 (subjects) x 5 (phases) x 4 (paths) = 520 trials. This section presents the results of analysis on these data. Non-linear (logarithmic) transformation was performed in order to meet the model residual distribution requirement of ANOVA analysis. The major results are organised into three groups, respectively addressing issues related to translation in 3D, rotation in 3D and the controllability of all 6 degrees of freedom with one hand.

A2.3.1 Anisotropic Performance in Translation

Repeated measure variance analysis on the translation RMS Errors X_{rms}, Y_{rms}, Z_{rms} as defined in equation (8) was conducted with one between-subject factor (controller type) and three within-subject factors (dimension, learning phase, and tracking path). Significant main effects included dimension (X, Y, Z) (F(2, 48) = 59.03, p<.0001), learning phase (F(4, 96) = 98.9, p<.0001), and tracking path (F(3, 72) = 12.73, p<.0001). A significant interaction was also found between dimension and learning phase (F(8, 192) = 6.96, p<.0001).

Of particular interest for the present report are th[e] pairwise contrast comparisons (Howell, 1992) whic[h] showed that tracking errors in the X, Y and Z dimensions were significantly different from each other. The means of the X, Y, Z RMS errors are shown in Figure A2.2. As expected, the mean error in the Z direction was significantly greater than those in the other two directions (X vs. Z contrast: F = 114.48, p< .0001; Y vs. Z contrast,

[[

F=48.8, p<.0001). In terms of magnitude, the mean of Z_{rms} is 39.64% greater than the mean of X_{rms} and 16.54% greater than the mean of Y_{rms}. This indicates that the 3D display with particular depth cues implemented in this experiment was sufficient for enabling satisfactory performance in the depth dimension; the difference in fact is well below one level of about 400% previously reported with a monoscopic display (Massimino, Sheridan, and Roseborough, 1989) .

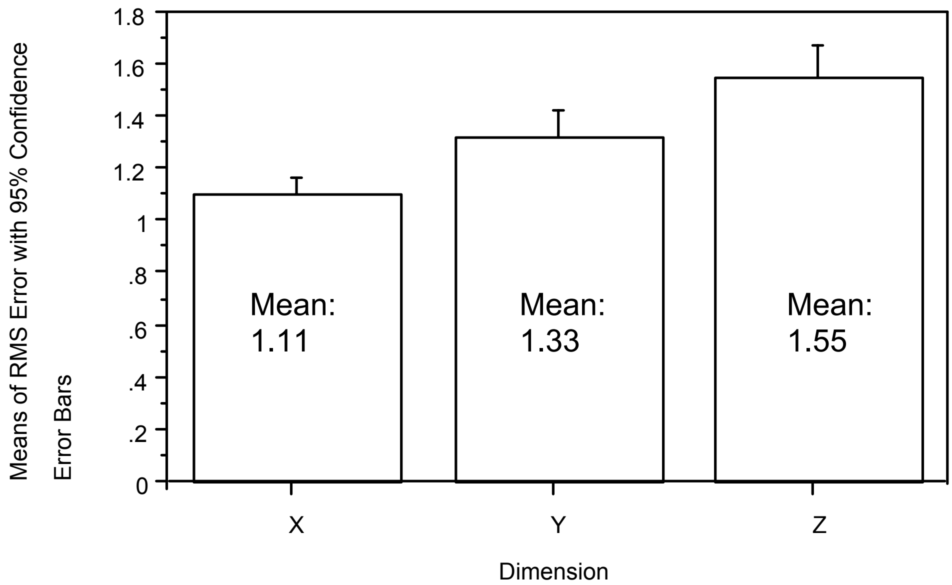

Figure A2.2 Means of RMS tracking errors in horizontal (X), vertical (Y) and depth (Z) dimensions

Interestingly, the mean error in the Y direction was significantly greater than the mean error in the X direction by 19.8% (X vs. Y contrast: F = 13.79, p<0.001). This was somewhat surprising, given that both Y and X are planar dimensions. The first possible cause was the resolution difference between the vertical and the horizontal dimensions in the stereo display. On the 120 Hz CRT display used, stereoscopic presentation was implemented by means of splitting the display memory into top and bottom halves: one half for left view and one half for right view. The vertical resolution of the stereo display was therefore less than half of the horizontal resolution. However, the RMS tracking errors were at the level of 1 graphic unit or greater (Figure A2.2) which was an order of magnitude higher than the vertical resolution threshold (0.04 graphic unit). This means that the resolution difference was must likely not the cause. The second explanation of the performance difference between the virtual and the horizontal dimensions was possible bias in the input controllers or human motor actions which might have made the horizontal dimension easier to manipulate than the vertical dimension. Such a hypothesis, however, could not be supported by further analyses either. Two types of controllers were used in the experiment, differing both in electronic design and in manipulative features. The elastic controller involved hand movement while the isometric controller required tensions only (force and torque) and yet the same relative performance pattern in the X, Y and Z directions ($X_{rms} < Y_{rms} < Z_{rms}$) was found for both types of controllers (Figure A2.3). It is therefore highly unlikely that, if some biases had existed in either the controller used or the motor actions required, they would have been identical for the two different controllers.

