Investigation of Visual Interface Issues in Teleoperation Using a Virtual Teleoperator

by

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Abstract

This thesis describes a research project which examined visual display issues in the navigation of remotely-operated (teleoperated) vehicles. Specifically examined was the possibility of increased operator disorientation when video images are isomorphically transformed to the orientation of the operator's head. The working hypothesis was that the addition to the visual scene of a computer-generated representation of the body of the teleoperated vehicle would reduce operator disorientation.

To test this hypothesis, a computer-based teleoperation simulation system was developed. The system permits easy modification of the dynamics of motion for the simulated vehicle, the content of the simulated ("virtual") environment in which the vehicle operates, and the human-interface methods. The simulation system will be further developed and used to carry out future studies relating to human-interface issues in teleoperation.

Eight subjects took part in the experiment. Two tasks were performed repeatedly by each subject over a series of one or two practice sessions and six test sessions. Two-dimensional, three degree-of-freedom inertial vehicle dynamics were simulated in both tasks. One task involved locating random targets and navigating the simulated vehicle to these targets. The second task involved navigating the simulated vehicle around a set of obstacles arranged in a square pattern. Three display configurations were compared: a typical NTSC television monitor, a head-mounted display with fixed views, and the head-mounted display with the views isomorphically transformed to the operator's head movements. Subject were tested on each display configuration both with and without a representation of the vehicle body added to the visual scene.

Performance was generally best with the monitor and worst with the head-mounted display with head-motion-slaved views. In those performance metrics showing a large disparity between these two display configurations, displaying the vehicle body image improved performance with the head-mounted display to the extent that there was no significant difference between the two display modes, thus confirming the experimental hypothesis. It was, however, observed that displaying the vehicle body image tended to improve the operators' control of the orientation of the simulated vehicle but degrade their control of the velocity of the vehicle. It was conjectured that this degradation in controlling vehicle velocity might be eliminated by performing similar experiments with more visual differentiation between the vehicle body image and the surrounding environment. Finally, it should be noted that, due to insufficient pre-experimental training of the subjects, the data were highly influenced by learning effects.

Thesis supervisor:	Harold L. Alexander
Title:	Bradley Career Development Assistant Professor of Aeronautics and Astronautics

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Chapter 1 Introduction

Teleoperation is a field of research at the Laboratory for Space Teleoperation and Robotics (LSTAR) that deals with the remote operation of vehicles by human operators, allowing remotely-operated vehicles to replace humans in performing tasks in environments that are in some way hostile to human life. In such environments, using teleoperation rather than human presence to perform certain tasks can be safer and less expensive.

Two important aspects of any teleoperation system are how the human operator receives feedback concerning the state of the vehicle and how the operator inputs commands to the system to get the vehicle to perform the desired actions. These two human-interface functions usually are bundled into the design of a single workstation called a "control station."

The primary feedback provided to the operator in most teleoperation is visual. Typically there are one or more video cameras mounted on the vehicle itself and, depending on the application, possibly one or more video cameras trained on the vehicle and mounted on objects in the environment around the vehicle. If only one camera is used, the signal from that camera is fed to a video display device (usually a standard television monitor) that is part of the control station. With multiple cameras, multiple displays are used. Commands are most often input to a teleoperation system by one or more hand-controllers manipulated by the human operator. Although most hand-controllers sense displacement of the controller, some instead sense the amount of force or torque that is applied to the controller.

Telerobotics is closely related to teleoperation. In teleoperation, the remote vehicle is under the continuous, direct control of a human operator. Telerobotics, on the other hand, refers to systems where the remote vehicle has some on-board control laws that govern its routine operation; the human operator supervises the autonomous operation of the vehicle, providing inputs to the system only occasionally. Telerobotics is more useful for repetitive, rigidly-defined tasks, since a telerobot can perform such a task nearly indefinitely while a human operator will eventually succumb to fatigue. Teleoperation must be used instead of telerobotics for situations that are too complex to be performed autonomously, as when little is known about the environment or how to accomplish the task. These situations require the projection of human ingenuity to the work site via a teleoperator. In this thesis, the term telescience is used to encompass the fields of telerobotics and teleoperation.

1.1 Uses of Teleoperation and Telerobotics

Telescience is used in a wide variety of applications spanning the land, sea, and space environments. Common to all of these applications is that a task must be performed in an environment that is hostile to human life. The main land-based applications of teleoperation are the handling of materials that are radioactive or otherwise hazardous and the apprehension of armed criminals. In the ocean, where humans cannot survive below a few hundred feet without the support of complex and expensive vehicles, teleoperators are used to map the geography of the ocean floor, research ocean life at great depths and search the ocean floor for man-made articles such as sunken ships and aircraft data recorders.

The environments which derive the most benefit from the use of telescience, however, are external to Earth: Earth orbit, and the surfaces of other planets. These environments present unique and significant challenges to vehicle design. The zero-g dynamics of Earth orbit make vehicle control difficult, and the high radiation and extreme temperatures of the environment must be endured. Telerobotic vehicles designed to explore the surfaces of other planets must survive an environment of extreme temperatures and pressures and "intelligently" navigate through their environment given little prior information.

Exploration of these off-Earth environments stands to benefit much from telerobotics because they are so hostile; the economic cost of life-support systems that can operate in such environments is enormous. There is also a significant risk of death due to life support system failure or accidents. In Earth orbit, it would therefore be safer and cheaper to use telerobots for applications such as the construction of large structures and the repair and maintenance of satellites. Telerobots provide the only available option for exploring other planets as it is not feasible for humans to do so at present.

1.2 Methods of Space Teleoperation Simulation

Because it is a difficult and extremely expensive process to design and build a system and launch it into space, there has been an emphasis on developing and improving ways of simulating space teleoperation. The prominent factor in the dynamics of a teleoperator maneuvering in space is that there are effectively no external forces on the vehicle. Objects in space are in a continual free-fall with no gravitational force and no drag forces large enough to affect the vehicle on time scales typical to teleoperation. There are three common methods for simulating the no-external-forces condition that applies in space teleoperation: the use of air-bearing tables or air-cushion vehicles, neutral-buoyancy simulation, and computer simulation.

Air-bearing tables and air-cushion vehicles are used to achieve motion of some vehicle or platform in two dimensions with only extremely small external forces acting upon the system. An air-bearing table is a flat table with holes distributed across its surface. Air is continuously pumped through the holes in the table. When an object with a flat, smooth surface is placed on the table, the air exiting the holes in the table's surface forms a narrow cushion between the table and the object, keeping the object floating just above the surface of the table. Because the object floats on a boundary layer of air, it can move virtually frictionlessly across the surface of the table. An air-cushion vehicle operates on a similar principle: the vehicle stands on one or more puck-shaped supports, air is forced out through holes in the surfaces of the pucks, and the vehicle moves over a flat, smooth surface. Both of these methods allow a highly accurate simulation of zero-external-force dynamics, and they have been used in research on a variety of autonomous docking and target-capture tasks. The drawback is that the dynamics of these systems are only two-dimensional, while many tasks that can be envisioned for teleoperators in space would require full three-dimensional motion.

Neutral buoyancy simulation, which is employed extensively in the LSTAR (Eberly, 1991) allows full three-dimensional motion with vehicles designed to operate underwater. A neutral-buoyancy vehicle is constructed so that its buoyancy force (due to the weight of the volume of water it displaces) exactly cancels its weight; there are no external forces on the vehicle when it is at rest. This type of vehicle is also designed so that its center of buoyancy is at the same point as its center of mass; thus there are no external torques on the vehicle when at rest. Although neutral-buoyancy vehicles can maneuver underwater free of the influence of gravitational forces, when the vehicle is in motion there are significant water-drag forces acting upon the vehicle opposite its direction of motion. Neutral-buoyancy simulation is very useful for simulating teleoperation in space for tasks where the vehicle moves only at low speed because full three-dimensional space dynamics are simulated. The major drawbacks are that drag forces make the simulation unrealistic when the vehicle is in motion and that neutral-buoyancy vehicles, because they must operate underwater, are difficult to design and maintain.

The final commonly-used simulation technique is that of computer simulation. The first step is to model the dynamics of the vehicle to be simulated and the visual aspects of the environment in which the vehicle is to operate. These models are then incorporated into a software system, allowing the computer to perform the same function that an actual teleoperator would -- the computer takes input from the human operator and provides visual feedback on the state of the vehicle. The computer software first uses the operator's commands and its model of the vehicle's dynamics to determine the motion of the vehicle, and then uses its model of the environment to create a computer-graphics representation of the image that would be seen by a video camera mounted on an actual teleoperator operating in that environment.

The problem with computer simulation is the need for extremely expensive computers to produce high-fidelity graphics images with the cues that are present in real world visual fields: shadows, reflections, solid surfaces with texture, etc. If somewhat lower-fidelity images are acceptable, however, computer simulation can be reasonably inexpensive and, unlike neutral-buoyancy simulation, is extremely flexible. Given a computer-based teleoperation simulator, changing virtually any aspect of the configuration of the vehicle (e.g., where the simulated video camera is mounted on the vehicle) or the environment surrounding the vehicle can be done quickly and easily through software. Similar changes can be quite labor-intensive with neutral-buoyancy vehicles. Another advantage of computer simulation is that the dynamics of the simulated vehicle can also be changed easily to represent any system that can be modeled. Although it is possible to design closed-loop control systems for neutral-buoyancy vehicles that alter the vehicle's dynamics, the range of dynamics that can be modeled is limited by the performance of the sensors and actuators that are employed.

1.3 Background

Many research groups in teleoperation are currently focusing their attention on the concept of telepresence. The goal of telepresence is to deliver sensory information to and receive command inputs from the human operator in as "natural" a manner as possible. Sensory feedback and command formats are designed to mimic sensory input/physical motions that humans experience in everyday life. A central idea in telepresence is that of "being there:" a feeling experienced by the human operator that he or she is actually being subjected to the motions of the teleoperator rather than observing and controlling them from a distance. Telepresence argues that the stronger the operator's sense of "being there," the better he or she will be able to control the teleoperated vehicle. With a strong sense of telepresence the operator is more easily able to draw upon natural human sensory processing and motor skills. Although sensory information inherent to the concept of telepresence includes visual, aural, tactile, and proprioceptive, the discussion here is restricted to the visual sense.

The earliest teleoperators were telemanipulators developed to handle radioactive material. These were operated in a direct-view configuration -- the operator was located near the manipulator, controlling it and observing its motions through a protective window. The first non-direct view teleoperators, limited by available technology, used video cameras and fixed television displays to provide visual feedback to the operator (Vertut and Coiffet, 1986). As practical head-mounted displays (HMDs) became available, it was a natural extension of telepresence to use these displays in teleoperation, as they permitted presentation of wide field-of-view, stereoscopic images. With HMDs, systems that track the orientation of an operator's head can be used in conjunction with camera-pointing servomechanisms on teleoperators to slave camera pointing to the rotation of the operator's head. Without such a system, because the camera is rigidly attached to the teleoperator, the view presented to the operator is fixed with respect to the teleoperator (usually looking toward the "front" of the vehicle). With a head-tracking system, the operator can rotate his or her head and the camera on the vehicle will undergo the same rotations. This effectively places the operator's head at the location of the camera: if the operator rotates his or her head ninety degrees to the right, the camera on the teleoperator will do the same, and the operator will see whatever is located to the right of the vehicle. If the operator looks straight up, the camera on the vehicle will point straight up (with respect to the vehicle itself) and the subject will see whatever is above the vehicle, and so on.

There has been some debate over the effects of stereoscopic views on visual perception in remote vision. Results reported by Tharp et al. (1989) state that in teleoperation, stereoscopic views provide a better sense of telepresence than monoscopic views and would be expected to increase performance on many tasks. Evidence obtained by Pepper and Hightower (1984) support this argument by demonstrating better performance with a stereoscopic than monoscopic presentation on two tasks. Additional research by Pepper et al. (1983) indicates that when using a head-mounted display depth-perception is improved under both stereoscopic and monoscopic viewing conditions when the images are isomorphically transformed by the operator's head movements (as described above). All of this evidence supports the intuitive idea that a head-mounted display with head-slaved views gives the strongest possible visual sense of telepresence and should therefore result in superior task performance in teleoperation when compared to other visual display modes.

The results cited above all involve telemanipulation tasks with a fixed frame of reference. Another important aspect of teleoperation is the navigation of a teleoperator from one point to another, involving some combination of target acquisition and identification, obstacle avoidance, and precise vehicle control. Although an HMD with head-tracking gives superior performance in telemanipulation tasks, it is not clear how it influences performance on navigation tasks where the vehicle is moving through its environment. As described by Pepper et al. (1983), "... helmet mounted stereo TV display might also place additional demands on the operator which may or may not be offset by performance gains associated with the added degree of complexity and sophistication" (p. 173). It is possible that using an HMD with head-tracking to navigate a teleoperator induces disorientation in the operator and actually degrades performance.

A problem encountered by some fighter pilots may be relevant to disorientation during teleoperation. The bubble canopies of high-performance fighter aircraft give pilots a very large field of view of the environment outside the aircraft. When looking out through these clear canopies, pilots often will not have any part of their own aircraft in sight. Pilots have reported becoming disoriented while searching the sky for targets because of the lack of a visual reference to their own aircraft. To counter this, some have marked the insides of their canopies to provide an orientation reference when no other part of the aircraft is in sight (Alexander, 1991). This disorientation problem could also affect persons controlling teleoperators while using an HMD with head-tracking and no vehicle reference.

1.4 Hypothesis

The study described in this thesis is concerned with operator disorientation in teleoperator navigation when using an HMD with head-tracking. In this display configuration the transformation between the operator's command inputs to the vehicle and visual scene presented on the display combines both the motion of the vehicle and the orientation of the operator's head. The operator has access to both the combined transformation through the interpretation of the visual scene and the head-orientation transformation through proprioceptive and vestibular sensors. In order to control the vehicle precisely, however, the operator needs an accurate estimate of the motion of the vehicle. The hypothesis tested in this thesis is that in tasks which require significant head movement, the operator often will have difficulty accurately determining the motion of the vehicle from the available information and therefore will not be able to control the vehicle as precisely as when using a display with fixed views. This may, depending on the nature of the task, negate the performance increase gained from the ability to visually scan the environment by rotating one's head with head-tracking.

It is proposed to use a computer to perform the same function as the markings on the inside of the fighter aircraft canopies discussed above. Adding a representation of the body of the teleoperated vehicle to the visual scene should provide cues that will allow the operator to more easily and accurately estimate the motion of the vehicle. The vehicle body image is predicted to provide more explicit information on head-orientation, as well as a fixed reference (when the head is held motionless) that will allow more accurate estimates of the velocities of objects in the visual field. The viewing transformation needed to generate this vehicle body image in real time depend only on the operator's head orientation, information that is readily available from the head-tracking system.

Chapter 2 Implementation

The teleoperation simulation system developed to perform this experiment consists of several major components. The control station, made up of a computer, input/output (I/O) box, two hand-controllers, and a head tracker, allows the operator to input his or her commands to the simulated vehicle. A Silicon Graphics, Inc. (SGI) graphics workstation obtains operator input information from the control station, calculates the dynamics of the simulated vehicle, and draws a view as it would be seen by a video camera mounted on the vehicle. The video signal from the graphics workstation is routed to one of three video devices which the operator views while he or she is controlling the simulation. Figure 2.1 shows the interconnections between the different components of the system.

Because the simulation is designed to study human-interface issues, the operator is typically asked to perform some well-defined task. Although the operator would not know the details, there is an exact definition for computing when the task is complete and a way of measuring how well the operator has performed the task. For the purposes of this thesis, one "run" refers to an operator performing a specific task from beginning to end a single time.

2.1 Control Station

The control devices used by the operator to command inputs to the simulation are two three-degree-of-freedom (DOF) hand-controllers and a six-DOF mechanical-linkage head tracker. The states of these devices are read in real-time by the control station computer.

The hand-controllers are mounted on a platform in positions such that the operator can comfortably grasp one in each hand while seated at the control station. Although each of the six total DOF of the two hand-controllers can be assigned through software to control any aspect of the simulated vehicle's dynamics, commands affecting rotation of the vehicle are assigned to the right-hand controller and commands affecting vehicle translation are

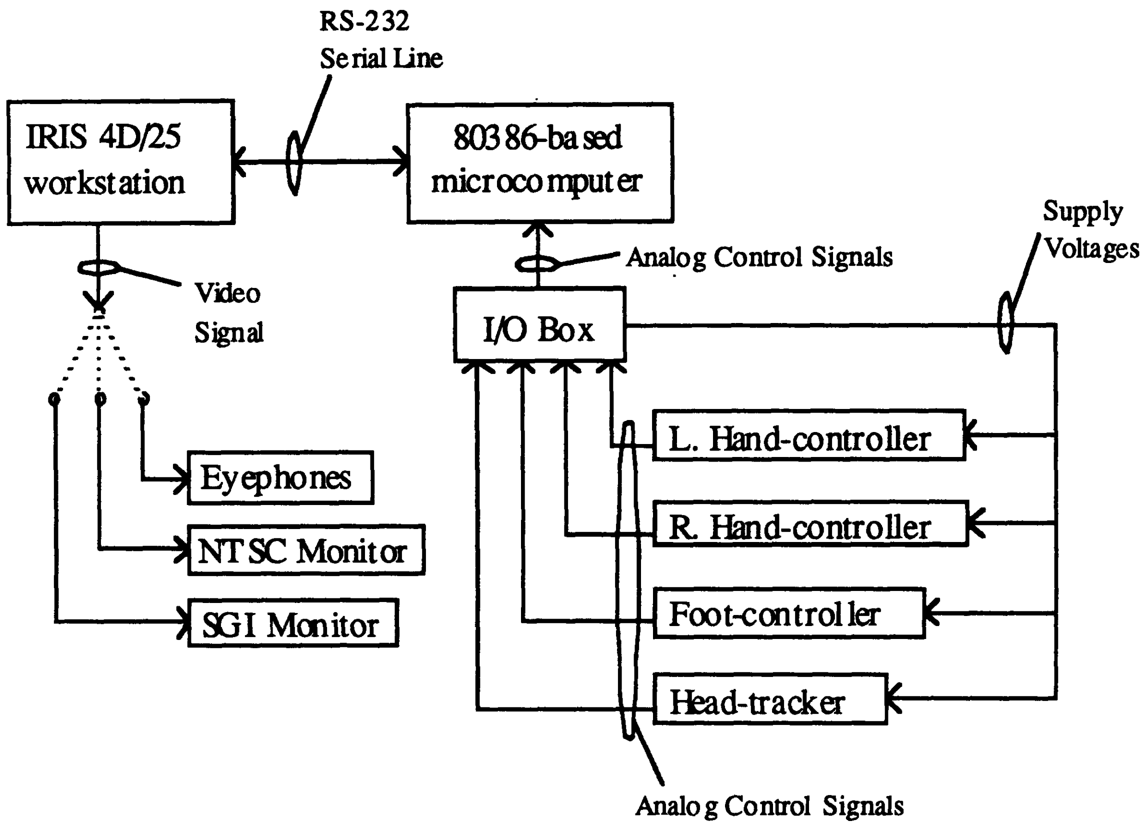

Figure 2.1 - Block Diagram of Teleoperator Simulation System

assigned to the left-hand controller. This rule is based on the assumptions that, for most tasks, teleoperators require more precise rotational control than translational control and that most people are more dextrous with their right hand than with their left.

The motions of the hand-controllers are tailored to their functions in controlling the vehicle. Both hand-controllers can be rotated around their front-to-back and side-to-side axes; the right hand-controller can also be twisted around its vertical axis, while the left hand-controller can be displaced up and down. The right hand-controller is appropriate for controlling vehicle rotation because it can be rotated about its own yaw, pitch, and roll axes, which are used to command rotation about the corresponding vehicle axis. Although the left controller rotates (rather than translates) in two axes, the tip of the controller's handle is far enough from the axes of rotation that it can be effectively be displaced in the up-down and side-to-side directions. Translation of the left hand-controller in the up-down, side-to-side, and front-to-back directions corresponds to translation of the simulated vehicle in the corresponding vehicle directions.