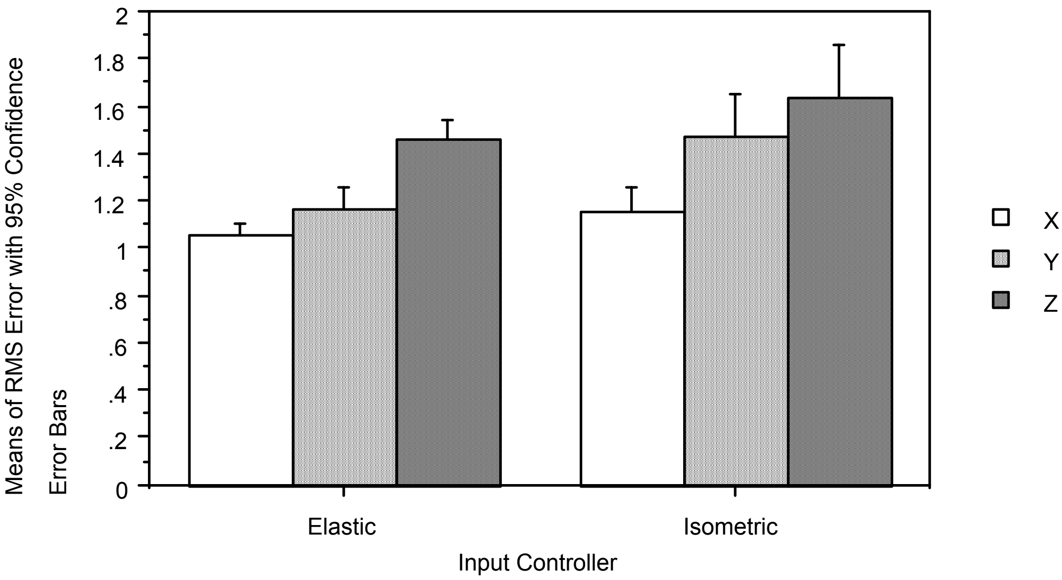

Figure A2.3 Translation tracking errors with two types of input controllers

Another possible source of variation is the particular tracking path used. Since each tracking path was randomly generated, there exists a probability that movement in the Y dimension might have been more difficult than in the X dimension along a particular path. That possibility was also rejected, however. When no input control was applied to the cursor movement (in the baseline test), the means of X_{rms} were in fact *greater* than the means of Y_{rms} in three of the four tracking paths (Figure A2.4). However, subjects' relative performance patterns ($X_{rms} < Y_{rms} < Z_{rms}$) were consistent across the four distinct target trajectories (Figure A2.5), independent of the amount of target movement in each dimension.

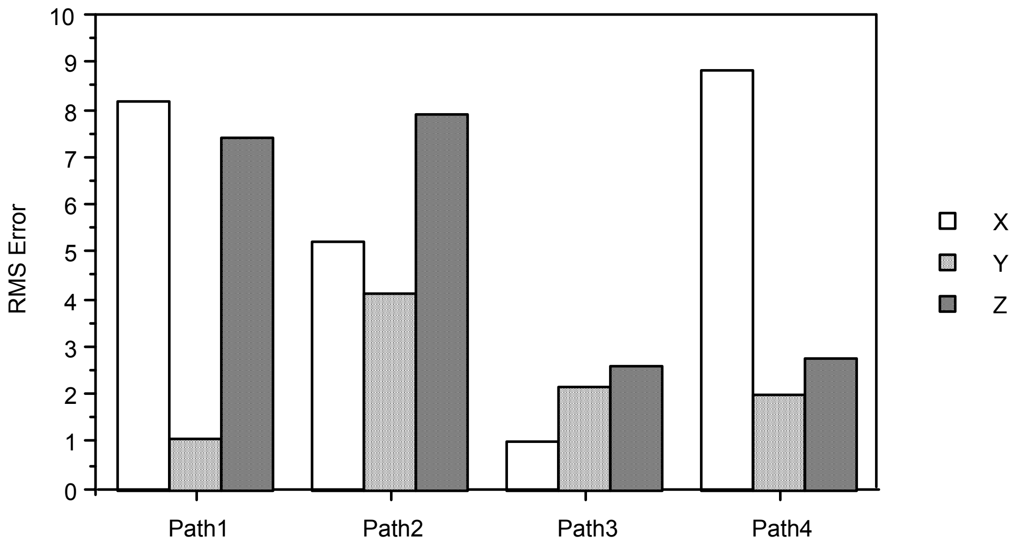

Figure A2.4 Baseline test: RMS errors when no input control was applied

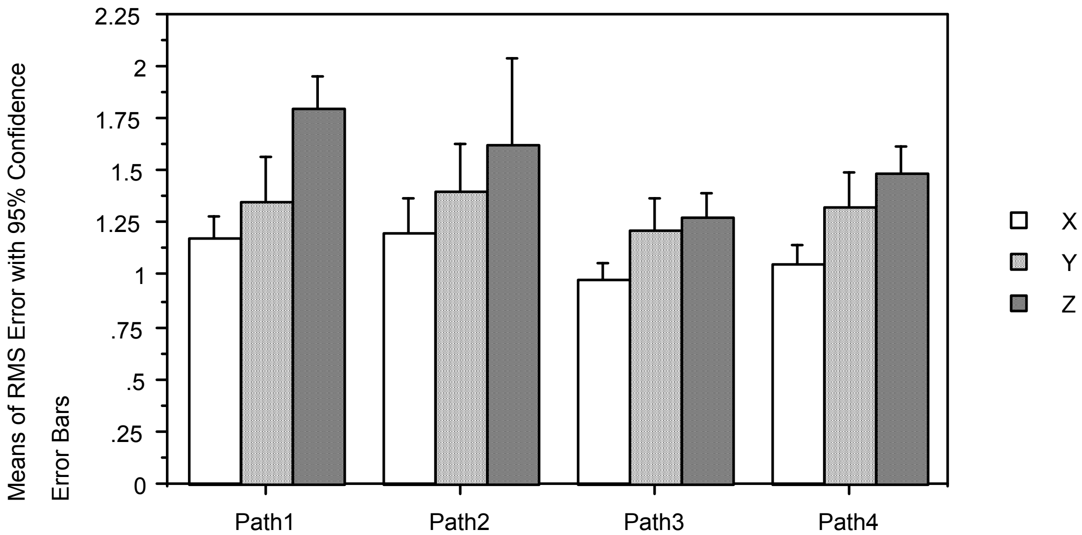

Figure A2.5 Consistent performance pattern in X, Y, Z across four tracking paths

The puzzle of the X and Y difference was better clarified when performance was examined in relation to experimental phase. The X, Y and Z error components were significantly affected by subjects' practice (dimension X phase interaction: $F(8, 192) = 6.96$, $p<.0001$). As Figure A2.6 illustrates, error in the Y dimension initially was as great as that in the Z dimension. As practice progressed and learning took place, however, it approached the error level of the X dimension, with a consistent pattern across all four distinct tracking paths (Figure A2.7) and for the two types of input controllers (Figure A2.8). These consistencies were confirmed by the absence of significant interactions between dimension, phase and path ($F(24, 576) = 0.867$, $p = .65$) and between dimension, phase and input ($F(8, 192) = 1.35$, $p = .22$).