The head tracker is a mechanical-linkage system designed and built in the laboratory. To measure translation in three dimensions and rotation about all three DOF of an operator's head with respect to a fixed base. The fixed-base end of the linkage attaches easily to a standard camera tripod while the free end attaches to a strap on the head-mounted display that passes over the top of the operator's head.

The head-tracker contains two straight rods, each approximately two feet in length, connected by a joint which is free to rotate about a single axis of rotation. There are additional groups of single-axis joints at each end of the linkage (Fig. 2.2). The end attached to the fixed base has two joints, which rotate in the yaw and pitch axes. The joint connecting the two rods also rotates in the pitch axis. The end attached to the operator's head has three joints which rotate in the pitch, roll, and yaw axes. One side of each joint is connected to the base of a potentiometer, while the opposite side is attached to the shaft of the potentiometer. The potentiometer shaft serves as the joint's axis of rotation, and the angle of the joint is equal to the rotation angle of the potentiometer shaft. The end taps of each potentiometer are connected to positive and negative supply voltages, so the voltage at the variable tap is proportional to the shaft rotation angle and therefore the joint angle.

Although the head-tracker was designed with the ability to calculate three-dimensional translation and three-DOF rotation of the operator's head, the control station software calculates only three Euler angles that represent the rotation of the operator's head. Because it is much simpler to design a camera pointing system for a teleoperator that only rotates the camera, rather than rotating and translating it, a rotation-only camera pointing system is modeled in this experiment. Since all six joint angles are already available to the

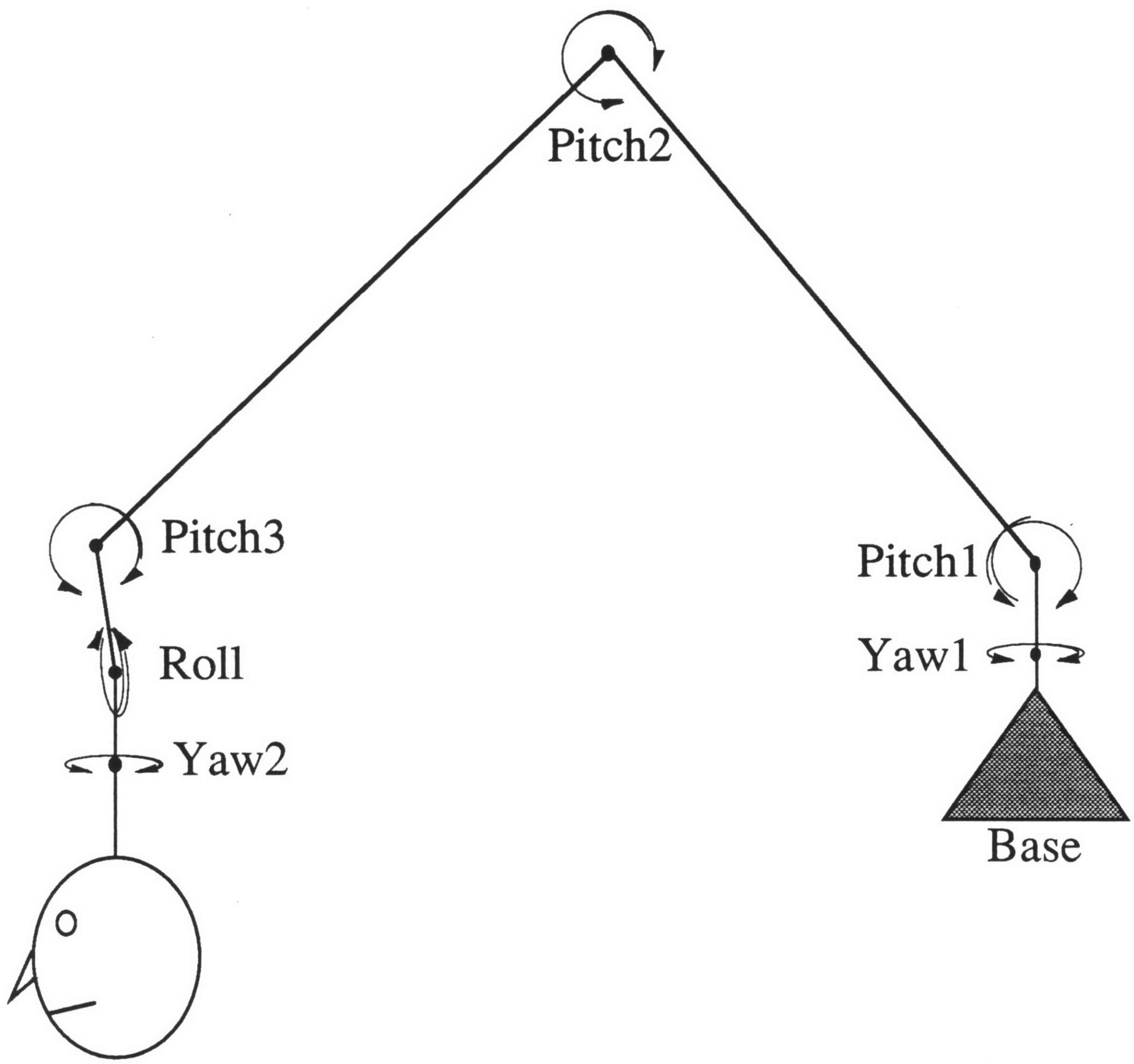

Figure 2.2 - Head-Tracker Joint Arrangement

software, it would be a straightforward task to simulate a system that provides for camera rotation and translation in the future.

The plate that attaches the head-tracking linkage to the operator's head is not aligned to the head's yaw-pitch-roll reference frame, which slightly complicates the software transformations relating to slaving the image perspective to head orientation. Assuming the head undergoes no translation, the head-tracking linkage would directly measure the pitch-roll-yaw Euler angles of the head (using addition and subtraction of the pitch1, pitch2, and pitch3 angles in Figure 2.2 to get net pitch, and taking the roll and yaw angles directly from the roll and yaw2 joints in the figure) if the attachment plate were aligned with the plane containing the head's pitch and roll axes. Because of the location of the attachment point, however, the plate is pitched down slightly with respect to that plane. To account for this misalignment, the following transformations are performed: first a pitch down of the appropriate magnitude is executed, then the yaw, pitch, and roll rotations measured directly by the linkage are performed, and then a pitch up of the same magnitude as the initial pitch down is performed. This results in an isomorphic transformation between the operator's head orientation and the net transformation performed on the graphic images.

The I/O box serves as a convenient interface between the hand-controllers and the head tracker and the control station computer. Through single connectors to each unit, the I/O box supplies the appropriate supply voltages to each hand-controller and the head-tracker and routes the three signal voltages from each hand-controller and the six from the head tracker to a single connector. A cable links this single connector with the A/D board in the computer.

The control station computer is a Gateway IBM PC-compatible computer based on a twenty megahertz Intel 80386 microprocessor. The Gateway is equipped with an Industrial Computer Source twelve-bit, sixteen-channel analog-to-digital (A/D) conversion board. The A/D board is used to convert the voltage signals from the hand-controllers and head-tracker to digital values which can be accessed by software running on the Gateway. The Gateway communicates with the graphics workstation via a serial line at 19,200 baud.

The software running on the control station was written in the C programming language. The program runs through a loop which waits for a request signal from the IRIS, samples the current hand-controller-displacement and head-tracker joint angle voltages via the A/D board, processes the values, and sends the results to the IRIS. The data processing involves subtracting offsets from the values just sampled and using calibration information to convert the new values into a meaningful form. Offsets must be subtracted from the data because the hand-controllers do not output exactly a zero voltage when they are not being displaced (when they are centered) and the head-tracker joints do not output a zero voltage when the operator is looking straight ahead. The offsets must be measured fairly frequently, as the hand-controller and head-tracker zero-offsets differ slightly from day to day, and the head-tracker zero-offsets also vary between operators. New offsets are determined each time the Gateway software is executed. To reduce sensitivity of the measured zero-offset values to random noise and glitches in the voltage signals, each channel is read ten times consecutively and the average of those readings is stored as the zero-offset. This averaging method is also used, again to reduce noise effects, each time the head-tracker joint angles are measured during normal operation. The hand-controller values are sampled only once per loop, because their values are not as critical as those of the head tracker and multiple samples would slow execution of the program.

Figure 2.3 shows the layout of the control station. The cart at left in the figure contains the control station computer and computer monitor and the hand-controllers. Behind the chair is the tripod that serves as the base for the head-tracking linkage. One of the linkage's straight rods can be seen extending up and left to the middle joint, near the top of the picture, with the second rod running back down to the HMD, which is sitting on top of the cart next to the right hand-controller. Figure 2.4 shows a subject wearing the HMD, with the head-tracking linkage attached to the HMD at to the tripod base in the background.

Figure 2.3 - Control Station Layout

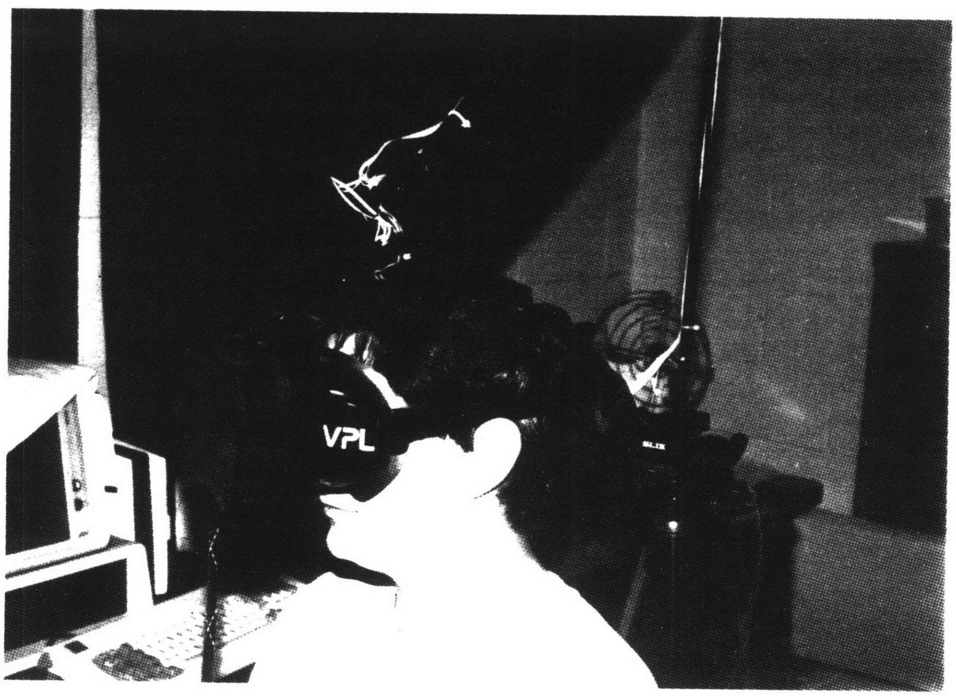

Figure 2.4 - Subject Wearing Head-Mounted Display, with Head-Tracking Linkage

2.2 Graphics Workstation

The control-station computer sends hand-controller and head-tracking state information via the serial link to a Silicon Graphics IRIS 4D/25 graphics workstation. The IRIS computer is based on a twenty MHz microprocessor and contains specialized hardware for performing fast two- and three-dimensional viewing transformations. It is supplied with a library of graphics subroutines for controlling the graphics hardware from C.

The IRIS software is constructed around a loop which calculates the dynamics of the simulated vehicle based on hand-controller deflections, calculates a current viewing transformation based on the state of the vehicle and head tracking information, and draws a current view of the environment. The program stores information about the state of the vehicle and the operator's command inputs on disk each time through the loop and stores information about the operator's performance at the end of each run. The software is designed to be flexible in terms of the contents of the environment in which the simulated vehicle operates, the dynamics of the simulated vehicle, the task that is performed, and the video-display system that is used.

The simulated, or virtual, environment in which the simulated vehicle operates consists of a set of polygons that are defined by the three-dimensional coordinates of their vertices in a "world" coordinate frame. For the purposes of this research, all environments have been drawn as wire-frame-outlined polygons with no solid surfaces, shading, or depth ordering. This was done to allow the simulation to run at an acceptable update rate on the IRIS that was used. Because of limitations in the setup of the video hardware, only monochrome images can be displayed (with up to sixty-four gray levels).

The simulated vehicle can be programmed to reproduce virtually any dynamics desired. Figure 2.5 defines the various translational and rotational axes in the vehicle coordinate frame. Relative to the vehicle, the X-axis points directly backward, the Y-axis points to the right, and the Z-axis points down. The roll, pitch, and yaw axes of rotation are the X-, Y-, and Z-axes, respectively. The most extensive dynamics that have been modeled are six-DOF inertial dynamics. In this mode, the vehicle is free to move and rotate in three dimensions, with the operator commanding translational accelerations along the vehicle's X-, Y-, and Z-axes and rotational accelerations about the vehicle's pitch, roll, and yaw axes.

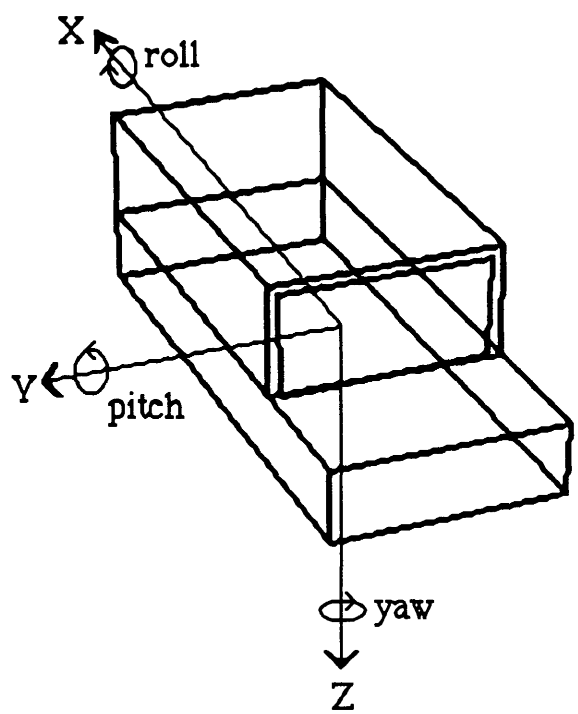

Figure 2.5 - Simulated-Vehicle Axis Definitions

A state-vector is maintained containing the position, orientation, and velocity of the simulated vehicle. The state variables are the three components (X, Y, and Z) of the location of the vehicle in the world coordinate frame, translational velocity components along the world X, Y, and Z axes, yaw-pitch-roll Euler angles relative to a reference orientation fixed in the world coordinate frame, and rotational velocities about the vehicle roll, pitch, and yaw axes. The algorithm employed by the dynamics subroutine each time through the loop is described below.

The variables used are:

mass = vehicle mass
inertia = vehicle moment of inertia (assumed to be the same about any axis)
dt = time step
fxcmd, fycmd, fzcmd = commanded forces to apply in vehicle frame X, Y, and Z axes
txcmd, tycmd, tzcmd = commanded torques to apply about vehicle roll, pitch, and yaw axes
xw, yw, zw = location of vehicle center in world coordinate frame
vxw, vyw, vzw = vehicle's translational velocity components along X, Y, and Z axes of world coordinate frame
ϕ, θ, ψ = roll, pitch, and yaw Euler angles

$\dot{\phi}$ $\dot{\theta}$ $\dot{\psi}$ = rates of change of roll, pitch, and yaw Euler angles
p, q, r = components of vehicle's rotational velocity about the vehicle roll, pitch, and yaw axes

$\dot{p}$ $\dot{q}$, $\dot{r}$= rates of change of rotational velocity components about vehicle roll, pitch, and yaw axes

The first step is to calculate the rate of change of the Euler angles based on the current Euler angles and the body-frame rotational velocities:

$$\dot{\phi} = p \quad + q * \sin(\phi) * \tan*(\theta) \quad + r * \cos(\phi) * \tan(\theta)$$

$$\dot{\theta} = \quad q * \cos(\phi) \quad - r * \sin(\phi)$$

$$\dot{\psi} = \quad q * \sin(\phi) / \cos(\theta) \quad + r * \cos(\phi) / \cos(\theta)$$

Next the accelerations in the body frame are calculated based on the current acceleration-command values (which are proportional to the hand-controller displacements):

$\dot{vxb}$ = fxcmd / mass

$\dot{vyb}$ = fycmd / mass

$\dot{vzb}$ = fzcmd / mass

$\dot{p}$= txcmd / inertia

$\dot{q}$= tycmd / inertia

$\dot{r}$= tzcmd / inertia

The translational accelerations in the body frame are then transformed into world frame coordinates using the current Euler angles:

$$\dot{vxw} = \dot{vxb} * \cos(\theta) * \cos(\psi)$$
$$+ \dot{vyb} * [\sin(\phi) * \sin(\theta) * \cos(\psi) - \cos(\phi) * \sin(\psi)]$$
$$+ \dot{vzb} * [\cos(\phi) * \sin(\theta) * \cos(\psi) + \sin(\phi) * \sin(\psi)]$$

$$\dot{vyw} = \dot{vxb} * \cos(\theta) * \sin(\psi)$$
$$+ \dot{vyb} * [\sin(\phi) * \sin(\theta) * \sin(\psi) + \cos(\phi) * \cos(\psi)]$$
$$+ \dot{vzb} * [\cos(\phi) * \sin(\theta) * \sin(\psi) - \sin(\phi) * \cos(\psi)]$$

$$\dot{vzw} = - \dot{vxb} * \sin(\theta)$$
$$+ \dot{vxb} * \sin(\phi) * \cos(\theta)$$
$$+ \dot{vxb} * \cos(\phi) * \cos(\theta)$$

Finally, the state variables are incremented by their current derivatives multiplied by the time step:

$$vxw = vxw + \dot{vxw} * dt$$
$$vyw = vyw + \dot{vyw} * dt$$
$$vzw = vzw + \dot{vzw} * dt$$

$$xw = xw + vxw * dt$$
$$yw = yw + vyw * dt$$
$$zw = zw + vzw * dt$$

$$p = p + \dot{p} * dt$$
$$q = q + \dot{q} * dt$$
$$r = r + \dot{r} * dt$$

Three-DOF inertial dynamics are easily modelled by setting the Z-axis force- and roll- and pitch-axis torque-commands to zero and using the calculations above. This allows translation of the vehicle in the X-Y plane and rotation about the yaw axis only. The operator then commands forward-backward (X-axis) and side-to-side (Y-axis) translational accelerations and rotational acceleration about the yaw (Z) axis.

One additional set of dynamics is modeled: that of driving a car-like vehicle. In this case, as in the three-DOF inertial case mentioned above, the vehicle translates in the X-Y plane and yaws about the Z-axis. The operator commands forward velocity and turning radius of the vehicle (the component of the vehicle's velocity along the Y-axis is always zero). A first-order lag is inserted between commanded forward velocity and actual forward velocity to make the response more realistic and prevent instantaneous changes in the vehicle's velocity.

Because the IRIS runs the UNIX multitasking operating system (and therefore the processor's time is split between the user's program and a number of background tasks), the actual length of time it takes to execute a particular code segment can vary over time. If the simulation program were allowed to cycle through its main loop as quickly as possible, each loop would take a different amount of time to complete and each set of dynamics calculations would be performed using a slightly different time step. This would be undesirable because it would eliminate the possibility of performing any kind of frequency analysis on the stored vehicle-trajectory data. Also, the screen update rate would vary over time, which is highly undesirable: it could have a significant effect on an operator's performance and mask the effects of other variables.

The program is structured to ensure that the dynamics calculations are always performed using the same time step; this enforced time step is passed as a parameter to the program when it is executed. The program keeps track of two independent time values: the current time and an "integration" time. (The system clock that was used has a resolution of 0.01 seconds.) Integration time is the time up through which the vehicle's state variables have been integrated. The algorithm that was employed is the following: each time through the main loop, the dynamics calculations are performed once using the enforced time step and the integration time is increased by the enforced time step. The program then compares the current time to the integration time. If they are equal, the program continues and the loop executes from the beginning. If the current time is earlier than the integration time, the comparison is carried out again. If the current time is later than the integration time, the dynamics are called again using the enforced time step (and the same command input values as the previous dynamics calculation), the integration time is again advanced by the enforced time step, and the program returns to the comparison between the current time and the integration time.

The above algorithm ensures that the dynamics are integrated forward in equal increments every time through the main loop. If a run through the loop takes less time than the enforced time step, the program waits for the current time to catch up to the integration time and then continues. If a loop-run takes longer than the enforced time step, the state variables are integrated forward by the enforced time step a second time, the integration time jumps ahead of the current time, and then program waits for the current time to catch up to the integration time. The only problem with this system is that when a loop run takes longer than the enforced time step, the dynamics are calculated twice while the screen is only updated once: one screen update is skipped. The enforced loop time is chosen to be long enough so that this happens only very rarely.

As mentioned previously, a person controlling the simulation is typically asked to perform a specific task in the virtual environment. In many cases only two aspects of the simulation need to be tailored for a particular task: the environment, which has been discussed, and the calculations that are performed in measuring the operator's performance. These performance calculations are carried out throughout each run, and the results are stored in a disk file at the end of the run. Although most of the environments that have been experimented with have been purely static, dynamic environments are easily accommodated as well. The subroutine which uses the current state information to determine when the task is complete can also be programmed to update some aspect of the environment based on the current state of the simulated vehicle. This was done in the randomly-appearing posts task (see Chapter 3) to remove each target when the vehicle came within a certain distance and display the next target.

Three video displays can be used with the teleoperation simulator: two fixed monitors and a head-mounted display (HMD) system. One monitor is the high-resolution SGI cathode-ray-tube monitor that is provided with the IRIS workstation. The SGI monitor is a nineteen-inch diagonal, sixty hertz, non-interlaced color monitor with a resolution of 1280 (horizontal) by 1024 pixels (vertical). The second monitor is a 25-inch cathode-ray-tube color monitor manufactured by NEC which accepts NTSC-standard video signals in either composite or red-green-blue (RGB) format.

The HMD is the Eyephones system (VPL Research, Inc.); it consists of two color liquid-crystal display screens with focussing optics mounted in a unit which is worn on the head. Each screen is seen by one eye, with some overlap in the fields of view of the two screens to allow for stereoscopic viewing. A harness passes over the top of the head and attaches to a counterweight which rests against the back of the head. The counterweight balances the torque applied to the head by the weight of the display, which sits in front of the eyes. The resolution of each screen is 360 by 240 pixels, and the optics create a field of view of eighty degrees by sixty degrees for each eye (VPL Research Inc., 1989).

Chapter 3 Experiment Design

This chapter describes the two tasks that were performed in the experiment, gives the definitions of variables that were saved to rate the subjects' performance on each run, and describes the experimental procedure. A number of tasks that were examined and discarded during the development of the experiment are presented, as well as the reasons why each was not chosen for the final experiment.

3.1 Rejected Task Descriptions

This section presents some sets of task/environment/vehicle dynamics that were experimented with and discarded in developing the setups that were used in the current experiment. The reasons for not using each setup are presented, with a focus on the issues as they relate to the use of the different display configurations that were to be compared in the experiment.

One environment that was tested and discarded was an extension of that used in an experiment performed by Cinniger (1991). It consisted of a series of rectangles arranged in three-dimensional space to form a tunnel (Fig. 3.1). Each rectangle had a cross at its center and was augmented with several lines perpendicular to the plane of the rectangle to provide added orientation cues to the operator when viewing the rectangle. The operator's task was to fly along a trajectory defined by connecting the centers of the rectangles. The performance metrics that were used were the distance of the simulated vehicle from the center of each rectangle as the vehicle passed through the plane of that rectangle, and the time it took to pass through each rectangle from the time that the plane of the last rectangle was crossed.

Probably the most important feature that was added to the original setup used by Cinniger was the placement of distant "stars" in the environment. In Cinniger's experiment, the only visible objects in the vehicle's environment were a cube and a grid.

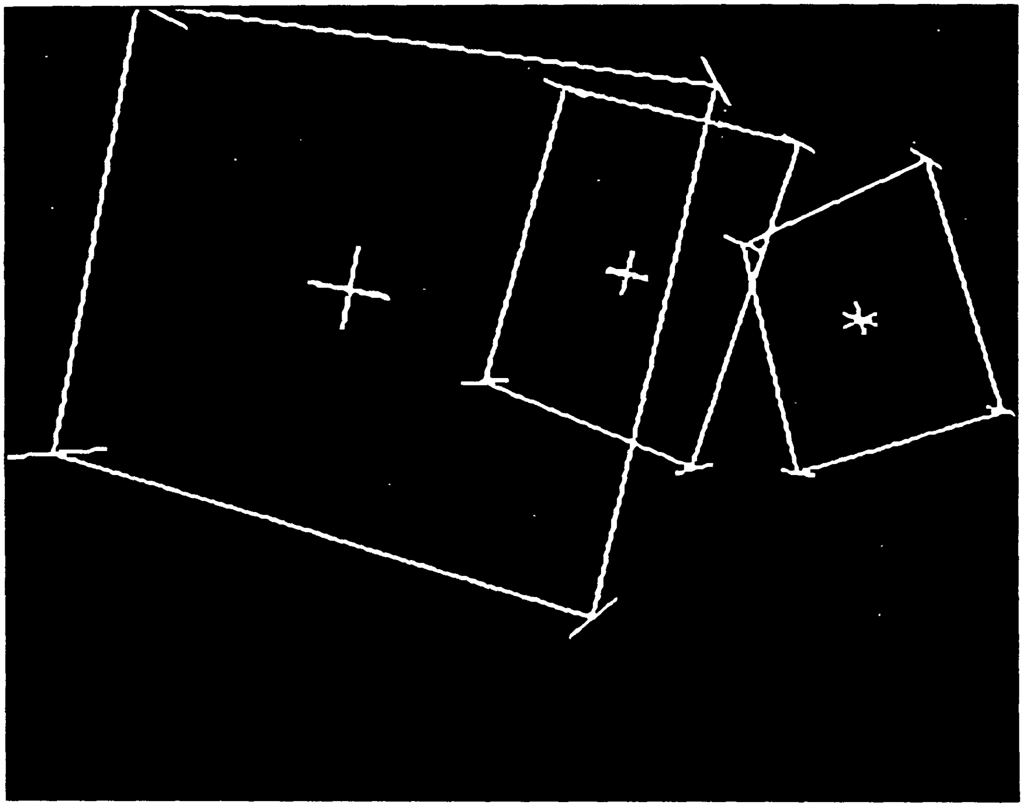

Figure 3.1 - Fly-Through Rectangles Environment

When the vehicle was oriented such that those objects were not visible, the operator saw only a blank display. So when the objects were not visible, there was absolutely no information available to the operator on the motion of the vehicle; all he or she could do was wait for the cube and grid to come back into view by chance. When the main features of the environment are not in view, the star-field (each star a single illuminated point in three-space and visible in all directions) provides motion cues to the operator. It was felt that it was realistic to add the star-field relative to most teleoperation applications because there are few situations where the environment around the working area is entirely featureless and provides no motion cues. The star-field was included in all environments described in this chapter.

Six-DOF inertial dynamics were used for the "fly-through rectangles" task. Each component of translational acceleration was made proportional to the deflection of one axis on the translational-hand-controller and each component of rotational acceleration was made proportional to the deflection of an axis on the rotational hand-controller. This simulated the control of a thruster-propelled vehicle in three-dimensional space with no disturbance forces.

Though this setup did provide some useful data, there was very wide performance variation between subjects. Some were able to complete the task reasonably quickly and accurately while others were only marginally able to complete the task at all. Therefore the data obtained were highly distributed and not useful in determining the influences of the experimental variables on performance. While subjects in Cinniger's experiment showed marked learning effects, and by the end of the experiment most could control the vehicle acceptably well, the amount of experience some subjects needed before reaching a level of acceptable performance was too great to be practical for the current experiment.

A simpler setup, designed to obtained more focused data, provided only one controllable DOF to the subject. This task involved driving a car-like vehicle on the surface of a planar "ground grid." Forward speed of the vehicle was fixed and the turning radius was made inversely proportional to the twist on one axis of the rotational hand-controller. The hand-controller thus acted as a steering wheel for the vehicle. The vehicle-body representation used in this setup and all setups described below resembled an automobile, with a framed windshield and a hood in front of the operator's eye location, and window outlines to the sides of and behind the eye point (Fig. 3.2).

The first task that was run using this combination of dynamics and environment was one of following a visible trajectory. A curved line constructed of a series of circular segments of various radii and lengths, was placed on the ground grid, and the operator's task was to follow the line as accurately as possible. The performance metric would be some average deviation from the presented trajectory. Because the speed of the vehicle was

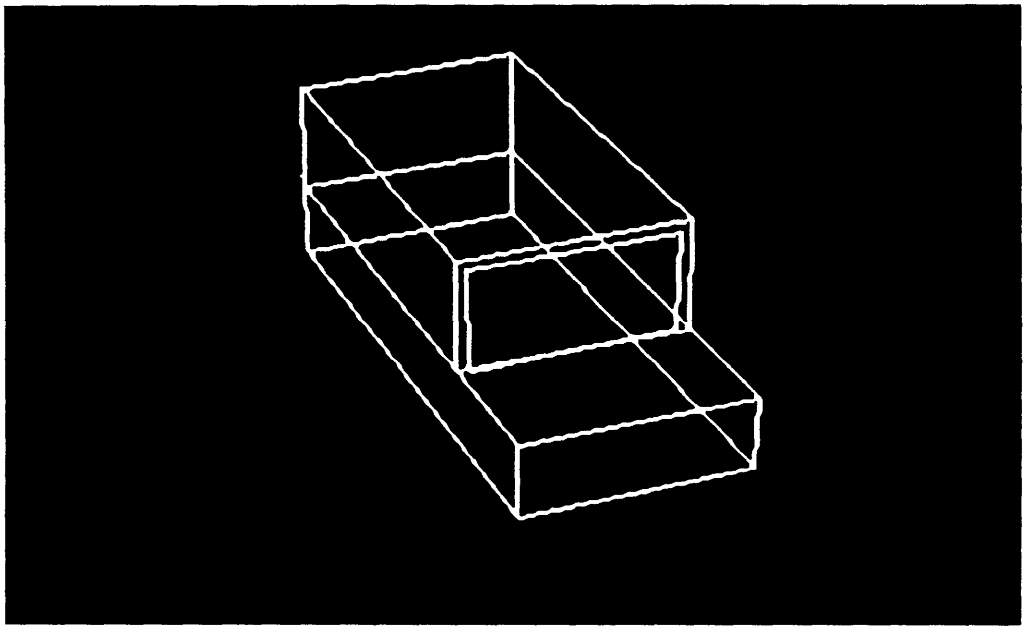

Figure 3.2 - Vehicle-Body Representation Used in All Experiments

fixed, time to complete the task did not reflect performance.

After experimenting with this task, it was apparent that it was too easy and that performance did not significantly vary with the visual configuration used. The problem was that the task did not require keeping track of any objects that were not directly ahead of the vehicle and would not have encouraged operators to make use of head-tracking when it was available. The task also did not require the operator to keep track of the orientation of the vehicle with respect to some external reference. Subjects quickly learned that the easiest way to perform the task, even with head-tracking available, was to stare straight ahead and simply twist the hand-controller when the path turned.

It was thought that giving the subjects obstacles to avoid, rather then showing them exactly the trajectory that should be followed, would make the task somewhat more difficult. So the above car-like dynamics were again used, but with a row of posts placed on the grid instead of the line representing the trajectory to follow. The subject's task was to slalom through the line of columns: driving to the right side of the first column, crossing over to pass to the left of the second, back to the right side of the third, and so on. Unfortunately, after examining trajectories followed by different subjects for the different visual displays it was clear that after a small amount of practice there was very little difference between performance using the different display configurations. Although the task was slightly more difficult, the subject still could perform best by focussing his or her attention directly ahead of the vehicle. This was because of the dynamics of the simulated vehicle: the vehicle was always travelling straight ahead, so there was no reason for the operator to look in any other direction.

To encourage the operator to make use of head-tracking, three-DOF (two-dimensional) inertial dynamics were experimented with because they allow the vehicle's velocity vector to point in any direction, independent of the orientation of the vehicle. The operator controlled translational accelerations along the fore/aft and left/right vehicle axes and rotational acceleration about the vertical (yaw) axis of the vehicle. Although one subject could not control the vehicle well enough to complete the task, several others quickly learned to perform the task well. The subjects who did perform the task all chose the strategy of simply to accelerating the vehicle forward to begin moving along the line of posts and then using side-to-side translational acceleration to move back and forth between the posts. The subjects never changed the orientation of the vehicle, and were effectively still controlling a one-DOF system. Once again, with a small amount of learning all subjects could perform the task very well, and there was little difference evident between the different display configurations.

3.2 Experiment Task Descriptions

Subjects performed two different tasks during the course of the actual experiment -- the "random-posts" task and the "square-of-posts" task. The tasks were performed in nearly identical environments with identical vehicle dynamics. Both tasks used three-DOF inertial dynamics that allowed the subject to maneuver the vehicle in a plane. The subjects pushed the translational hand-controller away from them or pulled it towards them to command translational accelerations along the vehicle's X-axis in the forward or backward directions, respectively. Deflection of the translational-hand-controller to the left or right commanded Y-axis translational accelerations to the left or right, respectively. Twisting the rotational-hand-controller around the vertical axis to the right or left commanded rotational acceleration of the vehicle about its yaw axis in the corresponding direction. Both tasks were designed to ensure that the subjects would make use of all three DOF of control available. The environments for both tasks contained a grid that represented the "ground" below the vehicle, and distant stars.

The mass, moment of inertia, maximum applied force and maximum applied torque of the vehicle were determined by trial and error to make the vehicle responsive enough that the tasks could be completed in a reasonable amount of time, but not so hyper-responsive as to make it too difficult to control. The mass was set at 500 kg, with independent maximum applied forces along the X- and Y-axes of 500 N. The maximum accelerations in the X and Y directions were therefore: $a = \text{force} / \text{mass} = 500\ \text{N} / 500\ \text{kg} = 1\ \text{m/s}^2$. The moment of inertia about the yaw axis was set at $3000\ \text{kg}\cdot\text{m}^2$, with a maximum applied yaw torque of 500 N·m. So the maximum rotational acceleration was: $\alpha = \text{torque} / \text{inertia} = 500\ \text{N}\cdot\text{m} / 3000\ \text{kg}\cdot\text{m}^2 = 0.167\ \text{rad/s}^2 = 9.55\ \text{deg/s}^2$.

The enforced time-step used in the dynamics calculations (see Chapter 2) was also chosen by trial and error. It was selected to be as short as possible while still resulting in only a very few skipped screen updates (approximately one skipped update in 10,000 time steps). The value that was used for both tasks was 0.05 seconds, a twenty hertz update rate.

3.2.1 Random-Posts Task Description

This first task required the subjects to repeatedly acquire a target and then maneuver the simulated vehicle to that target. The vehicle always began at the same location and with the same orientation in the middle of the ground-grid. As soon as the run began, there would be a post (two meters high and 0.2 meters square in cross-section) placed somewhere in the environment. The post might or might not be immediately within the subject's field of view. The subject's mission was to locate the post and navigate the vehicle directly to, and through, the post. Subjects were told that they were to impact the post with the vehicle oriented so that the front of the vehicle was pointed directly toward the post and with the vehicle's velocity vector pointing directly toward the post. When the vehicle approached to within three meters of the post, that post would disappear and another would appear in a different location. The subject then was to navigate to the next post, aligning the vehicle's orientation and velocity as before. One run on this task consisted of locating and navigating to eight posts consecutively.

Figures 3.3 and 3.4 show the view that would be seen by a subject as the vehicle was about to reach a post; the post is directly in front of the vehicle, the ground-grid is below the vehicle, and the stars are in the "sky." By comparing the two figures it should be clear which lines are part of the environment and which are part of the vehicle-body image. Although it is not reflected in the figures, in the views that were presented to the subjects during the experiment the lines and points making up the environment (the ground, the posts, and the stars) were of lower intensity than those of the vehicle-body representation. Figure 3.5 shows the view seen by a subject making use of head-tracking to look at a post that is not directly ahead of the vehicle.