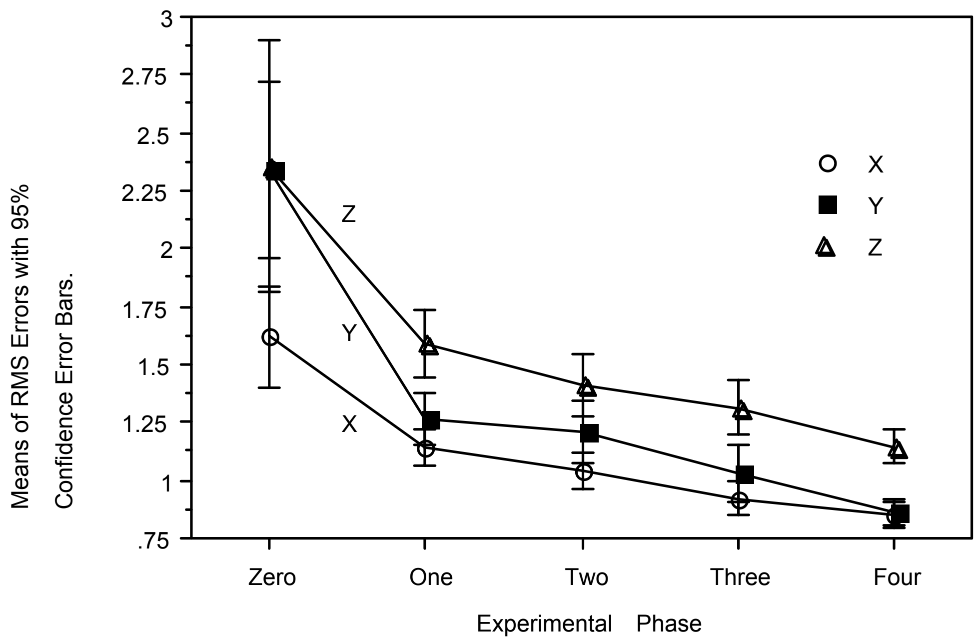

Figure A2.6 The evolution of Y_{rms} in relation to X_{rms} and Z_{rms} as a function of experimental phase

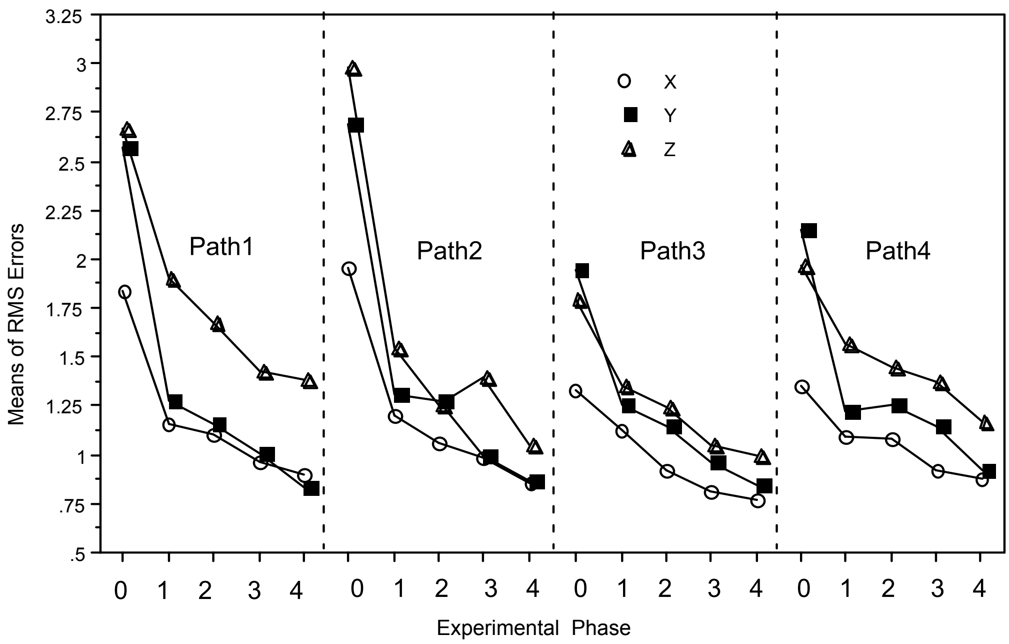

Figure A2.7 Error evolution for four distinct tracking paths

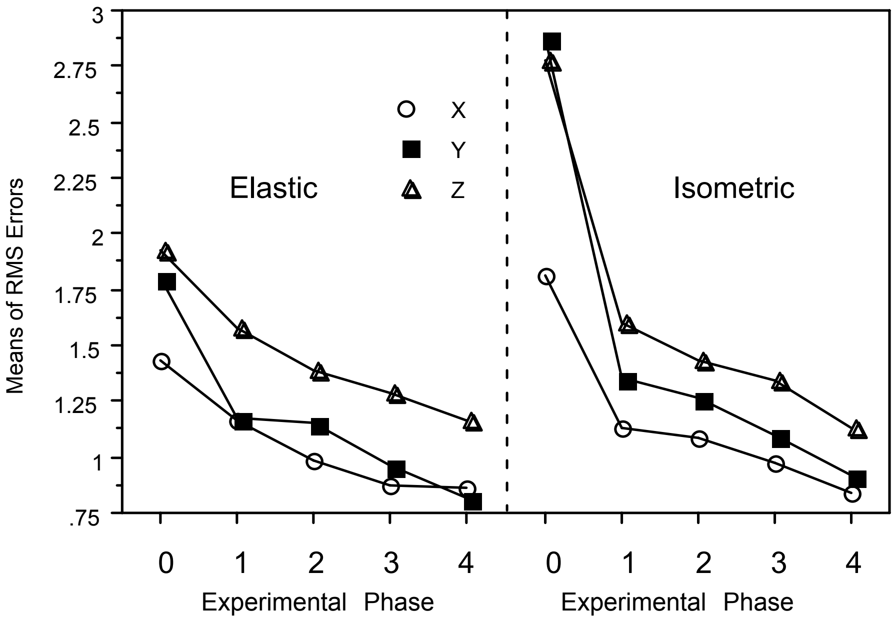

Figure A2.8 Error evolution for both input control modes

The change of performance in Y relative to the other dimensions therefore suggests that the inferior performance in Y is due neither to perception nor to action (motor control) per se, but is a matter of attentional bias. In the early stage of learning, when subjects had difficulties in managing all of the dimensions simultaneously, they apparently gave higher attentional *priority* to horizontal errors than vertical errors. In the later stage of learning when their performance had improved in general and attentional resources were thus freed-up some what, subjects performed equally well in controlling errors in the X and Y dimensions.

The performance difference between the Z dimension and the X dimension is both perceptual and attentional. In Phase 0, the mean of Z_{rms} was 45% greater than X_{rms}. In Phase 4, this difference was 35%. Although more attention might have been paid to the Z dimension in the later stages of the experiment, which reduced the relative difference between X and Z dimension (from 45% to 35%), the mean Z_{rms} was still larger than that of X_{rms} due to the inherent difficulty of perceiving in depth, even when using sophisticated depth cues.

The hypothesis of attention priority is a plausible one in light of evolution and daily life. In the natural world, there are more horizontal movement to human visual stimulation than virtual ones. Animals, including birds, move mostly in horizontal direction. The psychological literature indicates that while there is no acuity difference between horizontal and vertical vision, human tend to be more *sensitive* to horizontal than to vertical length differences (Berman, Cunningham, and Harkulich, 1974) , as indicated by the shorter reaction times in the horizontal dimension (Gottsdanker and Tietz, 1992).