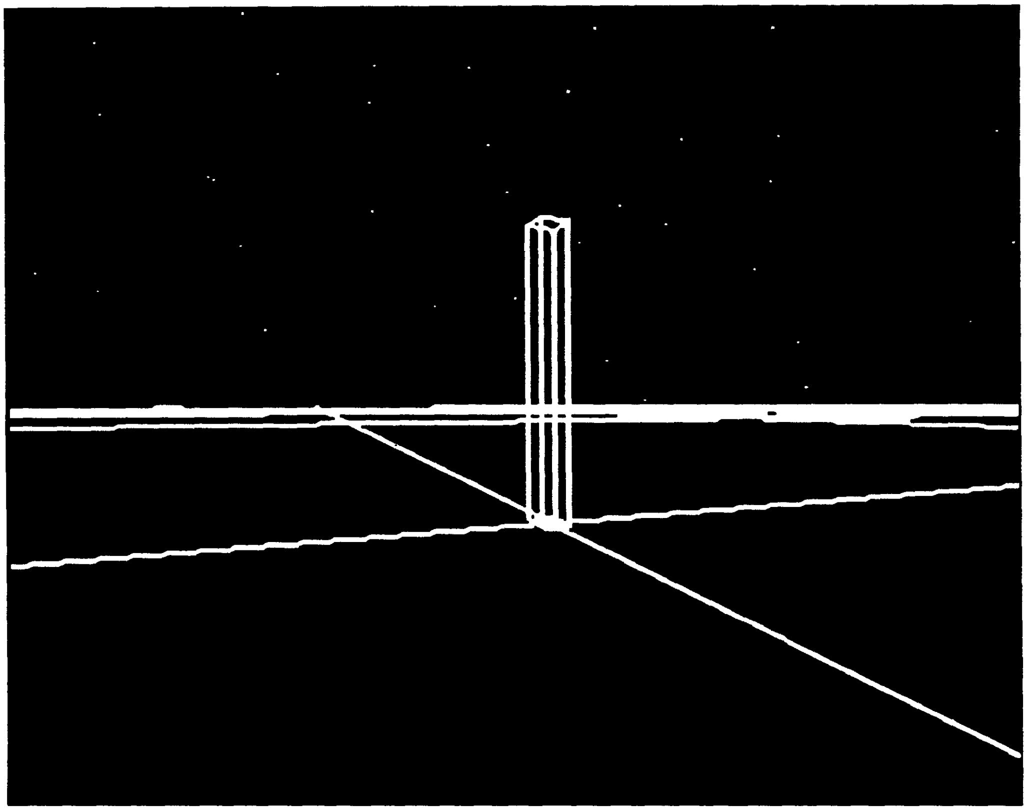

Figure 3.3 - View of a Post Without the Vehicle Body Displayed

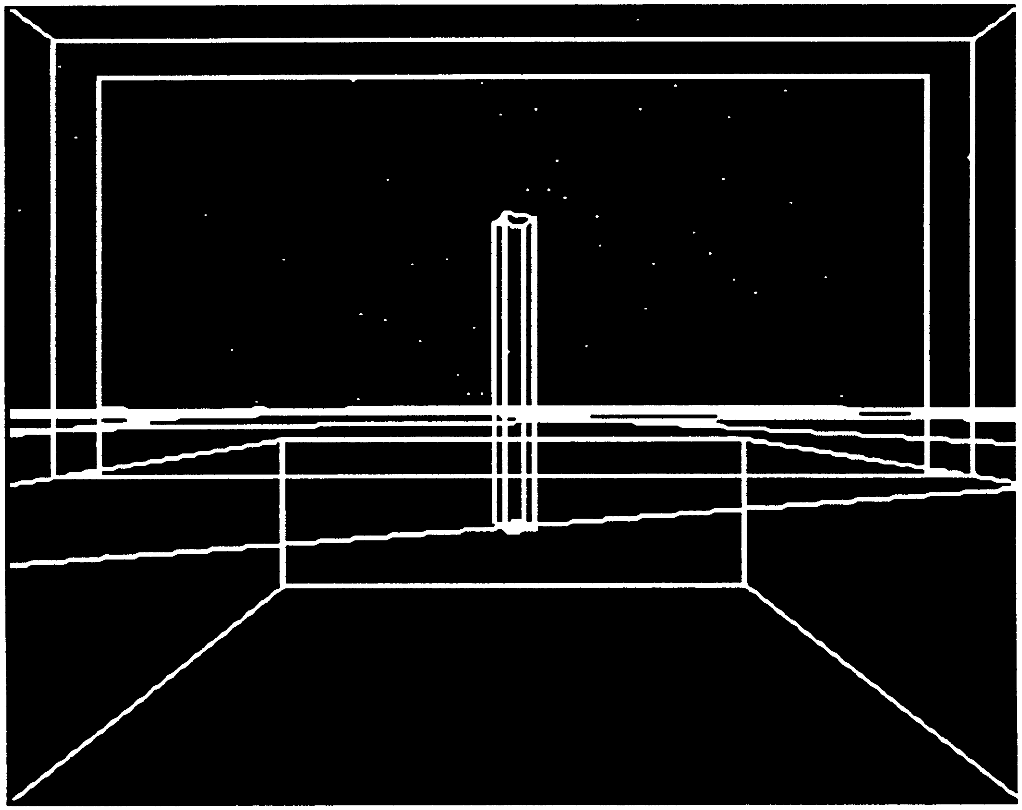

Figure 3.4 - View of a Post With the Vehicle Body Displayed

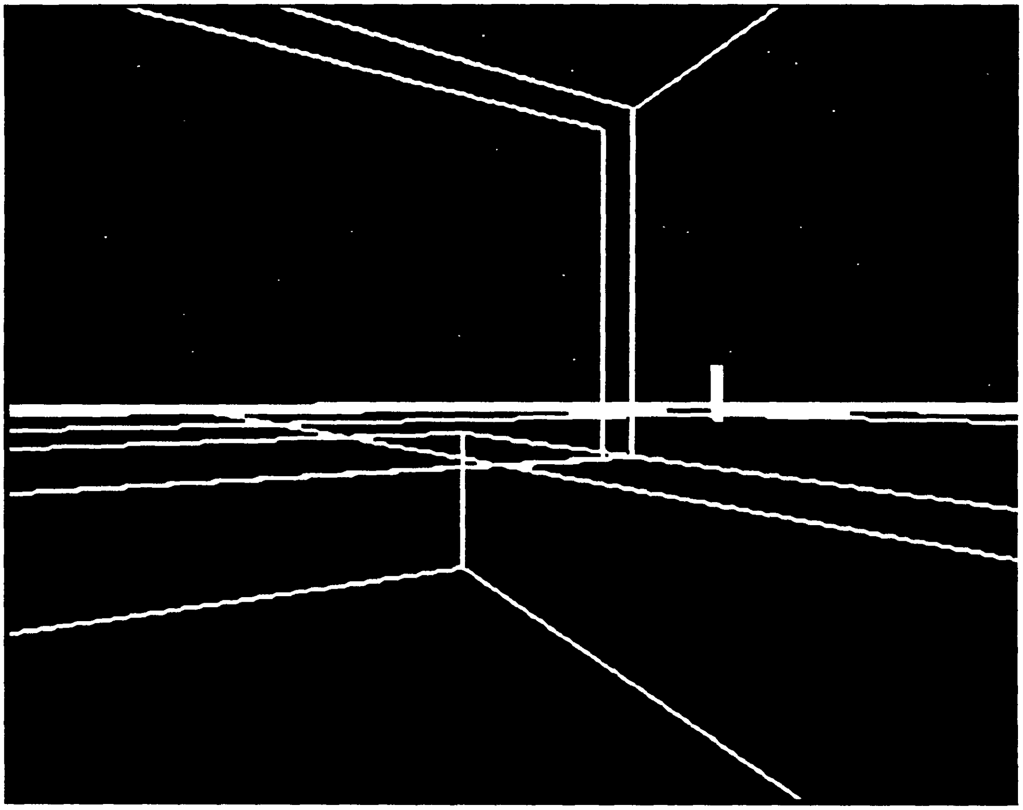

Figure 3.5 - View of an Off-Center Post With the Vehicle Body Displayed

To keep the subjects from learning the patterns and anticipating the locations of upcoming posts, no subject was tested on the same set of post locations twice. It was therefore necessary to create a number of sets of post locations (with the locations of eight posts, one run's worth, per set). The positioning of the posts was carefully designed to balance a number of factors. The distance between posts was kept constant at twenty meters to ensure that the time it took to reach each post reflected the difficulty the subject had in locating and navigating to the post rather than differences in the distances between posts.

To ensure that all runs were of comparable overall difficulty, the posts within each set were distributed among eight angles. For each post the "post angle" was defined as the angle between a line connecting that post to the previous post and another line connecting the previous post to the post before it. For the first post, post angle was defined relative to the initial orientation of the vehicle. In the example shown in Figure 3.6, the post angle for the first post would be zero degrees (because it is straight ahead relative to the initial orientation of the vehicle), the post angle for the second post would be 45 degrees (turns to the right are defined as positive), and the angle for the third would be -135 degrees. Assuming that the subjects navigated directly from one post to the next, the post angle for a particular post would be the angle (positive or negative, depending on direction) through which the subject had to rotate the vehicle, after reaching the previous post, such that the current post lay directly ahead of the vehicle. The eight post angles in each set were distributed evenly around the circle (at -180, -135, -90, -45, 0, 45, 90, and 135 degrees) to test subjects equally on targets that may be located anywhere around the vehicle.

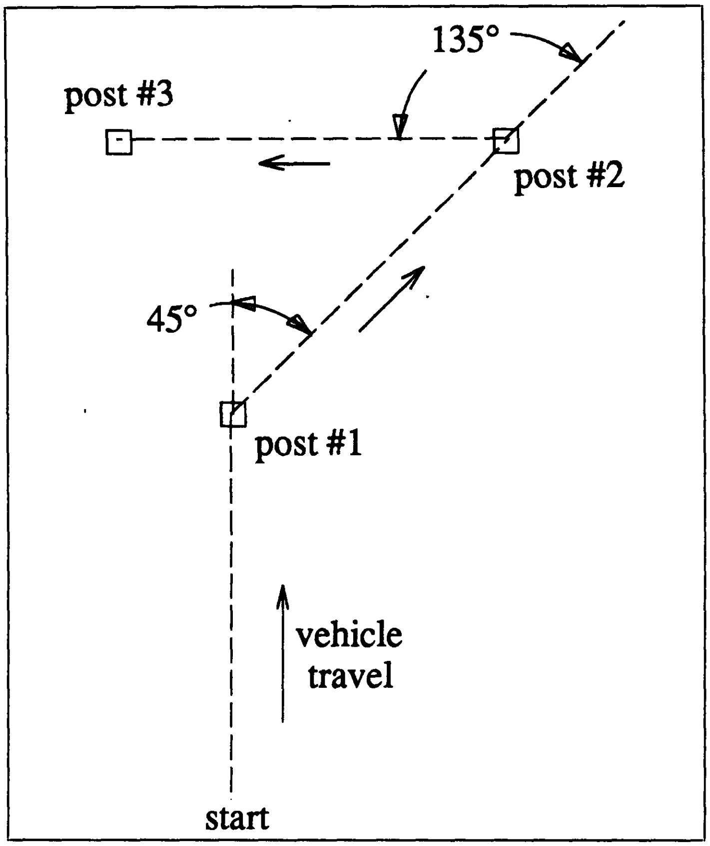

Figure 3.6 - Definition of Post Angles

3.2.2 Square-of-Posts Task Description

The environment in this second task was static, rather than having objects appearing and disappearing as in the random-posts task. In addition to the ground-grid and the stars, there were eight posts (of the same dimensions as in the random-posts task) located in fixed positions on the grid. These posts were arranged in a square pattern: there were four corner-posts and four side-posts (Fig. 3.7). The subjects' "mission" in this task was to circumnavigate the square of posts, maneuvering around the outside of the corner posts and passing to the inside of the side posts (Fig. 3.8). Subjects were told to navigate as fast as possible while still maintaining sufficient control over the vehicle to be very unlikely to hit or pass on the wrong side of a post. To balance out any biases subjects might have had in turning the vehicle to the left versus to the right, subjects circumnavigated the square an equal number of times in the clockwise and counter-clockwise directions (as looking at Fig. 3.8) in each test session. The vehicle began each run at one of two positions and with one of two orientations, depending on which direction the subject was to travel around the square during the run.

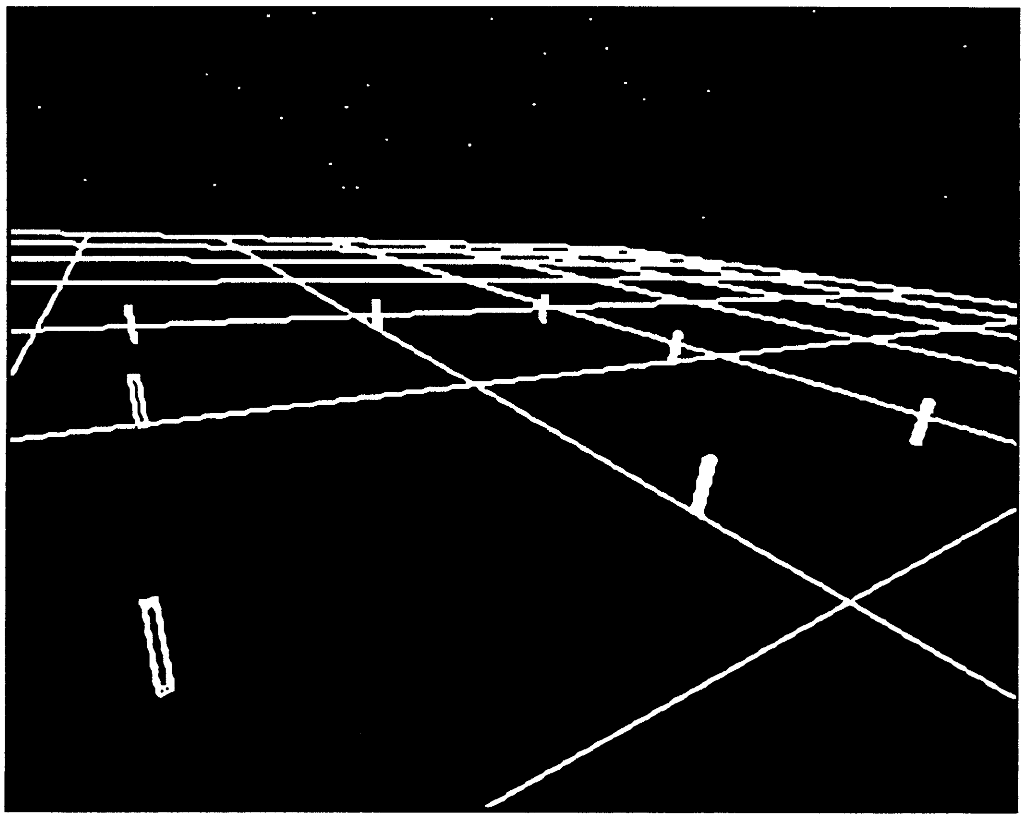

Figure 3.7 - "Aerial" View of Square-of-Posts Environment

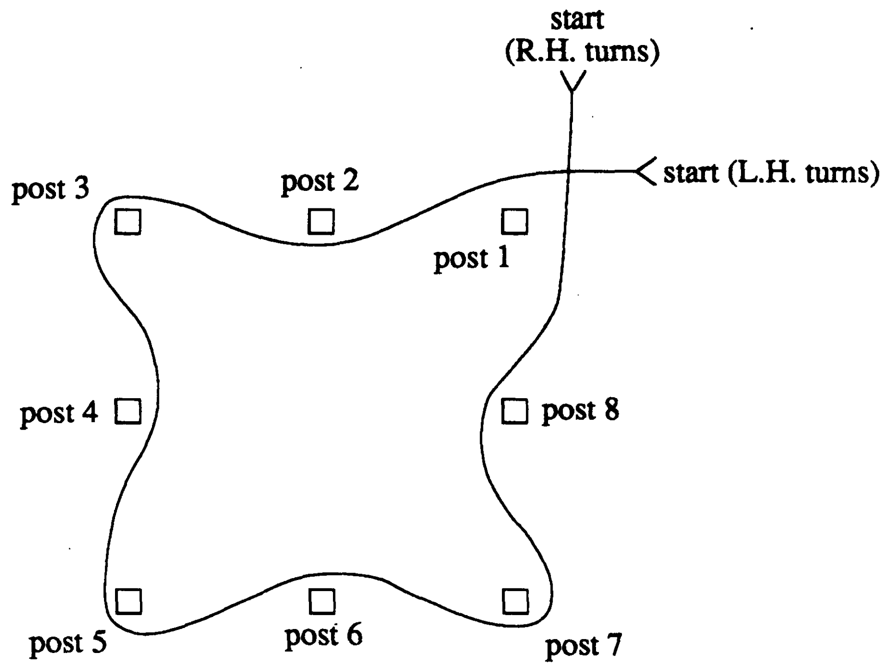

Figure 3.8 - Arrangement of Square of Posts With Sample Trajectory

Subjects were not told in which direction they would be turning around the square before performing a run. The direction of travel was clear, however, from the view at the beginning of a run. Figure 3.9 shows the initial view when it was desired to make right-hand turns around the corners (travelling clockwise according to Figure 3.8), and Figure 3.10 shows the initial view when left-hand turns were desired (travelling counter-clockwise by Figure 3.8). Figure 3.11 shows the same view as Figure 3.10, but with the vehicle-body image displayed. As the figures show, the initial positions of the vehicle were offset slightly to the side on which the first post must be passed.

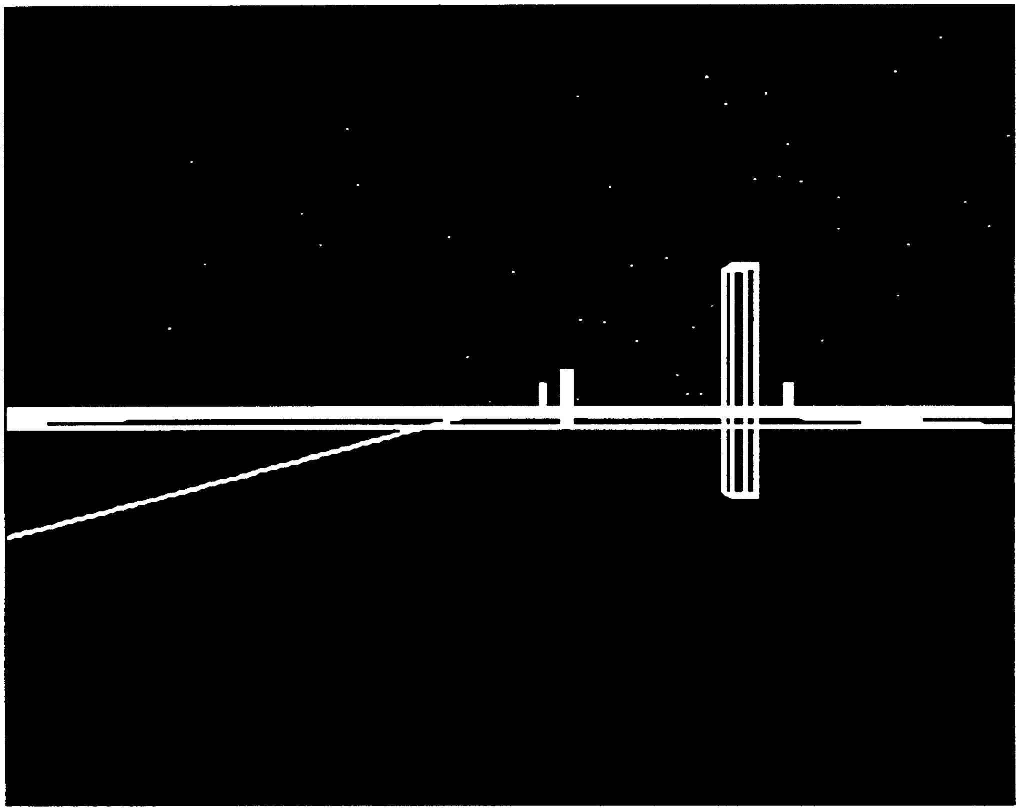

Figure 3.9 - Initial View for Right-Hand Turns Around Square (Without Vehicle Body)

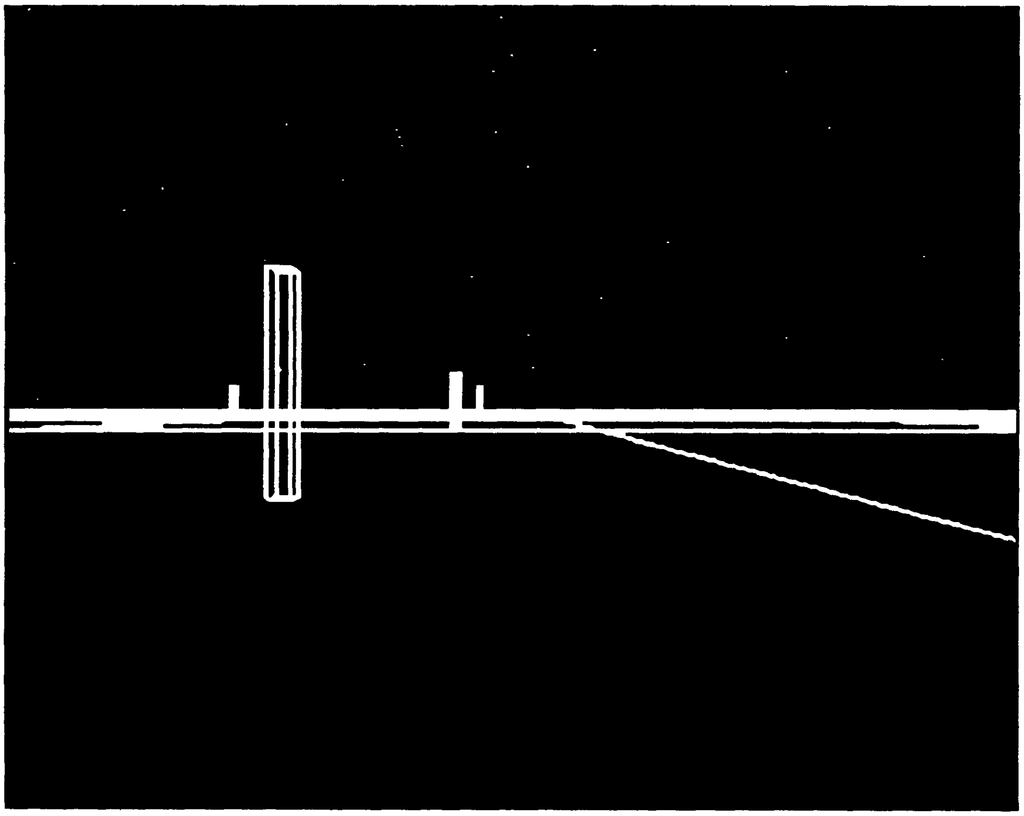

Figure 3.10 - Initial View for Left-Hand Turns Around Square (Without Vehicle Body)

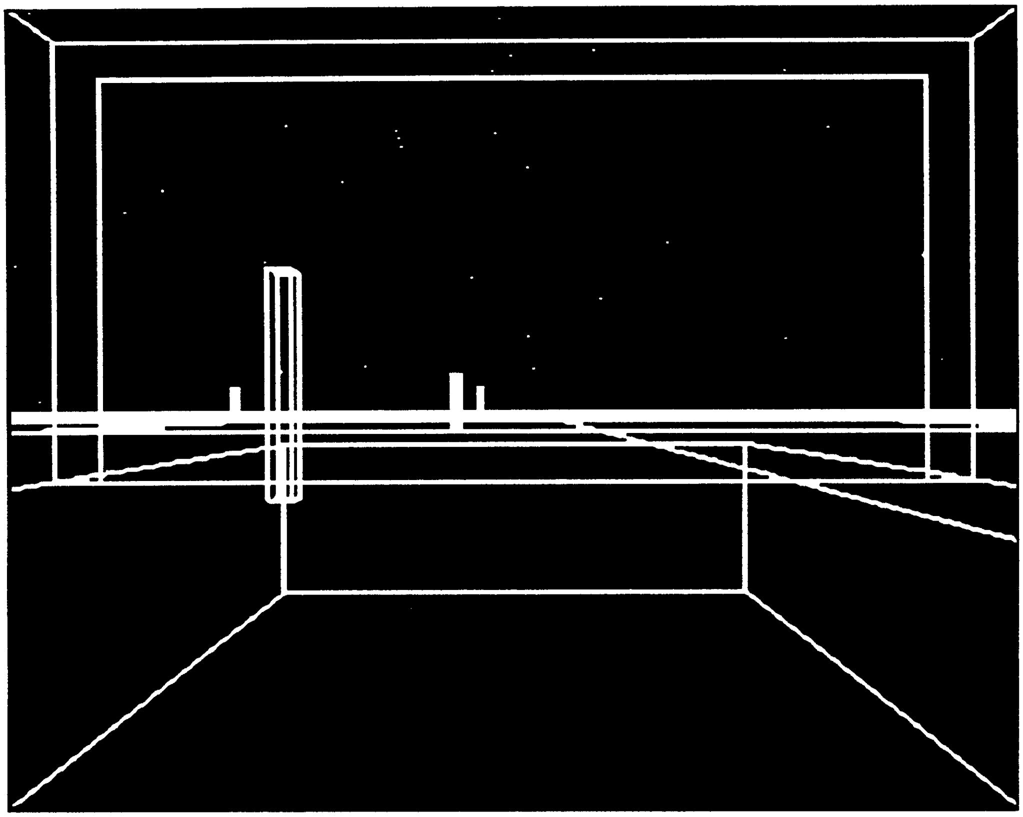

Figure 3.11 - Initial View for Left-Hand Turns Around Square (With Vehicle Body)

One potential design problem was encountered while running the experiment. One subject was very clearly taking advantage of the layout of the environment, and others may have been doing so to a lesser degree as well. In designing this task, it was intended that the subjects would have to keep the corner posts in sight, or at least keep track of the posts' locations if they were not visible, while reorienting the vehicle to round the corners of the square. Because of the positioning of the square of posts on the grid, however, subject #8 was able to use the grid-lines to avoid keeping track of the corner posts. When approaching a corner, he would translate forward and pass outside of the corner post, but rather than keeping track of the location of that post, he would keep the vehicle (and his head, when head-tracking was performed) pointing straight ahead. When he reached the next grid-line he would stop the vehicle using backward translational acceleration, and rotate in the appropriate direction. He quickly picked up on the fact that because of the locations of the grid-lines, he could stop the vehicle at the first line he encountered past the corner and be guaranteed to have passed by the corner post. The grid should be altered in future experiments so it does not provide these unwanted cues.

3.3 Dependent-Variable Definitions

The variables stored for each run were: total distance, total time, and total integrated values of each of the three DOF of control available to the subject. Total distance measured the distance travelled by the vehicle during a run. It was calculated based on the same assumption as the vehicle dynamics calculations: that the vehicle traveled in a straight line during each time step. These short straight-line distances were summed for each run to get total distance. It was anticipated that having a greater total distance travelled on one run versus another would indicate that the subject's control over the vehicle was more sloppy.

Total time was simply the amount of time elapsed from the beginning to the end of each run. Time was measured by accessing a hardware clock on the IRIS with a resolution of 0.01 seconds. Although subjects were told that accuracy was more important than speed in their performance on the tasks, how long they took to perform the tasks should reflect how comfortable they felt controlling the vehicle: if they felt more comfortable with their control of the vehicle using one display configuration, they would maneuver the vehicle more quickly through the task and take less time to complete it.

The integrated control values measured how much total control the subjects applied in accomplishing the tasks. In a real thruster-controller vehicle these values would be directly related to how much total fuel was expended to control the vehicle in each of the three DOF. The three variables are the summations, or "integrations," over a run of the absolute values of the commanded X- and Y-axis forces and Z-axis torque during each time step. Due to an oversight in developing the simulation software, the total values were not multiplied by the length of the time steps over which they were summed (which was 0.05 seconds), so the integrated forces and torque were recorded and analyzed in units of 20*N·s and 20*N·m·s, respectively.

Three additional variables were stored for each post in the random-posts task: orientation error, velocity error, and time to reach that post. The advantage of storing these values for each post rather than summing them over a run is that they can then be analyzed for the influences of the different post angles, in addition to display configuration. All three variables are measured for a particular post at the point when the vehicle approaches to within three meters of the center of the post. The time to reach each post, or "post time," is simply the time when the previous post was reached subtracted from the time upon reaching the current post. As with total time, this should reflect how comfortable the subjects feel with their control over the vehicle.

The orientation-error variable is the angle between a line from the vehicle's location to the center of the post and a line along the X-axis of the vehicle (Fig. 3.12). If the vehicle is rotated such that the post lies directly ahead, the orientation error will be zero. If the vehicle is oriented such that, when looking straight ahead along the vehicle's negative-X-axis, the post is offset thirty degrees to the left, the orientation error will be thirty degrees. Orientation-error should indicate how good the subject's sense of the orientation of the vehicle is and should come into play when using the display configurations with head-tracking, where the view seen by the subject is not always looking directly forward of the vehicle.

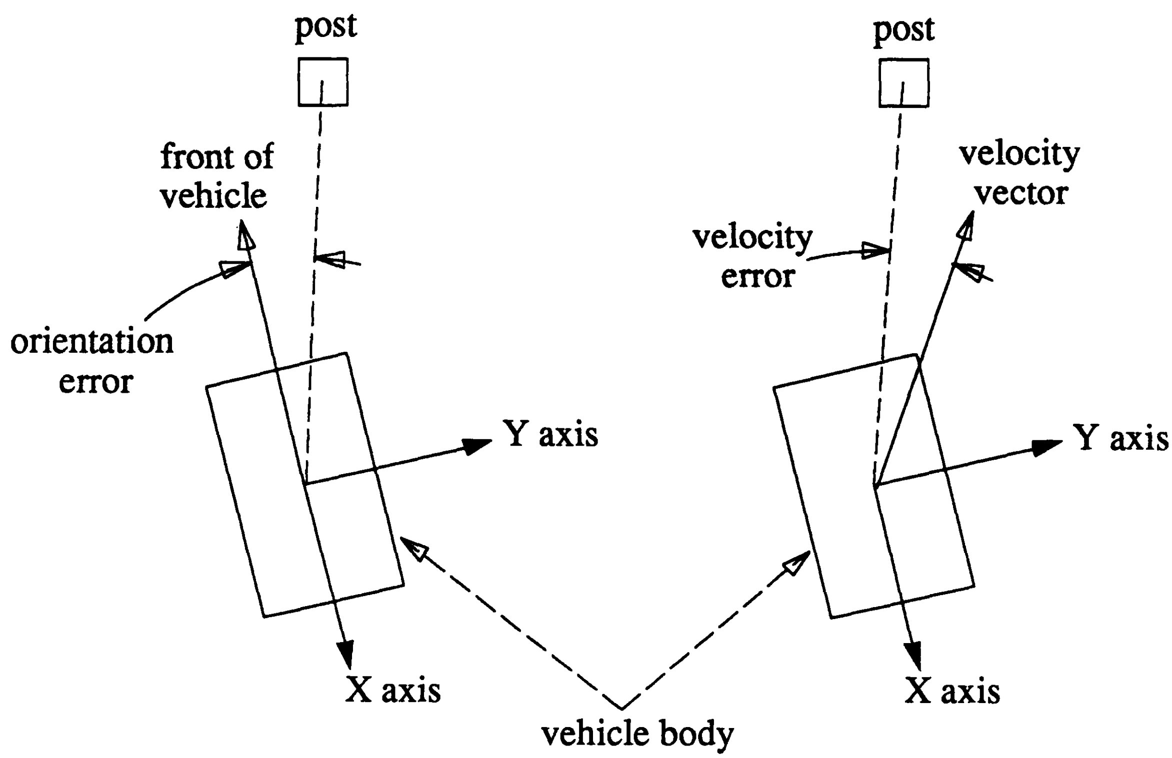

Figure 3.12 - Orientation Error and Velocity Error Definitions

Velocity-error measures the angle between a line from the vehicle's location to the center of the post and the direction of the vehicle's velocity vector (see Fig. 3.12). If the vehicle is moving directly at the post, regardless of how it is oriented, the velocity error will be zero. If this is not the case, even if the vehicle is oriented so that the post appears directly ahead, the velocity error will be non-zero. Velocity-error should reflect how well the subject can detect motion cues from the visual scene and apply the appropriate commands to achieved the desired vehicle motion.

The one additional variable that was measured for each post in the square-of-posts task was the distance of closest approach to each of the eight posts in the square. Although the subjects were given no "correct" distance at which to pass the posts, they were told to be as consistent as possible. This consistency would be directly related to the consistency of the post distances.

3.4 Experiment Design

Three different display setups were tested in the experiment: the fixed NTSC monitor, the HMD with a fixed perspective, and the HMD with a head-slaved perspective (i.e. with head-tracking). Each of these displays was tested both with and without an image of the vehicle body being displayed, resulting in a total of six display configurations.

Eight subjects had one or two practice sessions, during which no data were recorded, and six test sessions. Each subject had only one session in a day. During the first practice session, each subject was played an audio tape containing a recorded introduction to the experiment (see Appendix B). After listening to the tape, the subjects were shown which axes on the hand-controllers were used to control the simulated vehicle. Subjects then went through four runs, including two each of the random-posts and square-of-posts task. Two runs were made with the monitor (one with and one without the vehicle-body image), one with the HMD without head-tracking, and one with the HMD with tracking. While the subjects were performing the tasks, the experimenter tried to answer questions while trying not to influence the subjects' strategies or give out any information not available to the other subjects. At the end of the practice session, subjects filled out a questionnaire which gathered information on abnormalities in the subjects' vision and any experience they may have had in areas that could affect their performance on the experiment (see Appendix C).

Some subjects still were not able to reliably complete one or both of the tasks by the end of the first practice session. These subjects were given a second practice session in which they repeatedly performed the task or tasks they had difficulty with until they reached an adequate level of performance. Had time permitted, it would have been beneficial to give all subjects more practice sessions, as it was clear that even those who could successfully perform the tasks were not entirely comfortable doing so, and were still learning and adapting their strategies.

Each test session consisted of six runs, one each of the six display configurations. To simplify the design of the test matrix, subjects performed the same task for all six runs in a session. The test matrix (Table 3.1) was designed by creating pseudo-randomly arranged sets of the numbers from one to six (representing the six display configurations) and doing counterbalancing.

Table 3.1 goes here (Test Matrix, Excel file).

Table 3.1 - Test Matrix

One sequence of numbers (which happened to be the sequence 1,2,3,4,5,6) was made up for subject #1 on the first day. This sequence was reversed and used for subject #1 on the second day. Subject #2 used the reversed sequence on the first day and the original sequence on day two. The same method, with three different sequences, was used to create configuration orderings for the other six subjects for the first two days. To generate orderings for days three and four, the sequences for days one and two were swapped between pairs of subjects: subjects #1 and #2 went through the sequences on days three and four that subjects #3 and #4, respectively, had on days one and two. Subjects #3 and #4 performed the sequences on days three and four that subjects #1 and #2, respectively, had on days one and two. The same swapping was carried out between the sequences for subjects #5 and #6 and those for #7 and #8. The first half of the algorithm was repeated on days five and six: four pseudo-random sequences were generated and assigned to four subjects on day five and the other four subjects on day six, and the remaining sessions were filled in by counterbalancing between subjects within each day and between days five and six within subjects.

The task to be performed each day was assigned so that learning effects would be evenly balanced between the two different tasks. Which direction the subject had to travel around the square of posts on each run within a session was also arranged to balance learning effects between the two directions. Sets of random post locations for the random-posts task were generated by taking the set of eight possible post angles and picking angles from it, one at a time, based on the output of a random-number generator. The post locations were then generated based on the chosen sequence of post angles. Twenty-four such sets were generated; Table 3.2 gives the order of post angles for each set . A set of post locations was chosen for each run in such a way that differences between the sets of locations would not mask the effects of the display configurations on performance: across the entire experiment (all subjects on all days), each of the six display configurations was performed exactly once using each of the 24 sets of post locations.

	post #1	post #2	post #3	post #4	post #5	post #6	post #7	post #8
set #1	135	90	-180	45	-135	-90	-45	0
set #2	-90	135	-180	-135	90	45	-45	0
set #3	135	-180	-90	90	0	-135	-45	45
set #4	0	135	-135	-180	45	-90	-45	90
set #5	135	-90	0	-180	45	-135	90	-45
set #6	135	-90	-45	-135	-180	0	45	90
set #7	-135	45	90	0	-45	-90	-180	135
set #8	135	90	45	-45	-90	0	-135	-180
set #9	135	-180	-45	45	90	-135	-90	0
set #10	45	-90	-45	135	90	0	-135	-180
set #11	90	-45	0	45	-135	-180	135	-90
set #12	45	0	-135	-180	-90	-45	90	135
set #13	135	-180	-45	-135	90	45	-90	0
set #14	135	90	-90	-135	45	0	-45	-180
set #15	-180	45	0	90	-45	-135	135	-90
set #16	-45	90	-135	0	135	45	-180	-90
set #17	45	0	-180	-45	-90	135	-135	90
set #18	90	-135	135	-90	-180	-45	0	45
set #19	0	-180	90	-90	45	-135	-45	135
set #20	-45	-135	-180	-90	45	90	0	135
set #21	-90	-180	-135	-45	45	90	135	0
set #22	-90	-135	-180	45	-45	135	90	0
set #23	135	-90	90	-180	0	-135	-45	45
set #24	135	45	90	-180	-135	0	-45	-90
set #25	135	-135	-90	90	-45	-180	45	0

Table 3.2 - Order of Post Angles for Each Set of Random Post Locations

3.5 Experimental Procedure

A carefully planned procedure was followed during each test session to ensure that there were as few uncontrolled variables as possible. When a subject arrived, he or she sat down at the control station and was given a few moments to rest. When the subject was ready to begin, he or she donned the HMD and a program that measured the subject's effective inter-ocular distance was run. The program is based on a code segment provided in the manual for the HMD (VPL Research Inc., 1989). The program displays a vertical stick to one eye and a circle to the other. The subject relaxes his or her eyes and then use the buttons on the IRIS mouse to command the program to move the circle and stick closer together or farther apart. When the circle appeared to be lined up directly below the stick, the subject indicated that this was so and the program was halted. The inter-ocular distance calculated from the final positions of the ball and stick was stored in a disk file that was later read by the simulation code.

While the subject was wearing the HMD and running the inter-ocular distance program, the room lights were shut off. This was done to cut down on the glare from the fixed-monitor screen that can make it difficult to see the displayed image; the lights were kept off for the entire session so that the subject's eyes would not have to continually re-adjust to different light levels. The subject then performed six runs in succession. Between runs, the display screens were cleared to black to cut down on eye fatigue. To further reduce uncontrolled variation between runs, the information that had to be provided to the subjects before each run was spoken and stored in digitized sound files. Before each run, the IRIS played back the appropriate files to tell the subject which display configuration he or she would be using. The computer told the subject to get ready, paused for three seconds, and then told the subject to begin and began running the main program loop.

Chapter 4 Results and Discussion

Two different approaches were taken in analyzing the experimental results: statistical analyses were performed on the dependent variables that were recorded during each run, and a qualitative analysis was performed by actually looking at the trajectories followed by the vehicle on each run. In the latter case, comments were noted for each run and each run was categorized according to how "well" the task was accomplished. These categorizations were grouped together and used to compare the different configurations. In both types of analysis the two tasks were treated independently.

4.1 Statistical Analysis

Appendix A gives detailed results of the statistical analysis of all dependent variables that were measured. This section briefly summarizes the statistical results and discusses their meanings, as related to the original hypotheses. For definitions of the variables discussed see Chapter 3.

4.1.1 Random-Posts Task Statistical Analysis

The root-mean-square (RMS) orientation error of all subjects was lowest with the monitor-display and the vehicle-body shown. This configuration was slightly better than the HMD with vehicle-body configuration and significantly better than all others. The HMD-with-head-tracking-and-vehicle-body-not-displayed had an RMS error larger than any other configuration by a factor of 2.3 or more. When the image of the vehicle body was shown with the HMD, with tracking, performance improved: only the monitor-with-the-body configuration was significantly better. The monitor and HMD-without-head-tracking were not significantly different, and adding head-tracking to the HMD significantly reduced performance only when the vehicle body was not displayed.

As predicted, subjects controlled the orientation of their vehicle poorly when the vehicle body was not displayed under the HMD-with-head-tracking configuration. Although the subjects already had access to the information provided by display of the vehicle-body (through proprioceptive feedback from the neck muscles), that display provided this information with higher precision and in a much more easily accessible form. Thus augmented, performance with the HMD-with-tracking was roughly comparable to that with the other two display formats.

With respect to velocity error, the monitor-without-vehicle-body configuration gave the least, and the HMD-with-head-tracking-and-vehicle-body produced the largest RMS errors. The HMD with head-tracking was significantly worse than the monitor and the HMD without tracking. The HMD without tracking was slightly worse than the monitor without the vehicle body and significantly worse when the body was displayed. Adding the vehicle body made no significant difference for the monitor and HMD with tracking, but significantly worsened performance for the HMD without tracking.

Head-tracking significantly reduced the precision of the subjects control of the direction of the vehicle's velocity vector. There are basically two aspects to precise control of the vehicle's velocity: detecting the current velocity vector, and applying the appropriate commands to change it to the desired velocity vector. Adding head-tracking probably interfered with the link between these two tasks. Command forces are applied with respect to a vehicle-fixed coordinate frame; current velocity is sensed, however, by interpreting motion in the visual field. Without head-tracking these two coordinate frames are fixed with respect to each other. When head-tracking is performed, however, the relationship between the two frames depends on the orientation of the subject's head. Unless the subject holds his or her head perfectly still, there is a dynamic transformation between what the subject sees and the directions in which the subject's force commands are applied that may be difficult for the subject to keep track of.

Adding the vehicle-body image either made no significant difference or significantly increased velocity errors. Although it was expected that displaying the vehicle body would make little difference in the subjects' ability to control the vehicle's velocity under those configurations without head-tracking, it did, in fact, worsen performance. This may have because it was difficult with the body present for subjects to tell which lines were part of the environment and which were part of the body. The body-image interfered with the motion cues provided by the ground grid. This interference could have had a greater effect with the HMD than with the monitor because the monitor's higher resolution gives a clearer picture than the HMD, and makes it easier to interpret motion cues. Thus, the negligible difference made by the vehicle-body may be due to offsetting effects: the interference by the body-image with detection of motion cues was offset by the useful head-orientation information the body-image provided. According to this theory, if a higher-resolution HMD were used with head-tracking, displaying the vehicle body would reduce velocity error as it reduced orientation error.

The instructions to the subjects emphasized accuracy: they were told to navigate only as fast as was consistent with the highest accuracy. Therefore, the time it took to reach each post should be a good indicator of how comfortable and in control the subjects felt with each configuration. Although it was intended to place each post twenty meters from the previous one, a software error placed two posts in one set (of the 24 sets) of random post locations farther than that. Those twelve data points (two posts times the six subjects that were tested on that set of random post locations) were therefore omitted from the analysis of "post times." They were included in the analysis orientation and velocity errors because it was felt that the extra distance would not affect those variables.

Subjects' post times were, on average, slightly greater for the HMD-without-head-tracking than for the monitor, and slightly greater for the HMD-with-tracking than without. Although the body-image had no significant overall effect, it did have a very significant effect on the difference in times between the HMD-with- and without-head-tracking setups. When the vehicle body was not displayed, the average time to reach east post was fifteen percent longer with head-tracking than without (using the HMD only), and the data were much less consistent in the latter case. When the body was displayed, however, adding head-tracking made little difference in overall performance or consistency. This is probably due again to the difficulty subjects experienced with head-tracking in relating their intended direction relative to the visual field to the necessary commands in the vehicle-fixed reference frame. This confusion caused them to take slightly longer to reach each post when the body was not visible; the added difficulty was eliminated when the body was displayed.