A2.3.2 Performance in Rotation

Based on the decomposed rotational tracking errors R_{xrms}, R_{yrms} and R_{zrms}, as defined in equation (13), a repeated measure variance analysis with one between-subject factor (controller type) and three within-subject factors (R_{xrms}, R_{yrms} and R_{zrms}, experimental phase, and tracking path) showed the following significant main effects: dimensional components R_{xrms}, R_{yrms} and R_{zrms} ($F(2, 48) = 5.632$, $p < 0.01$), experimental phase ($F(4, 96) = 48.76$, $p<.0001$), and tracking path ($F(3, 72) = 3.33$, $p=0.25$). The effect of dimensional components R_{xrms}, R_{yrms} and R_{zrms} was not affected by experimental phase (Dimension x Phase: $F(8, 192) = 2.10$, $p=0.66$).

The differences between R_{xrms}, R_{yrms} and R_{zrms} components are shown in Figure A2.9. Comparison contrast tests indicated that the rotation vector component along the Z axis (R_{zrms}) was significantly smaller than those along the X and Y axes (R_{xrms} vs. R_{yrms}: $F = 27.94$, $p < 0.0001$; R_{yrms} vs. R_{zrms}: $F = 14.88$, $P < 0.001$). On average, R_{yrms} was slightly smaller than R_{xrms}, but this difference was not statistically significant ($F = 2.04$, $p = 0.16$). These results are congruent with the analysis of the translational errors: R_{zrms} was the smallest, because orientation mismatches about the Z axis did not involve displacements in the Z dimension and therefore were most easily to be perceived. Orientation mismatches about the X and Y axes, on the other hand, both involved displacements in depth, resulting in greater R_{xrms} and R_{yrms}. R_{yrms} was slightly smaller than R_{xrms} because rotation about the Y axis involves horizontal changes while rotation about the X axis involves vertical changes. For the given size of the target and the cursor, the dimensional differences in rotation were less pronounced than for translations.

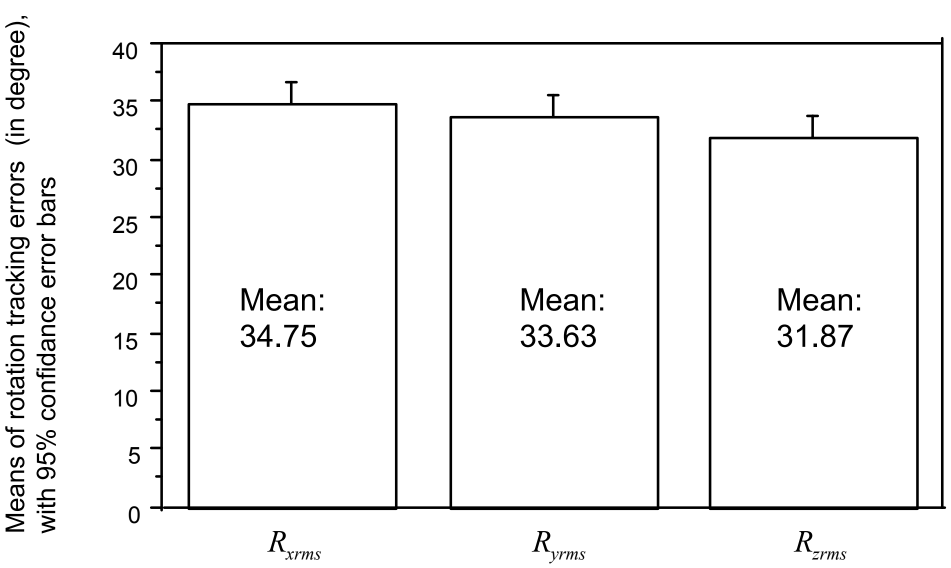

Figure A2.9 The means of decomposed rotational errors

A2.3.3 Controlling Both Translation and Rotation with One Hand

This subsection analyses subjects' performance in managing all six degrees of freedom with one hand. During the experiment, it was observed that when subjects could not do the tracking task very well, especially in the early stage of the experiment, they tended to ignore rotations and concentrated on moving the cursor to catch the target in location (translation) only. This is apparently a reasonable strategy to take, since rotation errors have a limited range (+/-180 degrees at the greatest) while translation error is theoretically unlimited. In the later stage of experiment, the majority of the subjects appeared to be able to control all six degree of freedom concurrently. Figure A2.10 shows the means of translation error and rotation error of each individual subject in experimental phase 0 (first four trials). In the figure, translation RMS error T_{rms} is defined by equation (7) and rotation RMS error R_{rms} is defined by equation (12). In order to be comparable with translation errors, R_{rms} has been scaled by the radius of the target tetrahedron (i.e. rR_{rms}, where r = 3.55), which is equivalent to the distance moved by the tetrahedron vertices through the rotation.

A baseline test showed that the means of T_{rms} and R_{rms} (over four trials with distinctive paths) without any control were respectively 8.62 and 6.35 (corresponding to (180/π) *6.35 /r = 119.1°). The results in Figure A2.10 show that large individual differences exist. Two subjects, U and W, did not effectively control either translation or rotation (RMS errors were close to or even beyond the baseline levels). The other twenty