It took the subjects less time to reach posts that lay directly ahead of them than those requiring a change in direction -- longer, generally, the larger the angle through which the vehicle had to be rotated to line up on the next post. Most subjects showed a directional bias: that is, they tended to take longer to reach posts for which they had to rotate in one direction than those for which they had to rotate an equal amount in the opposite direction. This is explained by the nature of the task: without head-tracking, the only way to locate the next post is to rotate the vehicle until it comes into view, and then navigate to it. The subjects that showed a directional bias tended to rotate more often in a particular direction (i.e. to the right or to the left) when searching for the next post, and so found posts which were offset in that direction more quickly.

Subjects tended to reach the first post more quickly than the later posts. Because their initial velocity was zero, once they had the first post in view they could navigate directly to it -- there was no current velocity to correct for. For subsequent posts, however, the subjects had to overcome the vehicle's current velocity (which probably was not in the direction of the next post) in the process of navigating to that post.

Finally, the post times differed significantly from day to day. The first two days were nearly identical, but on the third day subjects took less time and were more consistent in getting to each post. This indicates that at least some of the subjects were still learning how to perform the task during the period in which they performed the experiment. Giving the subjects more training before taking data could have reduced this effect.

For the analysis of the total distance traveled by the vehicle per run, subject #1's data were thrown out because they were very different from the data for all other subjects. Most subjects navigated at a fairly low speed, and many did their best to stop the vehicle after hitting a post, before searching for the next. Subject #1 navigated at a very high speed and usually significantly overshot the posts. (See Section 4.2.1 for sample runs for a typical subject and for subject #1). The only variable that had a significant effect on total distance was "day." Subjects traveled, on average, 21 percent farther on the first day than on the second or third. This is, again, probably due to learning effects: the subjects were still getting used to the vehicle dynamics on the first day and so could not control it as precisely as on subsequent days.

As with the individual post times, the total times per run were slightly larger for the HMD without head-tracking than for the monitor, and slightly larger still for the HMD with tracking. Although head-tracking had little effect on run times for most subjects, the difference in overall means was caused by three subjects who took significantly longer with tracking than without. As with some variables discussed above, overall performance with respect to run time increased significantly over the three days of the task. The mean run time decreased by nearly twenty percent from the first day to the last. Once again this indicates that the subjects received insufficient training before the first session during which data were saved.

As with the individual post times, the difference in total run times caused by adding head-tracking (using the HMD) was highly influenced by the presence or absence of the vehicle body. Without the vehicle body displayed it took seventeen percent longer for each run with head-tracking than without, and the standard deviation was over twice as large for the with-tracking case. With the vehicle body shown there was virtually no difference in run times between the HMD with and without head-tracking.

The total integrated force along the vehicle X-axis applied per run was not significantly influenced by any of the experimental variables. Total integrated force along the vehicle Y-axis was influenced only by whether or not head-tracking was performed. Every subject applied more Y-command with head-tracking than without (using the HMD), and the overall average was over thirty percent greater with head-tracking. Subjects generally used X-command to change the magnitude of the vehicle's velocity vector (set the vehicle's speed) and Y-command to fine-tune the direction of the velocity vector as they approached each post. The fact that significantly more Y-command was used with head-tracking again indicates that subjects had more difficulty precisely controlling the velocity vector of the vehicle due to the extra transformation between the visual field and the vehicle-fixed reference frame in which commands were applied.

The analysis of integrated Z-axis torque command, or integrated applied rotational acceleration, revealed no consistent effects of any of the experimental variables. Several subjects applied significantly more rotational acceleration with the monitor than with the HMD, some applied significantly more with the HMD (without head-tracking) than with the monitor, and the rest showed no significant difference in overall mean torque across displays. The subject with the largest increase between the monitor and HMD was observed to rotate his head through very large angles (up to ninety degrees) while using the HMD without head-tracking, apparently because he had grown accustomed to rotating his head when using the HMD with head-tracking. The fact that the subject rotated his head significantly but saw no corresponding change in the visual field probably confused him, disturbing his sense of the motion of the vehicle. This may have required him to make more corrections to the vehicle's rotation. The same may have been true for the other subjects who rotated the vehicle more with the HMD than with the monitor.

As with the displays, some subjects applied significantly more rotational acceleration using the HMD without head-tracking, one applied more rotational acceleration with head-tracking, and the rest had no significant difference. All subjects followed approximately the same strategy in locating each post: after reaching one post, they would use a short command to begin the vehicle rotating, wait (while the vehicle rotated at constant velocity) until the next post was approximately straight ahead, and then used a short rotational command in the opposite direction to stop the vehicle's rotation. Most of the time subjects rotated the vehicle slowly enough so that when the post entered the visual field they could stop the vehicle's rotation by the time the post lay directly ahead. Occasionally, however, a subject would rotate the vehicle too quickly, would not be able to stop the rotation in time, and would overshoot the post and have to rotate back in the opposite direction to line up on it. This overshoot would cause more total rotational acceleration to be commanded. With head-tracking, the subjects could look slightly toward the side to which the vehicle was rotating -- the side from which the post would enter the visual field -- giving them a larger effective field-of-view and allowing them more time to stop the rotation of the vehicle without overshooting the post.

The one subject who applied more torque-command with head-tracking was the same subject mentioned above who rotated his head significantly without head-tracking. As opposed to the reduced overshoot generally seen with head-tracking as described above, this subject overshot the posts more often with head-tracking. To reach each post, the subject would look around until he located the post and then rotate the vehicle toward the post, matching the rotation of his head to the vehicle's rotation in order to keep the post in the center of his field of view. Because the post, which would be motionless on the display, was the most prominent object in the visual field, the subject seemed to lose track of the rotational velocity of the vehicle. He appeared to rotate the vehicle faster than he intended to, so that when he attempted to stop the rotation he would overshoot the post.

4.1.2 Square-of-Posts Task Statistical Analysis

In analyzing the distances of closest approach to each post, both the means and standard deviations of the numbers are important. The subjects were not told or shown exactly how closely to pass by each post; they were told only to avoid hitting the posts with the vehicle and to be as consistent as possible. The means of post-distances indicate how close subjects came to the posts, while the standard deviations reflect how consistent the subjects runs were.

Although the subjects generally passed closer to the posts using the HMD (without tracking) than the monitor, there was a nearly even split between those who came significantly closer with the monitor, those who did so with the HMD, and those who had no significant difference. There was little difference in consistency between the two displays.

Using the HMD, several subjects passed significantly closer to the posts when head-tracking was not performed than when it was, while for the rest head-tracking had no significant difference. Thus the overall mean distance was slightly smaller for the no-head-tracking case. The subjects were more consistent (lower standard deviation) without head-tracking than with it. The subjects who passed closer to the posts without head-tracking may have done so because they felt more secure in their control of the vehicle when operating in that configuration. When using head-tracking they may have needed to give the posts a wider berth to compensate for their lesser sense of control. The increased consistency without head-tracking may also be due to the subjects being able to control the vehicle more precisely, for the reason discussed in the section on the random posts task.

Three subjects came significantly closer to the posts with the vehicle-body displayed than without it, whereas displaying the body had no major effect on the other subjects. This may suggest that the three subjects affected gave themselves a slightly larger margin of error to allow for the body that they could not see. Consistency was somewhat worse when the body was displayed. This may have been due to the increased difficulty in detecting motion cues when the body is displayed.

Subjects typically passed close to the first post, and then closer to the side posts than the other corner posts. This makes sense in light of the fact that the subjects simply used translational acceleration along the Y-axis to get around the first corner post and the side posts but were forced to rotate the vehicle while getting around the corner posts. It is more difficult to simultaneously control the vehicle's translation and rotation, so most subjects gave the corner posts a wider margin of error to compensate for their less precise control of the vehicle at those points.

Although the mean post distances differed from run to run for the first two days, they were about equal for all runs on the third day. This may indicate that the subjects had learned the task better and were therefore more consistent by the third day. This is supported by the observation that the standard deviations for the second through sixth runs of each session were lowest on the third day.

The total distances travelled per run differed only by experiment day and presence/absence of the vehicle-body image. The mean total distances for seven of the eight subjects decreased steadily over the three days. The overall decrease from the first day to the last was just over ten percent. The overall standard deviation decreased by a factor of three from the first day to the last. This suggests that the experimental data were taken while the subjects were still learning the task.

The presence/absence of the vehicle body made a significant difference to only two subjects (#3, #4), who traveled significantly farther when the body was displayed and one (#7) who one travelled a significantly shorter distance when the body was displayed than when it was not. One subject (#3) who travelled farther when the body was displayed also passed farther from the posts with the body. His greater distance per run may simply reflect his less precise control when passing each post. This could also be true for subject #7. Subject #4, however, actually passed closer to the posts with the body displayed than without it. This subject's greater distance per run suggests less-accurate control of the vehicle, requiring a greater distance to reorient the vehicle in turning the corners of the square.

Looking at the total times per run of the subjects who had significant differences in their total distances per run reveals no clear relationship between the two variables; it seems the average speed at which those subjects navigated was independent of the distance they travelled. The only statistically significant finding was that the mean times of seven subjects, the mean times averaged over all subjects, the standard deviations for four subjects, and the overall standard deviations all decreased steadily from the first day to the third. In fact, the overall mean decreased by almost thirty percent and the overall standard deviation decreased by more than fifty percent. This is yet another indication that the subjects were still learning how to perform the task when the data-taking began.

Only the day variable was significant in the analysis of the integrated X-command for this task. Although the mean over all subjects decreased significantly from the first day to the second, only three subjects (#3, #5, #7) had means that were much higher on the first day. These three subjects were among those who had the most difficulty learning the task and probably were still learning how to perform the task during the first day. Averaged over all subjects, consistency improved steadily over the three days.

For the integrated Y-command variable only the display and run number of the day had significant effects. Subjects almost universally applied more total Y-command when using the monitor than with the HMD. This could have been be caused by the fact that the monitor, due to its higher resolution, provided better motion cues and allowed the subject to more precisely control the direction of the vehicle's velocity, at the expense of applying more total side-to-side acceleration.

The total Y-command increased over the runs within each session. For each session, the subjects probably felt "cold" for the first run or two of the day, and then became more comfortable with the task as the session continued. As the subjects became more comfortable within each session they probably attempted to control the vehicle's velocity more carefully, commanding more Y-axis acceleration.

Five of the subjects applied more total Z-axis commanded torque using the HMD than the monitor; the overall mean was fifteen percent larger and the overall standard deviation was seventy percent greater with the HMD. It is interesting to note that subject #6, who turned his head significantly when using the HMD with or without head-tracking (as described in the discussion for the random posts task above), had an increase of 65 percent in mean total Z-command and his standard deviation increased almost 400 percent in switching from the monitor to the HMD. He apparently again had difficulty using the HMD with a fixed view because he could not suppress the urge to rotate his head to look in different directions that was learned when using the HMD with head-tracking. Looking at all subjects other than #6, the display appears to have no significant effect on total Y-command.

As with many previous variables, learning effects were evident in the total Z-command data. The overall mean dropped 18 percent and the overall standard deviation dropped by a factor of nearly two between the first and second days, while there was little difference between the second and third days.

There was one effect relating to the presence or absence of the vehicle body that seemed to have arisen mostly, if not entirely, from the data belonging to subject #6. Switching from the monitor to the HMD significantly increased the overall mean and standard deviation of total Z-command when the vehicle body was not displayed, but made very little difference when the body was displayed. Without the vehicle body, subject #6's mean Z-command increased by more than a factor of two and his standard deviation increased by more than a factor of five when using replacing the monitor with the HMD, again probably due to his confusion when using the HMD without head-tracking. Among the other seven subjects there was no significant trend. With the vehicle body displayed, however, subject #6, as well as the rest of the subjects, showed no important pattern related to which display was used. It is likely that when using the HMD without tracking, seeing the vehicle body on the screen continually reminded subject #6 that even though he was turning his head, the view he was seeing was always directed straight ahead from the vehicle. This would reduce the confusion brought on by turning his head and not seeing the appropriately transformed view.

The final significant factor in the analysis of total Z-command was the influence of the vehicle body displayed/not-displayed factor on the difference between the HMD with and without head tracking. For the HMD without tracking, adding the body significantly decreased the overall mean and standard deviation of total Z-command. This decrease was, however, due mainly to subject #6 and one other subject with a large decrease; among the other subjects the body either made no difference or increased the mean total Z-command. For the HMD with head-tracking, displaying the vehicle body made little difference overall; some subjects used somewhat more total Z-axis thrust with the body while some used more without it. This is more in line with what was expected. The vehicle body display should reduce total Z-command slightly: subjects could track the passing posts by turning their heads rather than rotating the vehicle. The display should also, however, increase total Z-command: it is more difficult to detect the vehicle's velocity when the body is displayed, and this should lead to a larger number of corrections to the vehicle's trajectory.

4.2 Qualitative Analysis

The qualitative analysis based on examining trajectories did not turn out to be as useful as was originally hoped. One problem was that there were a total of 288 runs, which made it difficult to rate all runs on an objective and consistent scale. Although examining the trajectories revealed some interesting insights into how the subjects performed the tasks and some specific problems they had, the information obtained in examining the trajectories was too qualitative to make any judgements on the relative merits of the different configurations on it. The analysis is presented here mainly for the benefit of showing typical trajectories followed on each task.

4.2.1 Random-Posts Task Qualitative Analysis

There was no way that subjects could fail to accomplish this task, once they became sufficiently adept at controlling the vehicle to hit the posts. Although it was possible to miss a post and float past it, one could simply turn the vehicle around and attempt to collide with the same post again until successful.

Figure 4.1 shows a typical good trajectory for this task (taken from subject #2 using the monitor with the vehicle body displayed). Each arrow represents the position of the vehicle at one point in time, with the arrow pointing toward the front of the vehicle. The arrows and the squares are not drawn to scale. The spacing of the arrows is proportional to the velocity of the vehicle at each point, although the same spacing does not indicate the same vehicle velocity on different figures. The figure clearly shows the independence between the direction of the vehicle's velocity and the orientation of the vehicle that arises from the dynamics that were simulated.

On the run in Figure 4.1, the subject typically slowed the vehicle upon reaching each post, rotated to locate the next post, and headed directly for the next post. After reaching post three, however, post four appeared near the right edge of the monitor. Rather than rotating to bring the column directly in front of the vehicle, he used Y-axis acceleration to translate the vehicle to the right, without changing orientation, to reach the fourth post. It is also interesting to note that the subject did not slow down the vehicle after reaching post five, and he rotated the vehicle counter-clockwise to find the next post, so that by the time he located post six he had drifted a significant distance.

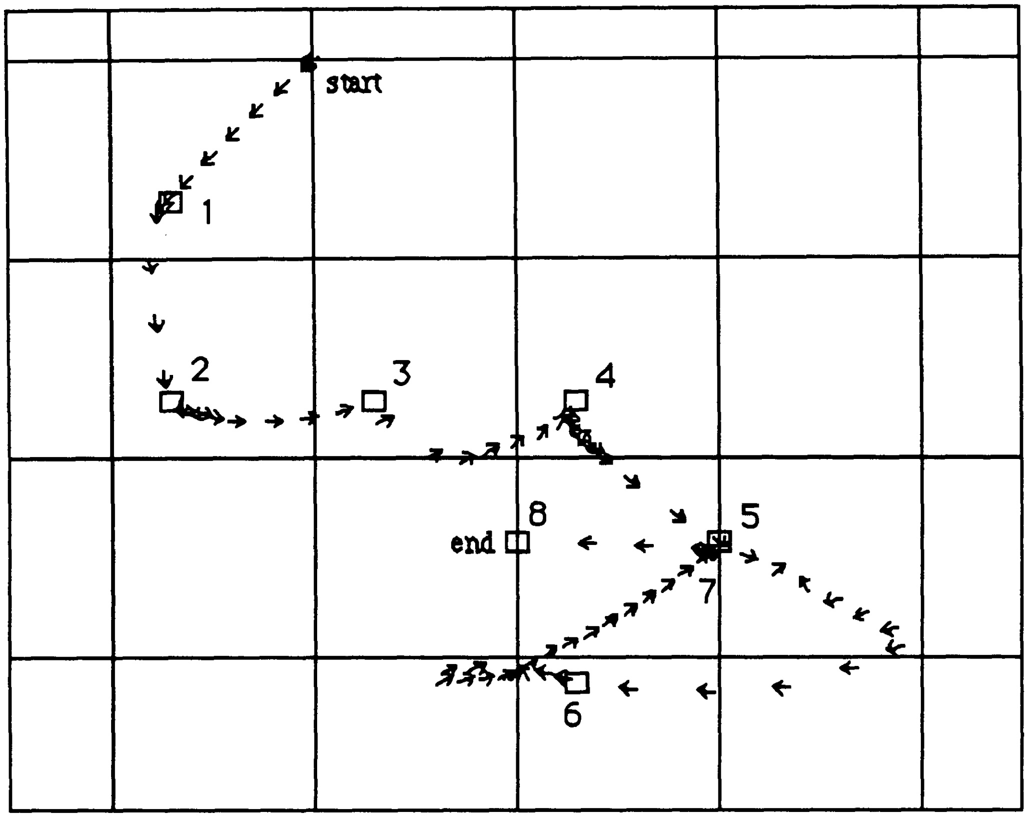

Figure 4.1 - Random Posts Task, Good Run

Figure 4.2 shows a slightly worse run than that above. It is taken from a run performed by subject #8 using the monitor without the vehicle body displayed. For most of the posts the subject did not slow down after reaching them and drifted past them while searching for the next posts. These large drifts are most evident between posts three and four and posts six and seven.

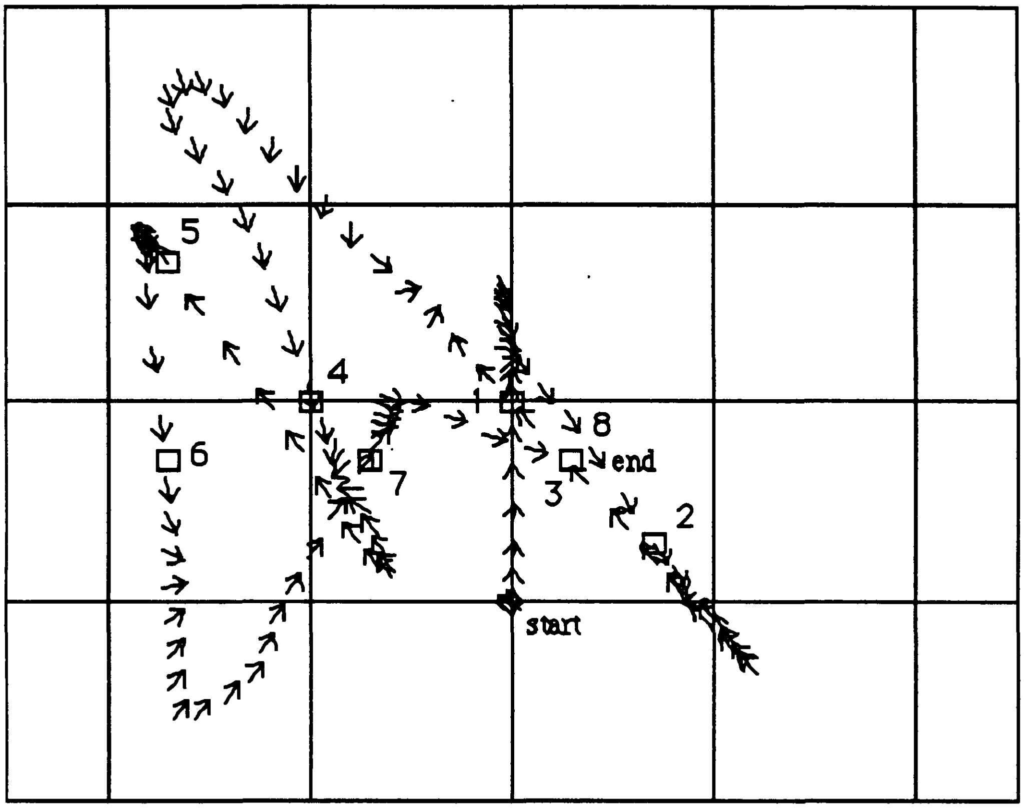

Figure 4.2 - Random Posts Task, Mediocre Run

The trajectory shown in Figure 4.3 was taken from subject #1, whose data were removed in the total distance statistical analysis as described in section 4.1.1. The subject used the HMD with head-tracking without the vehicle body displayed for the run. Although it is true that this was generally the most difficult configuration to use, the pattern of wildly overshooting every post was consistent in this subject's data. The subject technically followed the instructions at the beginning of the experiment: he attempted to line up his velocity and orientation with each post and then navigate to the post. He commonly drifted beyond the edge of the defined ground grid between posts. Because his average speed was relatively high, however, the total time data for subject #1 were not out of line from the rest of the subjects' data.

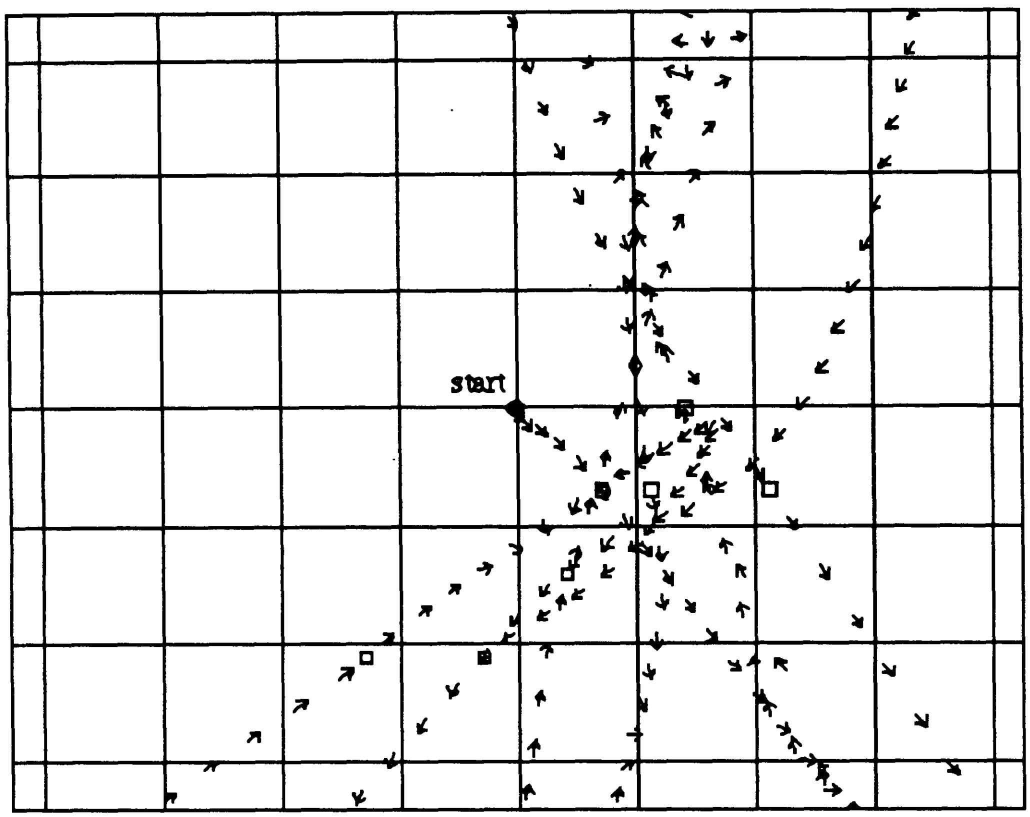

Figure 4.3 - Random Posts Task, Poor Run

4.2.2 Square-of-Posts Task Qualitative Analysis

It was possible to fail to accomplish to square-of-posts task by passing through or on the wrong side of one or more posts. Unfortunately, over the entire experiment there were a number of runs in which subjects did make these errors. The statistical analyses in Section 4.1 were performed using data from all runs, regardless of whether the tasks were correctly accomplished. Although the frequencies of incorrectly-performed runs were recorded in the qualitative analysis, these data are not presented because they were not meaningful.

Figure 4.4 shows a well-performed navigation around the square of posts. The figure shows how the subject only rotated the vehicle at the corners of the square, and used only side-to-side translational accelerations to pass inside the side posts, without changing the orientation of the vehicle. This strategy was typical of the subjects who performed well on this task.

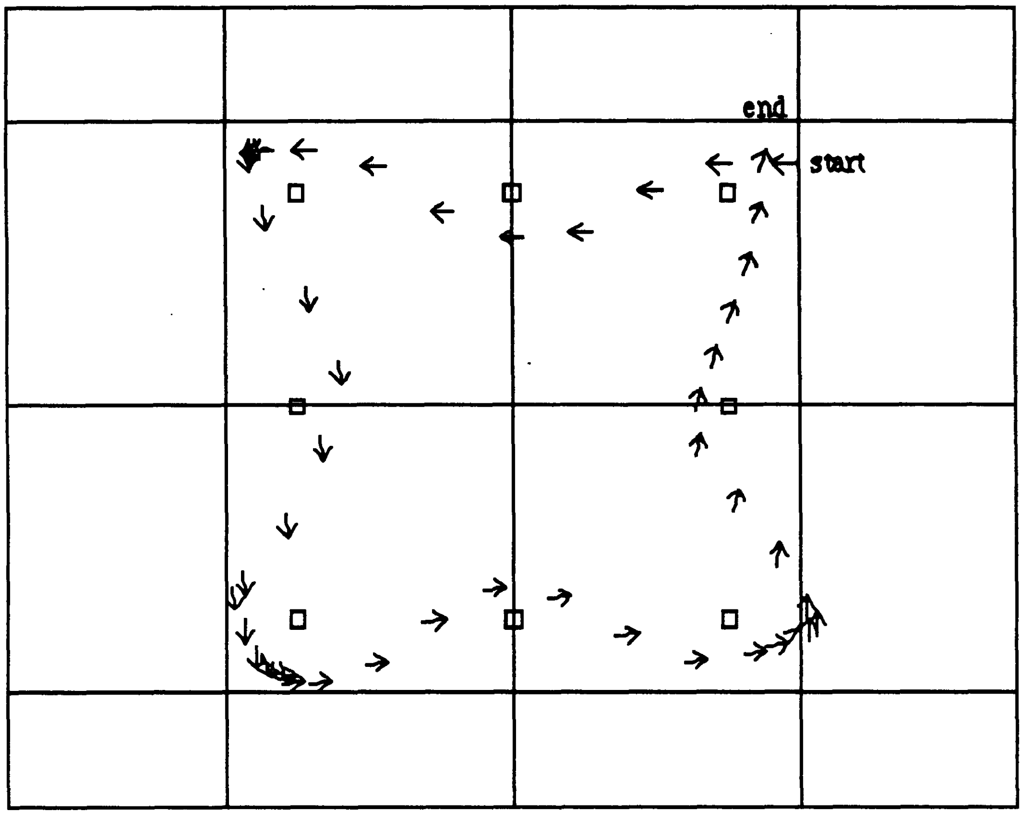

Figure 4.4 - Square of Posts Task, Good Run

Figure 4.5 is a trajectory plot for a slightly worse run. The run was performed by subject #5 using the monitor without the vehicle body displayed. Although the first half of the trajectory is good, the subject maneuvered the vehicle through the post on the left side of the square and then had severe difficulty for the rest of the run. The figure shows that the subject began moving across the top of the square with the vehicle still rotating, which probably led to his difficulty in getting around the top side post.

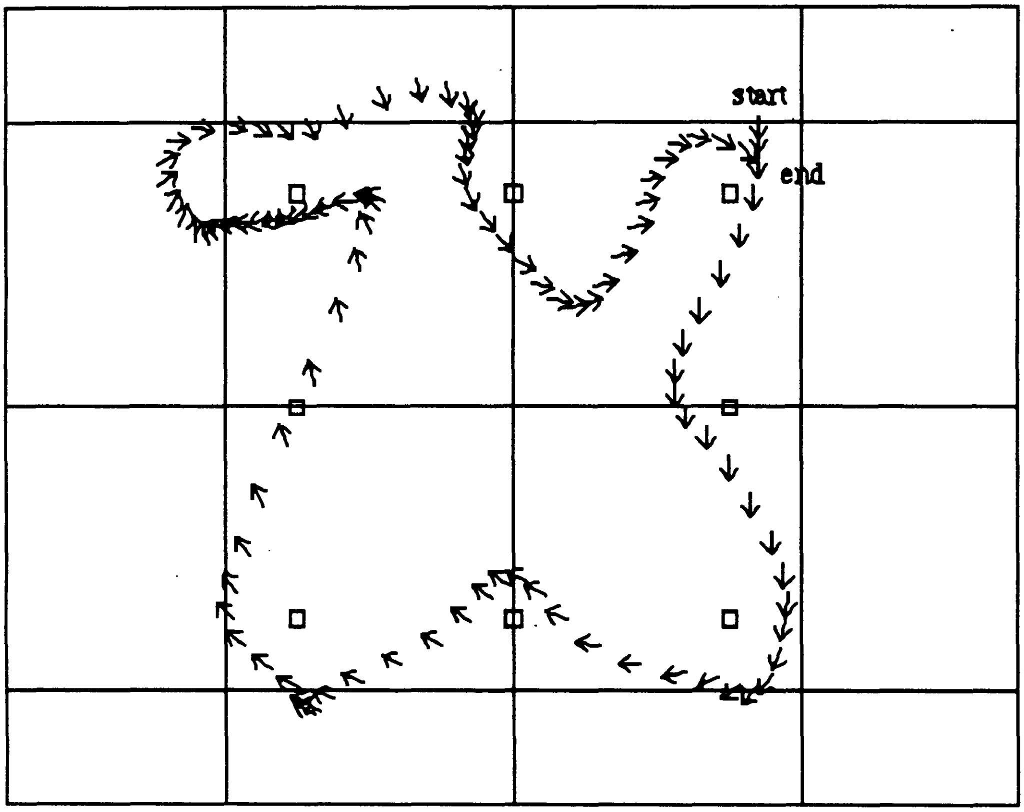

Figure 4.5 - Square of Posts Task, Mediocre Run

A very poorly-performed run is represented in Figure 4.6. The trajectory in the figure was performed by subject #6 while using the HMD with head-tracking without the vehicle body. The subject passed the first two posts correctly, but then had serious difficulty with the third. He drifted near the post for some time, and eventually through it, before navigating around the correct side. He had similar difficulty with the lower right-hand post. Although it appears that the subject clipped the lower-left-hand corner and right-hand side posts, because the posts are not drawn to scale and because the vehicle body was not displayed it probably appeared to him that he passed those posts correctly.

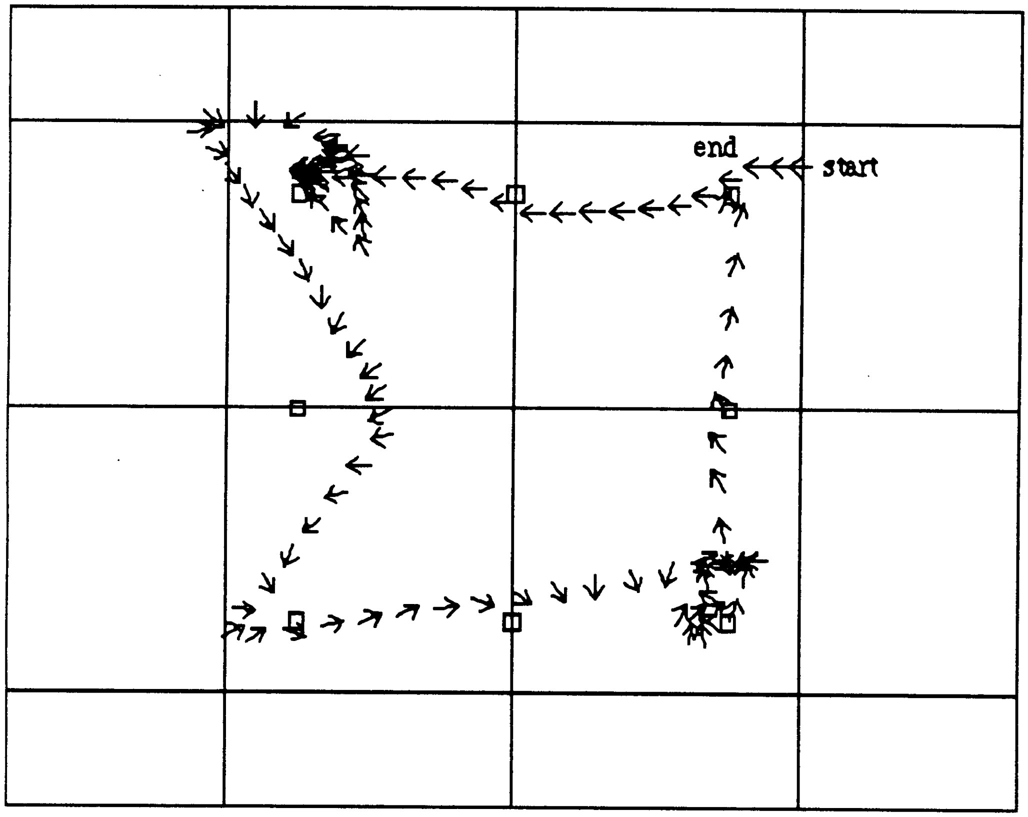

Figure 4.6 - Square of Posts Task, Poor Run

Chapter 5 Conclusion

The data obtained in this experiment consist of observations on how each one of a group of tenuously-related performance metrics was affected by changes in the experimental variables. This chapter generalizes on how the results relate to the original hypothesis. Suggestions for future research are also given based on what was learned in carrying out the current experiment and analyzing the results.

In general, the monitor resulted in the best performance regardless of how performance was measured; whether these differences were significant varied with the individual performance metrics. This is believed to be due to the fact the subjects were highly experienced at observing and interpreting images on a typical monitor or television display, whereas none of the subjects had any previous experience using an HMD. With more experience using an HMD it is possible that subjects could become equally or more adept at controlling a vehicle using that display.

Using the HMD with head-tracking was almost universally worse than using the HMD without tracking. In general, subjects' control over the orientation and velocity was worse with head-tracking active, and when there was a significant difference they took longer to complete the tasks and they applied more total command force. This was probably due to the fact that in humans the sense of head orientation available through proprioceptive feedback from the neck muscles is quite poor. When head-tracking is performed, a poor sense of head orientation leads to difficulty in interpreting how the vehicle is moving through the environment from the motions of objects observed in the visual field. Head-tracking would be expected to provide some benefit -- mainly in being able to quickly locate objects anywhere in the immediate environment by rotating one's head rather than the entire vehicle -- but this benefit seems to have been outweighed by the detrimental effects of the poor sense of head orientation.

According to observations made during the course of the experiment, it seemed that some subjects' performance when using the HMD without head-tracking may have been adversely affected by their experience using the HMD with head-tracking. Several subjects were observed to turn their heads slightly (and one significantly) during runs when using the HMD without head-tracking. Subjects also would sometimes forget, when using the HMD, whether head-tracking was going to be active or not between the time they were told what the next configuration would be and when they started a run. It is conceivable that during runs they would forget whether head-tracking was active or not and either not rotate their heads when head-tracking was available or turn their heads when head-tracking was not being performed. To test this hypothesis it would be interesting to perform an experiment where some subjects were tested on the monitor and HMD-without-head-tracking configurations and others were tested on the monitor and HMD with head-tracking.

The influence that adding the vehicle body representation to the visual scene had on performance, which was the focus of the original hypothesis, is difficult to discern from the experimental results. With all displays (monitor, HMD without head-tracking, HMD with head-tracking) adding the vehicle body image improved the operator's sense of the orientation of the vehicle. Improvement was greatest with the HMD with head-tracking; the HMD-with-head-tracking-without-the-body-image configuration resulted in an average error magnitude several times greater than any other configuration, while using the HMD with head-tracking with the body image displayed was not significantly worse than most other configurations.

Adding the vehicle body representation to the visual scene degraded the operators' ability to precisely control the velocity of the vehicle. This was surprising, as it was previously felt that the body would either make no difference or would improve velocity control. This degradation is believed to have been due to interference of the body image with the subjects' ability to pick up motion cues from the visual scene. The body image and objects in the environment were all drawn as wire-frame objects made up of white lines. Although the body image was brighter than the environment, which was done to allow operators to more easily distinguish between the two, it is possible that when the body image was displayed there were simply too many lines on the screen. This may have confused the subjects and made it more difficult for them to concentrate on observing the motions of the lines making up the environment.

It is not clear whether this effect would carry over from the simulation experiment carried out here to a setup using a real teleoperator, with a synthetic vehicle body image superimposed over a video image of an actual environment. It is possible that in that case the obvious difference between the synthesized body and the real environment would eliminate confusion between the two, so that adding the body image would not interfere with operators' control over vehicle velocity. It would be very useful to perform additional experiments using a simulation setup similar to that used for this experiment, but with the difference between the body image and the environment somehow emphasized -- by drawing the environment using color or solid objects while keeping the body image as a white wire-frame object, for example.

The effects of the different configurations were greatest on the variables that measured specific aspects of the vehicle's interaction with its environment: the velocity and orientation errors and individual post times in the random-posts task and the individual post distances in the square-of-posts task. The other variables -- total distance, time, and commanded force or torque applied in each DOF -- were more generalized, measuring sums of certain factors over entire runs. These more general variables showed fewer significant effects due to display configuration. Also, the specific variables on the random-posts task showed more effects due to display configuration than did that on the square-of-posts task. These facts seem to indicate the display configuration has a greater influence in cases where precise interaction is required between the vehicle and its environment. It is also evident, however, that how the display configuration affects performance depends highly upon what task is performed and what is important in completing the task (how performance is measured).

The single factor that had the more significant effects on the results for both tasks was on which day the data were recorded. The day variable was significant in over half of the performance-metric variables analyzed, and that effect was almost universally a steady improvement in performance over the three days on which the task was performed. Probably the most important piece of information learned in carrying out this experiment was that subjects require a large amount of training to perform teleoperation tasks using a vehicle with such unfamiliar dynamics as those used in this experiment. The data that were collected would have been much less influenced by learning effects, and may have revealed more effects of the experimental variables, if subjects had been given several more practice sessions before data were saved. Based on observations made during the course of the experiment, it appeared that subjects learned the random-posts task fairly quickly -- perhaps one additional practice session would have been sufficient -- but experienced significant learning effects on the square task throughout the experiment, which was perceived as being the more difficult task by most subjects. For the square task, a total of four or five practice sessions would be necessary to ensure that the subjects had reached the peaks of their learning curves.

In general, using the monitor resulted in the best performance, the HMD without head-tracking resulted in the second best, and the HMD with head-tracking gave the worst performance. Adding the image of the vehicle body to the visual scene had positive effects on some aspects of performance, negative on others, and no significant effects on still others. When the HMD with head-tracking was used, adding the vehicle body image greatly improved performance in several cases, so that performance on that display became comparable to performance using the other two displays. The amount of practice that subjects were given was clearly insufficient, and learning effects significantly influenced many of the results.

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Appendix A Statistical Analysis

Statistical analysis was carried out on all dependent variables for the random posts and square-pattern-of-posts tasks. Each variable within each task was analyzed independently, and the results of these separate analyses were combined and interpreted to identify overall trends (see Chapter 4). The Systat ANOVA statistics package, run on a Macintosh computer, was used to carry out the statistical analyses, and Microsoft Excel was used for various tabulation and formatting.

Table A.1 lists the meanings of the variables used in the ANOVAs. The subject, display, track, and body variables are self-explanatory. "Day" refers to the first, second, or third day of each task for each subject: i.e. if a subject did the random posts task the first day, the square task the second day, the square task the third day, etc., the first day would be day one in the random posts task analysis, the second and third days would be days one and two, respectively, in the square task analysis, and so on. The runday parameter represents the run number within the subject's session on a particular day; there were six runs per session.

In the random posts task, the "postnum" is the number of the post by order of encounter: the first post displayed is one, the second is two, and so on. The postang variable, which applies to the random posts task also, refers to the angle between the direction to the current post from the previous post, and the direction to the previous post from the post before it -- this is approximately the angle through which the operator has to turn after hitting one post to line up on the next. The angles represented by the values of postang of one through eight are -180, -135, -90, -45, 0, 45, 90, and 135 degrees respectively. "Sqdir" refers to the direction of travel around the square of columns in the square task -- a value of one indicates left turns around the corners, and a value of two indicates right turns. "Pnum" is the position of each post in the square; see Fig. A.1 for the arrangement of the posts.