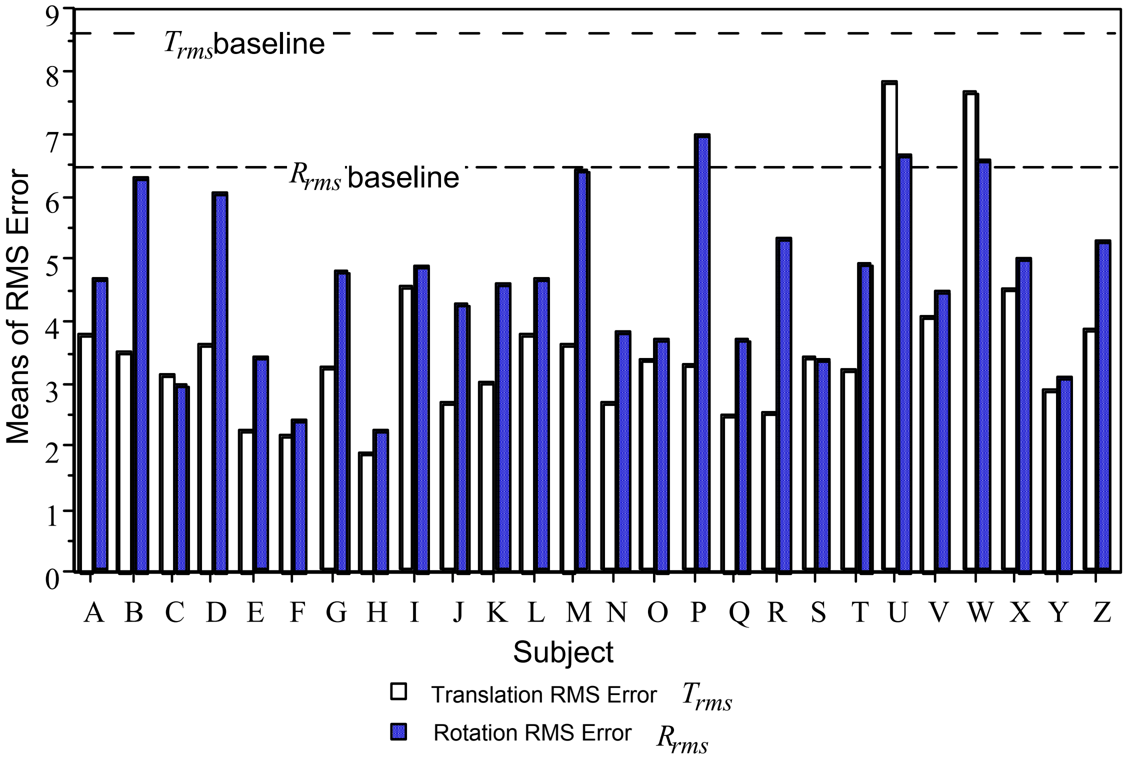

Figure A2.10 Individual performance in translation and rotation at Phase 0 (no practice). Baseline scores indicate performance levels with no control input. Rotation scores are scaled to levels comparable to translation scores (see text) four subjects controlled translations with varying degrees of success, but many of them could not manage rotations at this stage (no practice). Four of them, subject B, D, M, and P, were no more than 5% bellow the baseline rotation RMS error. These data show that without practice, 20 of 26 (76.9%) subjects were able to cope somewhat with both translation and rotation simultaneously; four of twenty six (15.3%) were only able to control translation effectively, 2 of 26 (7.7%) subjects could control neither translation nor rotation at all.

Figure A2.11 shows subjects' performance at the final phase of the experiment. After 40 minutes of practice, all subjects could control translations to a certain degree (more than a 50% reduction from the baseline). Two subjects (B and W) still could not effectively control rotation (less than 5% reduction from the baseline), 3 more (R, U, and Z) had more than 5% but less than 50% reduction from the baseline. These five subjects, (B, W, R, U, and Z) also had larger performance disparities between translation and rotation; their rotation errors were greater than translation errors by 185% (B), 83% (R), 82.8% (U), 197% (W), 126% (Z) respectively. The rest of the subjects (21 of 26 = 80.7%) controlled both rotation and translation, which required all 6 degrees of freedom, with some degree of success, as indicated by the substantial reduction in both translation and rotation from the baselines.

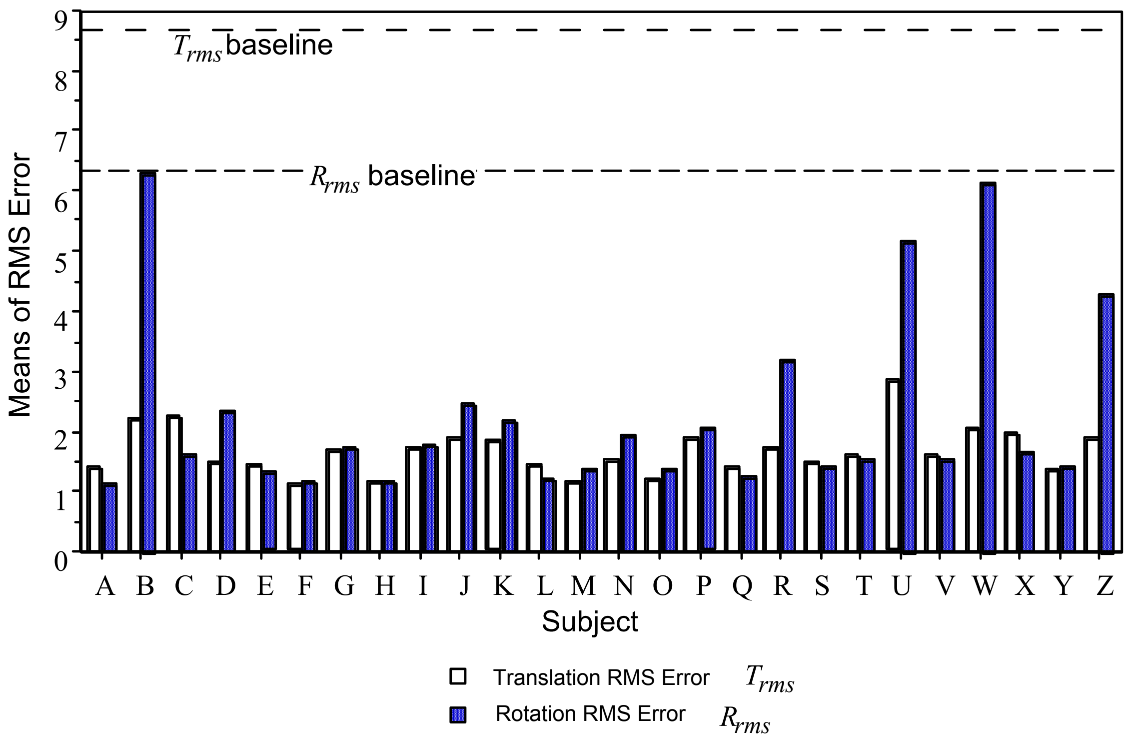

Figure A2.11 Individual performance in translation and rotation at Phase 5 (40 minutes practice).Baseline scores indicate performance levels with no control input. Rotation scores are scaled to levels comparable to translation scores (see text)

In summary, the data suggest that successful control of all 6 degrees of freedom is individual dependent. With 40 minutes of practice, more than 80% of the subjects could simultaneously manage both rotations and translation. A few subjects could not control all the degrees of freedom even by the end of the session. These subjects tended to concentrate on fewer degrees of freedom (translation only) of the task and ignore the others (rotation).

A2.4 Concluding Remarks

This appendix has analysed human performance in a 6 DOF pursuit tracking experiment through a dimensional decomposition method. This analysis has addressed a number of issues in 3D human machine interface evaluation with quantitative information, with respect to both the quality of depth display and on the controllability of 6 DOF inputs. With regards to display quality, the analysis showed that with the aid of interposition, perspective, binocular disparity and partial occlusion depth cues, users' performance in the depth dimension was reasonably close to performance levels in the horizontal and vertical dimensions. Depending on the practice time, the mean tracking error in the depth dimension was 45% (initially) to 35% (after 40 minutes of practice) larger than that of the horizontal dimension. Subjects tended to give higher attentional priority to the horizontal dimension than to the vertical dimension. Tracking error in the vertical dimension was larger than that of the horizontal dimension in the early stage of experiment and decreased to the level of the horizontal error in the later stage of experiment.

On the input side, the analysis indicated that large individual differences exist in the ability to simultaneously control six degrees of freedom. After 40 minutes of practice, more than 80% of the subjects could control both translations and rotations effectively (requiring all 6 degrees of freedom). It appears that in tracking 6 DOF movement, subjects tended to adopt the strategy of allocating their attention in a certain biased order. In the early learning stages, when they have not acquired sufficient skills to manage all the degrees of freedom, subjects tended to concentrate on translations and ignore rotations. Between the three dimensions of translations, they tended to give higher attentional priority to reducing horizontal errors over reducing vertical or depth errors.

Appendix 3

Detailed Statistical Results of the Experiments

A3.1 Experiment 1

Table A3.1.1 Repeated Measure Variance Analysis of Experiment 1 (overall)

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	7	7.292	1.042		
Technique	3	38.590	12.863	40.181	.0001
Technique * Subject	21	6.723	.320		
Phase	3	4.300	1.433	54.611	.0001
Phase * Subject	21	.551	.026		
Location	3	.198	.066	1.939	.1543
Location * Subject	21	.715	.034		
Technique * Phase	9	.302	.034	1.215	.3018
Technique * Phase * Subject	63	1.738	.028		
Technique * Location	9	.566	.063	2.451	.0184
Technique * Location * Subject	63	1.616	.026		
Phase * Location	9	.036	.004	.274	.9796
Phase * Location * Subject	63	.932	.015		
Technique * Phase * Location	27	.288	.011	.815	.7284
Technique * Phase * Location * Subject	189	2.473	.013		

Dependent: Log(Ctime)

Table A3.1.2 Contrast Tests Between Techniques in Experiment 1

Techniques	Mean	Std. Dev.	Std. Error	Contrast Test
Isotonic Position VS Isotonic Rate	**6.705** **10.547**	2.154 4.140	.110 .211	F-Value 21.226 **P-Value** .0002
Isotonic Position VS Isometric Position	**6.705** **16.933**	2.154 8.038	.110 .410	F-Value 86.769 **P-Value** .0001
Isotonic Position VS Isometric Rate	**6.705** **6.974**	2.154 3.548	.110 .181	F-Value .011 **P-Value** .9181
Isotonic Rate VS Isometric Position	**10.547** **16.933**	4.140 8.038	.211 .410	F-Value 22.163 **P-Value** .0001
Isotonic Rate VS Isometric Rate	**10.547** **6.974**	4.140 3.548	.211 .181	F-Value 22.197 **P-Value** .0001
Isometric Position VS Isometric Rate	**16.933** **6.974**	8.038 3.548	.410 .181	F-Value 88.719 **P-Value** .0001

Table A3.1.3 Repeated Measure Variance Analysis of Test 1 in Experiment 1

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	7	2.795	.399		
Technique	3	9.967	3.322	21.447	.0001
Technique * Subject	21	3.253	.155		
Location	3	.055	.018	.788	.5138
Location * Subject	21	.485	.023		
Technique * Location	9	.250	.028	1.385	.2138
Technique * Location * Subject	63	1.262	.020		

Dependent: Log(CTime)

Table A3.1.4 Contrast Tests Between Techniques in Test 1 in Experiment 1

Techniques	Mean	Std. Dev.	Std. Error	Contrast Test (df 1)
Isotonic Position vs. Isotonic Rate	**7.683** **13.319**	2.984 5.140	.305 .525	F-Value 17.515 **P-Value** .0004
Isotonic Position vs. Isometric Position	**7.683** **20.556**	2.984 10.738	.305 1.096	F-Value 50.681 **P-Value** .0001
Isotonic Position vs. Isometric Rate	**7.683** **9.067**	2.984 5.224	.305 .533	F-Value .654 **P-Value** .4279
Isotonic Rate vs. Isometric Position	**13.319** **20.556**	5.140 10.738	.525 1.096	F-Value 8.608 **P-Value** .0079
Isotonic Rate vs. Isometric Rate	**13.319** **9.067**	5.140 5.224	.525 .533	F-Value 11.401 **P-Value** .0029
Isometric Position vs. Isometric Rate	**20.556** **9.067**	10.738 5.224	1.096 .533	F-Value 39.824 **P-Value** .0001

Table A3.1.5 Repeated Measure Analysis of Test 4 in Experiment 1

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	7	1.698	.243		
Technique	3	9.047	3.016	36.491	.0001
Technique * Subject	21	1.736	.083		
Location	3	.077	.026	1.910	.1590
Location * Subject	21	.281	.013		
Technique * Location	9	.121	.013	.938	.4993
Technique * Location * Subject	63	.904	.014		

Dependent: Log(CTime)

Table A3.1.6 Contrast Tests Between Techniques in Test 4 in Experiment 1

Techniques	Mean	Std. Dev.	Std. Error	Contrast Test (df 1)
Isotonic Position VS Isotonic Rate	6.157 **8.658**	1.493 2.602	.152 .266	F-Value 11.760 **P-Value** .0025
Isotonic Position VS Isometric Position	6.157 **14.861**	1.493 6.578	.152 .671	F-Value 74.693 **P-Value** .0001
Isotonic Position VS Isometric Rate	**6.157** **5.940**	1.493 2.201	.152 .225	F-Value .515 **P-Value** .4811
Isotonic Rate VS Isometric Position	**8.658** **14.861**	2.602 6.578	.266 .671	F-Value 27.178 **P-Value** .0001
Isotonic Rate VS Isometric Rate	**8.658** **5.940**	2.602 2.201	.266 .225	F-Value 17.195 **P-Value** .0005
Isometric Position VS Isometric Rate	**14.861** **5.940**	6.578 2.201	.671 .225	F-Value 17.195 **P-Value** .0005

Table A3.1.7 Fisher's Protected LSD Post-Hoc Test on Ease of Use

	Vs.	Diff.	Crit. diff.	P-Value	
Isometric Position	Isotonic Rate	1.062	.793	.0111	S
	Isotonic Position	2.000	.793	.0001	S
	Isometric Rate	2.062	.793	.0001	S
Isotonic Rate	Isotonic Position	.938	.793	.0227	S
	Isometric Rate	1.000	.793	.0159	S
Isotonic Position	Isometric Rate	.062	.793	.8714	

S = Significantly different at 0.05 level

Table A3.1.8 Fisher's Protected LSD Post-Hoc Test on Fatigue

	Vs.	Diff.	Crit. diff.	P-Value	
Isometric Rate	Isotonic Position	.938	.873	.0366	S
	Isotonic Rate	.938	.873	.0366	S
	Isometric Position	2.375	.873	.0001	S
Isotonic Position	Isotonic Rate	0.000	.873	1.0000	
	Isometric Position	1.438	.873	.0026	S
Isotonic Rate	Isometric Position	1.438	.873	.0026	S

S = Significantly different at 0.05 level.

Table A3.1.9 Fisher's Protected LSD Post-Hoc Test on Overall Preference

	Vs.	Diff.	Crit. diff.	P-Value	
Isometric Position	Isotonic Rate	1.312	.755	.0016	S
	Isotonic Position	2.125	.755	.0001	S
	Isometric Rate	2.562	.755	.0001	S
Isotonic Rate	Isotonic Position	.812	.755	.0361	S
	Isometric Rate	1.250	.755	.0024	S
Isotonic Position	Isometric Rate	.438	.755	.2414	

S = Significantly different at 0.05 level.

Table A3.1.10 Repeated Measure Variance Analysis of Interaction

Source	df	Sum of Square	Mean Square	F-Value	P-Value
Subject	7	1.698	.243		
Resistance	1	.835	.835	8.583	.0220
Resistance * Subject	7	.681	.097		
Transfer Function	1	1.453	1.453	12.798	.0090
Transfer Function * Subject	7	.795	.114		
Resistance * Transfer Function	1	6.759	6.759	182.36	.0001
Resistance * Transfer Function * Subject	7	.259	.037		

Dependent: Log(CTime)

A3.2 Experiment 2

Table A3.2.1 Repeated Measure Variance Analysis of Experiment 2 (overall)

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Input	1	.108	.108	.220	.6432
Subject(Group)	24	11.726	.489		
Phase	3	7.164	2.388	90.476	.0001
Phase * Input	3	.203	.068	2.570	.0609
Phase * Subject(Group)	72	1.900	.026		
Location	3	.355	.118	4.524	.0058
Location * Input	3	.135	.045	1.716	.1713
Location * Subject(Group)	72	1.882	.026		
Block	2	.097	.048	5.154	.0094
Block * Input	2	.089	.045	4.761	.0130
Block * Subject(Group)	48	.450	.009		

A3.3 Experiment 3

Table A3.3.1 Repeated Measure Variance Analysis of Experiment 3 (Overall)

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Input	1	.169	.169	.430	.5181
Subject(Group)	24	9.407	.392		
Phase	4	5.795	1.449	113.697	.0001
Phase * Input	4	.129	.032	2.522	.0460
Phase * Subject(Group)	96	1.223	.013		
Path	3	.290	.097	12.679	.0001
Path * Input	3	.019	.006	.828	.4826
Path * Subject(Group)	72	.549	.008		
Phase * Path	12	.085	.007	1.630	.0828
Phase * Path * Input	12	.033	.003	.637	.8099
Phase * Path * Subject(Group)	288	1.249	.004		

Dependent: Log(tracking_error)

Table A3.3.2 Repeated Measure Variance Analysis of Phase 0 in Experiment 3

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Input	1	.244	.244	4.718	.0400
Subject(Group)	24	1.239	.052		
Path No	3	.180	.060	9.254	.0001
Path No * Input	3	.013	.004	.654	.5829
Path No * Subject(Group)	72	.466	.006		

Dependent: Log(Error)

A3.4 Experiment 4

Table A3.4.1 Repeated Measure Variance Analysis of Experiment 4 (Overall)

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Order	1	2.512	2.512	2.203	.1761
Subject(Group)	8	9.126	1.141		
Device	1	1.207	1.207	26.554	.0009
Device * Order	1	1.027	1.027	22.597	.0014
Device * Subject(Group)	8	.364	.045		
Phase	4	4.198	1.049	34.035	.0001
Phase * Order	4	.064	.016	.522	.7204
Phase * Subject(Group)	32	.987	.031		
Location	4	.421	.105	1.869	.1401
Location * Order	4	.153	.038	.680	.6110
Location * Subject(Group)	32	1.803	.056		
Block	1	.666	.666	26.440	.0009
Block * Order	1	.016	.016	.615	.4555
Block * Subject(Group)	8	.202	.025		
Device * Phase	4	.036	.009	.429	.7863
Device * Phase * Order	4	.734	.183	8.713	.0001
Device * Phase * Subject(Group)	32	.674	.021		
Device * Location	4	.192	.048	1.276	.2998
Device * Location * Order	4	.078	.020	.519	.7224
Device * Location * Subject(Group)	32	1.205	.038		

Dependent: Log(CTime)

Table A3.4.2 Between-subjects Repeated Measure Variance Analysis of Experiment 4 (Overall)

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Device	1	3.601	3.601	5.749	.0433
Subject(Group)	8	5.012	.626		
Phase	4	4.201	1.050	40.995	.0001
Phase * Device	4	.087	.022	.845	.5071
Phase * Subject(Group)	32	.820	.026		
Location	4	.782	.195	9.825	.0001
Location * Device	4	.173	.043	2.171	.0948
Location * Subject(Group)	32	.636	.020		
Block	1	.011	.011	.413	.5386
Block * Device	1	.003	.003	.102	.7572
Block * Subject(Group)	8	.205	.026		
Phase * Location	16	.734	.046	2.254	.0064
Phase * Location * Device	16	.220	.014	.675	.8139
Phase * Location * Subject(Group)	128	2.606	.020		

Dependent: Log(CTime)

Table A3.4.3 Within-subjects Repeated Measure Variance Analysis of Test 5 of Experiment 4

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Order	1	.636	.636	1.892	.2062
Subject(Group)	8	2.691	.336		
Device	1	.343	.343	15.805	.0041
Device * Order	1	.001	.001	.044	.8386
Device * Subject(Group)	8	.174	.022		
Location	4	.188	.047	1.362	.2689
Location * Order	4	.048	.012	.348	.8435
Location * Subject(Group)	32	1.107	.035		
Blocks	1	.112	.112	3.185	.1121
Blocks * Order	1	.066	.066	1.875	.2081
Blocks * Subject(Group)	8	.281	.035		
Device * Location	4	.157	.039	2.560	.0574
Device * Location * Order	4	.041	.010	.663	.6220
Device * Location * Subject(Group)	32	.490	.015		

Dependent: Log(CTime)

Table A3.4.4 Repeated Measure Variance Analysis Excluding Clutching Time in test 5 of Experiment 4

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Order	1	.669	.669	2.054	.1898
Subject(Group)	8	2.608	.326		
Device	1	.081	.081	5.324	.0499
Device * Order	1	.003	.003	.175	.6868
Device * Subject(Group)	8	.121	.015		
Location	4	.190	.047	1.460	.2372
Location * Order	4	.042	.011	.326	.8585
Location * Subject(Group)	32	1.039	.032		
Blocks	1	.116	.116	3.294	.1071
Blocks * Order	1	.060	.060	1.702	.2283
Blocks * Subject(Group)	8	.283	.035		
Device * Location	4	.158	.040	2.604	.0543
Device * Location * Order	4	.042	.010	.690	.6042
Device * Location * Subject(Group)	32	.487	.015		

Dependent: Log(C-NTime)

A3.5 Experiment 5

Table A3.5.1 Repeated Measure Variance Analysis of Trial Completion Times in Experiment 5

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	11	29.342	2.667		
Cursor	1	32.858	32.858	66.470	.0001
Cursor * Subject	11	5.438	.494		
Display	1	16.937	16.937	14.997	.0026
Display * Subject	11	12.425	1.130		
Phase	4	7.590	1.897	21.588	.0001
Phase * Subject	44	3.867	.088		
Trial_No	14	5.206	.372	12.549	.0001
Trial_No * Subject	154	4.564	.030		
Cursor * Display	1	6.777	6.777	6.677	.0254
Cursor * Display * Subject	11	11.116	1.015		
Cursor * Phase	4	.174	.043	.598	.6660
Cursor * Phase * Subject	44	3.192	.073		
Display * Phase	4	2.064	.516	5.615	.0010
Display * Phase * Subject	44	4.044	.092		
Cursor * Display * Phase	4	.959	.240	3.992	.0076
Cursor * Display * Phase * Subject	44	2.642	.060		

Dependent: Log(Time)

Table A3.5.2 Multiple Comparison Contrast Tests of Mean Completion Times in Experiment 5

Vs.		P-Value
SilkStereo	SilkMono	.31
SilkStereo	WireframeStereo	.05
SilkStereo	WireframeMono	.0001
SilkMono	WireframeStereo	.28
SilkMono	WireframeMono	.0001
WireframeStereo	WireframeMono	.0006

Table A3.5.3 Repeated Measure Variance Analysis of Error Rate in Experiment 5

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	11	114.636	10.421		
Cursor	1	176.849	176.849	92.157	.0001
Cursor * Subject	11	21.109	1.919		
Display	1	88.727	88.727	14.483	.0029
Display * Subject	11	67.390	6.126		
Phase	4	14.904	3.726	2.321	.0716
Phase * Subject	44	70.641	1.605		
Cursor * Display	1	31.318	31.318	7.468	.0195
Cursor * Display * Subject	11	46.126	4.193		
Cursor * Phase	4	5.673	1.418	1.123	.3579
Cursor * Phase * Subject	44	55.566	1.263		
Display * Phase	4	7.467	1.867	1.081	.3776
Display * Phase * Subject	44	75.997	1.727		
Cursor * Display * Phase	4	.512	.128	.065	.9920
Cursor * Display * Phase * Subject	44	86.649	1.969		

Dependent: sqrt(Error Rate)

Table A3.5.4 Multiple Comparison Contrast Tests of Mean Error Rate in Experiment 5

Vs.		P-Value
SilkStereo	SilkMono	.21
SilkStereo	WireframeStereo	.02
SilkStereo	WireframeMono	.0001
SilkMono	WireframeStereo	.21
SilkMono	WireframeMono	.0001
WireframeStereo	WireframeMono	.0003

Table A3.5.5 Repeated Measure Variance Analysis of Error Magnitude in Experiment 5

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	11	11.540	1.049		
Phase	4	4.933	1.233	3.966	.0078
Trial_no	14	3.812	.272	.790	.6791
Cursor	1	5.406	5.406	11.371	.0062
Display	1	13.512	13.512	18.187	.0013
Subject * Phase	44	13.681	.311		
Subject * Trial_no	143	49.305	.345		
Subject * Cursor	11	5.230	.475		
Subject * Display	11	8.173	.743		
Phase * Cursor	4	.678	.169	.397	.8097
Phase * Display	4	.471	.118	.427	.7880
Cursor * Display	1	4.438E-4	4.438E-4	.001	.9725
Subject *Phase * Cursor	43	18.395	.427		
Subject *Phase * Display	41	11.305	.276		
Subject *Cursor * Display	11	3.928	.357		
Phase*Cursor * Display	4	1.109	.227	1.105	.3751
Subject*Phase*Cursor * Display	26	6.519	.251		

Dependent: log(Error_magnitude)

Table A3.5.6 Multiple Comparison Tests of Mean Error Magnitude in Experiment 5

Vs.		P-Value
SilkStereo	SilkMono	.03
SilkStereo	WireframeStereo	.03
SilkStereo	WireframeMono	.0001
SilkMono	WireframeStereo	.97
SilkMono	WireframeMono	.005
WireframeStereo	WireframeMono	.007

Table A3.5.7 Repeated Measure Variance Analysis of Completion Times in Test 5 of Experiment 5

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	11	5.834	.530		
Cursor	1	7.244	7.244	90.765	.0001
Cursor * Subject	11	.878	.080		
Display	1	4.620	4.620	21.513	.0007
Display * Subject	11	2.362	.215		
Trial_No	14	1.162	.083	6.411	.0001
Trial_No * Subject	154	1.994	.013		
Cursor * Display	1	2.360	2.360	17.313	.0016
Cursor * Display * Subject	11	1.500	.136		
Cursor * Trial_No	14	.253	.018	1.665	.0682
Cursor * Trial_No * Subject	154	1.668	.011		
Display * Trial_No	14	.222	.016	1.702	.0603
Display * Trial_No * Subject	154	1.432	.009		
Cursor * Display * Trial_No	14	.099	.007	.738	.7335
Cursor * Display * Trial_No * Subject	154	1.481	.010		

Dependent: Log(time)

Table A3.5.8 Repeated Measure Variance Analysis of Error Rate in Test 5 of Experiment 5

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	11	49.144	4.468		
Cursor	1	25.639	25.639	26.565	.0003
Cursor * Subject	11	10.616	.965		
Display	1	12.722	12.722	6.049	.0317
Display * Subject	11	23.134	2.103		
Cursor * Display	1	4.310	4.310	1.530	.2419
Cursor * Display * Subject	11	30.990	2.817		

Dependent: Sqrt(error rate)

Table A3.5.9 Repeated Measure Analysis of Subjective Preference in Experiment 5

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Subject	11	5.062	.460		
Interface	3	74.229	24.743	54.359	.0001
Interface * Subject	33	15.021	.455		

Dependent: Rating

Table A3.5.10 Multiple Contrast Test Results of Subjective Preference in Experiment 5

Vs.		P-Value
SilkStereo	SilkMono	.01
SilkStereo	WireframeStereo	.0001
SilkStereo	WireframeMono	.0001
SilkMono	WireframeStereo	.002
SilkMono	WireframeMono	.0001
WireframeStereo	WireframeMono	.0001

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