Variable	Meaning
subject	Subject number (1-8).
display	Display used (1-monitor, 2-head-mounted display)
track	Head-tracking (1=without tracking, 2=with tracking)
body	Vehicle body (1=without body, 2=body is displayed)
day	Day number, within task (1-3)
runday	Run number within day (1-6)
postnum	(random posts task) Post number, in order of encounter
postang	(random posts task) Post angle
sqdir	(square task) Direction of travel around square
pnum	(square task) Number of post in square

Table A.1 - Independent Variables Used in ANOVAs

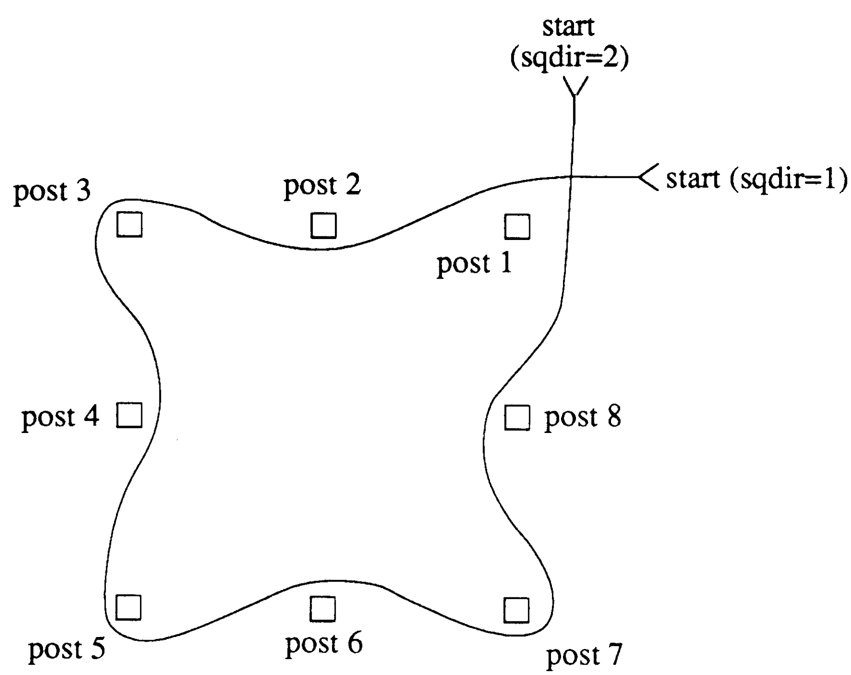

Figure A.1 - Square of Posts Layout

Because it does not make sense to use head-tracking with the monitor, the display and track factors in the ANOVAs are not strictly comparisons of the monitor versus HMD and head-tracking versus no head-tracking, respectively. "Display" compares the monitor without head-tracking on one hand, against the HMD without head-tracking and the HMD with head-tracking on the other hand. Therefore some of the variation in the display factor is actually due to variation between head-tracking and no head-tracking. Similarly, "track" compares the monitor without tracking and the HMD without tracking on one hand, against the HMD with tracking on the other, so the track effect contains some variation due to which display is used. To filter out these cross-effects, all data tabulated by display are compiled for the monitor versus the HMD without tracking, and data tabulated by head-tracking are compiled for the HMD without tracking versus the HMD with tracking.

A.1 Random Posts Task Analysis

The parameters measured for each individual post with which the subjects collided were the velocity error, orientation error, and time to reach the post (see Chapter 4). Parameters measured for each run of eight posts included the total time, distance travelled, and integrated X-axis and Y-axis forces and Z-axis torque commands for the run. The analyses of the velocity and orientation error variables differed slightly from that of the other dependent variables. For each of the other variables, such as the time to reach each post, the distribution of that variable, including all runs and all subjects, has some positive mean and some distribution about that mean. Performance differences between sample groups appear primarily as difference in means, while differences in standard deviations indicate only differences in consistency. The significance of the differences in means is calculated by ANOVA. The velocity and orientation errors can take on positive or negative values, however, and would be expected to have means near zero: subjects should err equally as often to one side as to the other. For these variables it is differences in variance that indicate performance differences; a larger variance (or standard deviation) indicates a greater average magnitude of error. F-tests are used to assess the significance of the differences in variance between groups.

A.1.1 Orientation Error

Table A.2 shows that for orientation error, the overall mean for each subject is small, as expected, and there is a wide range of standard deviations between subjects. Subject six had one standard deviation of 24.42 and an overall standard deviation of 10.77, while subject eight had an overall standard deviation of 3.05. Performance was worst on the HMD with head-tracking configuration for seven of the eight subjects, while performance for the HMD with head-tracking and the vehicle body displayed is closer to that for the first four configurations.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	-1.10	4.56	0.54	4.69	-5.40	6.85	0.03	3.73
monitor+body	-1.07	3.89	-1.15	3.74	-2.44	2.32	-1.47	4.49
HMD	2.57	4.14	1.98	9.38	-2.28	2.96	1.22	3.41
HMD+body	0.85	3.00	1.11	3.85	-1.46	3.14	-0.25	5.15
HMD+track	3.79	4.59	-4.93	16.60	-2.38	6.92	-4.07	12.83
HMD+track+body	2.77	3.71	1.73	2.72	-2.59	2.63	0.81	5.20
all configurations	1.30	4.02	-0.12	8.38	-2.76	4.58	-0.62	6.63

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	4.70	5.50	1.02	4.49	1.56	6.90	2.24	2.51	0.45	5.10
monitor+body	-0.89	7.99	-0.27	4.27	0.28	2.16	0.59	2.81	-0.80	4.32
HMD	3.53	8.40	4.54	3.35	1.95	2.95	2.31	2.99	1.98	5.30
HMD+body	6.17	7.92	2.45	3.89	0.56	3.48	1.20	2.87	1.33	4.45
HMD+track	5.22	12.11	-4.64	24.42	2.26	6.78	3.55	3.78	-0.15	12.81
HMD+track+body	-0.02	10.63	-1.20	5.95	-0.40	5.13	0.96	3.19	0.26	5.48
all configurations	3.12	9.01	0.32	10.77	1.04	4.92	1.81	3.05	0.51	6.91

Table A.2 - Orientation Error (in degrees) by Subject and Configuration

The distribution of orientation errors, including all subjects and configurations, is near-normal, indicating that the orientation error itself, rather than some transformation of the error, is appropriate to use in the ANOVA (Fig. A.2). The ANOVA results are listed in Table A.3. Factors that are significant at the p=.05 level shown in boldface. The subject, display, and track variables and the subject x track interaction are significant.

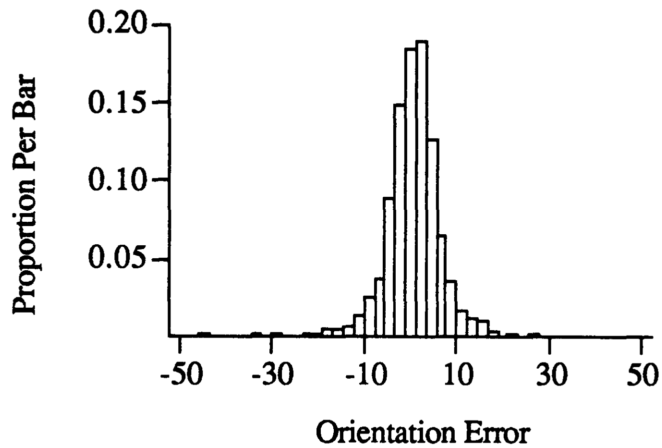

Figure A.2 - Distribution of Orientation Errors (in degrees)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**2186.119**	**7**	**312.303**	**6.421**	**0.000**
Display	**628.215**	**1**	**628.215**	**12.917**	**0.000**
Track	**575.283**	**1**	**575.283**	**11.829**	**0.001**
Body	30.381	1	30.381	0.625	0.429
Day	99.887	2	49.944	1.027	0.358
Runday	239.621	5	47.924	0.985	0.425
Postnum	307.285	7	43.898	0.903	0.504
Postang	419.184	7	59.883	1.231	0.282
Subject*Display	269.459	7	38.494	0.792	0.594
Subject*Track	**873.456**	**7**	**124.779**	**2.566**	**0.013**
Subject*Body	623.984	7	89.141	1.833	0.078
Day*Runday	283.315	10	28.331	0.583	0.829
Display*Body	16.777	1	16.777	0.345	0.557
Track*Body	50.373	1	50.373	1.036	0.309
Error	52865.419	1087	48.634		

Table A.3 - Orientation Error ANOVA

Six of the eight subjects had average orientation errors of larger magnitude with the HMD than with the monitor (Table A.4), seemingly indicating that the HMD induced more directional bias than the monitor. The probability of obtaining this result assuming that the monitor and HMD groups are identical must be evaluated, however, before assigning significance to the result. Assuming the null hypothesis, given eight independent samples (subjects) with a probability of "success" p and a probability of "failure" q, the terms of the following binomial expansion, taken from left to right, represent the probability of eight, seven, six, ... and zero successes respectively:

$$p^8 + 8p^7q + 28p^6q^2 + 56p^5q^3 + 70p^4q^4 + 56p^3q^5 + 28p^2q^6 + 8pq^7 + q^8$$

Assuming that the display has no effect on orientation error, the probability, p, for each sample that the HMD will result in a larger magnitude error for a particular subject is 0.5, as is the probability q that the monitor will cause a larger magnitude error. The probability of at least six of the eight subjects having greater error magnitudes for the HMD than the monitor is:

$$\text{probability} = (0.5)^8 + 8(0.5)^7(0.5) + 28(0.5)^6(0.5)^2 = 0.145$$

Thus, on the null hypothesis, one would expect a trend at least as interesting as the one which occurred 14.5% (about once in seven experiments) of the time -- too frequently to call the result significant. Although the ANOVA indicated that there was a statistically significant difference in means between the HMD and monitor, the difference is not meaningful.

	subject 1		subject 2		subject 3		subject 4			
	mean	stdev	mean	stdev	mean	stdev	mean	stdev		
monitor	-1.08	4.20	-0.30	4.28	-3.92	5.28	-0.72	4.16		
HMD	1.71	3.68	1.54	7.11	-1.87	3.05	0.48	4.39		
both	0.31	3.95	0.62	5.87	-2.90	4.31	-0.12	4.27		
	subject 5		**subject 6**		**subject 7**		**subject 8**		**all subjects**	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	1.91	7.35	0.38	4.38	0.92	5.10	1.42	2.77	-0.18	4.85
HMD	4.85	8.18	3.49	3.74	1.26	3.27	1.75	2.95	1.65	4.91
both	3.38	7.78	1.94	4.07	1.09	4.28	1.58	2.86	0.74	4.88

Table A.4 - Orientation Error (in degrees) by Subject and Display

When all subjects are averaged for the head-tracking and no head-tracking cases, there is significant variability between the cases, as indicated by the ANOVA (Table A.5). Three subjects, however, showed larger magnitude means for no-tracking versus greater means for tracking, and five showed smaller. There was no significant trend across subjects. Only some of the subjects had a large difference in means between tracking and no tracking, accounting for the significance of the subject x track interaction in the ANOVA. These statistically significant differences in means are not meaningful, however, because of the nature of the orientation error variable. Subject six, for example, has a difference in means of 3.49 - (-2.92) = 6.41, which of the same order as his overall standard deviation. But that subject actually erred, on average, 3.49 degrees in one direction without tracking and 2.92 degrees in the opposite direction with tracking; the difference in the magnitudes of the average errors is insignificant. All subjects performed better (as measured by standard deviation) without head-tracking than with it. If head-tracking did not effect orientation error, the probability of this happening would be $p = (0.5)^8 = 0.00391$ (once in 256 experiments), which is statistically significant.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	1.71	3.68	1.54	7.11	-1.87	3.05	0.48	4.39
HMD+track	3.28	4.16	-1.60	12.24	-2.49	5.18	-1.63	9.99
both	2.50	3.93	-0.03	10.01	-2.18	4.25	-0.57	7.72

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	4.85	8.18	3.49	3.74	1.26	3.27	1.75	2.95	1.65	4.91
HMD+track	2.60	11.58	-2.92	17.67	0.93	6.10	2.26	3.70	0.05	9.94
both	3.72	10.03	0.29	12.77	1.09	4.89	2.00	3.35	0.85	7.84

Table A.5 - Orientation Error (in degrees) by Subject and Head-Tracking

Table A.6 lists the results of F-tests performed between pairs of the six different configurations, with a symbol after each F-ratio that points up or left to the group which had the larger variance. The variances being compared were computing using all subjects' data. Using the monitor with the vehicle body resulted in the least variance, and was slightly better than the HMD with the body and significantly better than all other configurations. The HMD with tracking without the vehicle body resulted in the worst performance. For the monitor and HMD with tracking the with-body case had significantly less variance than the without-body case, while for the HMD without tracking adding the vehicle body reduced the variance slightly. Replacing the monitor with the HMD decreased variance when the vehicle body was absent but increased it with the body displayed. With the HMD, adding head-tracking increased variance highly significantly (by more than four times) for the without-body case, but did not significantly increase variance when the body was shown.

	monitor w/o body	monitor with body	HMD w/o body	HMD with body	HMD +tracking w/o body	HMD +tracking with body
monitor w/o body	1 p=1					
monitor with body	**1.729 ^ p<0.005**	1 p=1				
HMD w/o body	1.063 ^ p>0.1	**1.623 < p<0.005**	1 p=1			
HMD with body	**1.381 ^ p<0.05**	1.252 < p>0.1	1.299 ^ p<0.1	1 p=1		
HMD+tracking w/o body	**5.349 < p<0.001**	**9.249 < p<0.001**	**5.685 < p<0.001**	**7.385 < p<0.001**	1 p=1	
HMD+tracking with body	1.036 ^ p>0.1	**1.669 < p<0.005**	1.026 < p>0.1	1.333 < p<0.1	**5.540 ^ p<0.001**	1 p=1

Table A.6 - Orientation Error: F-Tests Between Configurations'

A.1.2 Velocity Error

Examining statistics for the velocity error, broken down by subject and configuration, reveals that most of the means are small in magnitude and fairly evenly-distributed in sign for each subject (Table A.7). The configurations which resulted in the worst performance for each subject are distributed among the four configurations using the HMD, while seven of the eight subjects performed the best using the monitor, either with or without the vehicle body.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	1.27	6.80	0.75	4.93	-0.77	3.64	-3.25	6.00
monitor+body	0.52	4.02	-0.22	4.03	-0.29	2.86	-1.21	4.09
HMD	-0.66	8.99	-1.25	5.01	-1.26	4.17	-0.62	5.13
HMD+body	-0.31	4.38	0.52	5.05	-0.46	3.09	-3.25	12.92
HMD+track	0.24	7.27	-0.68	4.23	-0.15	6.33	-2.42	5.01
HMD+track+body	-2.46	5.68	0.64	6.03	0.02	4.25	0.82	7.77
all configurations	-0.23	6.42	-0.04	4.92	-0.49	4.21	-1.66	7.43

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	7.44	6.46	0.51	6.00	2.16	4.89	1.15	2.44	1.16	5.33
monitor+body	-0.61	11.51	-1.58	8.48	-1.63	7.51	-1.70	2.51	-0.84	6.37
HMD	1.03	11.89	-1.92	5.64	0.06	5.11	1.67	3.58	-0.37	6.73
HMD+body	6.62	13.45	-0.69	7.70	-1.25	5.19	0.53	4.40	0.21	7.97
HMD+track	6.52	12.73	3.73	14.84	2.73	14.57	0.90	2.84	1.36	9.61
HMD+track+body	2.20	14.54	5.83	14.71	-3.55	12.11	0.41	4.96	0.49	9.66
all configurations	3.87	12.04	0.98	10.29	-0.25	9.06	0.49	3.58	0.34	7.78

Table A.7 - Velocity Error (in degrees) by Subject and Configuration

The distribution of velocity errors for all subjects and configurations is very close to normal (Fig. A.3), and Table A.8 gives the ANOVA results. The subject and body parameters and the display x body interaction were statistically significant.

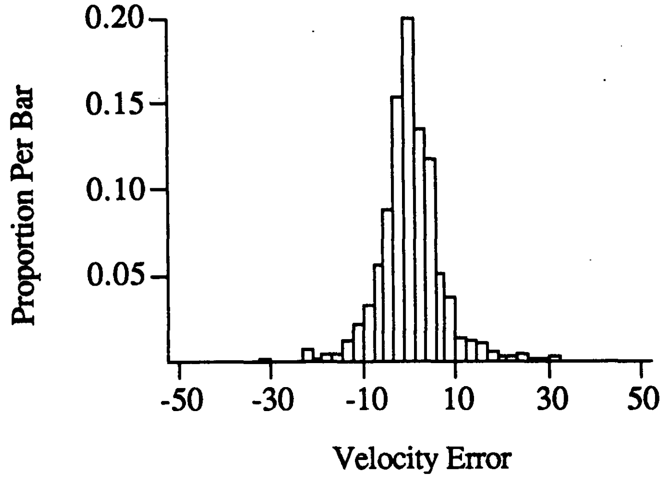

Figure A.3 - Distribution of Velocity Errors (in degrees)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**1507.830**	**7**	**215.404**	**3.533**	**0.001**
Display	18.992	1	18.992	0.311	0.577
Track	82.439	1	82.439	1.352	0.245
Body	**460.753**	**1**	**460.753**	**7.556**	**0.006**
Day	189.710	2	94.855	1.556	0.212
Runday	370.354	5	74.071	1.215	0.300
Postnum	309.829	7	44.261	0.726	0.650
Postang	328.577	7	46.940	0.770	0.613
Subject*Display	347.454	7	49.636	0.814	0.576
Subject*Track	374.415	7	53.488	0.877	0.524
Subject*Body	791.419	7	113.060	1.854	0.074
Day*Runday	905.823	10	90.582	1.486	0.139
Display*Body	**389.431**	**1**	**389.431**	**6.387**	**0.012**
Track*Body	104.530	1	104.530	1.714	0.191
Error	66280.623	1087	60.976		

Table A.8 - Velocity Error ANOVA

Table A.9 lists the velocity-error statistics grouped by the with- and without-body cases (each of which includes the monitor, the HMD with-, and the HMD without-head-tracking display cases). Despite the fact that the ANOVA indicated the body variable to be significant, the vehicle body had no effect on the means that was consistent across subjects. There was also no trend in standard deviations due to the body: three subjects had a larger standard deviation without the body and five without, and the difference in standard deviations averaged over all subjects was small.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
without body	0.28	7.68	-0.39	4.75	-0.73	4.81	-2.10	5.44
with body	-0.75	4.85	0.31	5.04	-0.24	3.41	-1.21	9.05
both	-0.23	6.42	-0.04	4.90	-0.48	4.17	-1.66	7.46

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
without body	4.99	10.95	0.77	9.94	1.65	9.29	1.24	2.97	0.72	7.48
with body	2.74	13.38	1.19	11.12	-2.14	8.69	-0.25	4.16	-0.05	8.20
both	3.87	12.22	0.98	10.55	-0.25	8.99	0.49	3.61	0.33	7.85

Table A.9 - Velocity Error (in degrees) by Subject and Body

Table A.10 shows that displaying the vehicle body made a much larger difference in mean error for the monitor than for the HMD. As before, however, the difference in means was due not to a large difference in the magnitude of the mean but to a change in sign, and is therefore not of interest.

	monitor		HMD	
	mean	stdev	mean	stdev
without body	1.16	5.95	-0.37	6.70
with body	-0.84	6.30	0.21	8.26

Table A.10 - Velocity Error (in degrees) by Display and Body

Table A.11 presents F-tests on velocity error between configurations and includes data for all subjects. The monitor without the vehicle body configuration had the best overall performance, while the HMD with head-tracking and the body resulted in the worst performance. For the monitor and HMD with tracking, adding the body reduced performance slightly. For the HMD without tracking, adding the body significantly worsened performance. In changing the display from the monitor to the HMD, performance was reduced both with and without the body, significantly so in the former case. With the HMD, adding head-tracking significantly worsened performance for both the with- and without-body cases.

	monitor w/o body	monitor with body	HMD w/o body	HMD with body	HMD +tracking w/o body	HMD +tracking with body
monitor w/o body	1 p=1					
monitor with body	1.118 < p>0.1	1 p=1				
HMD w/o body	1.267 < p<0.1	1.133 < p>0.1	1 p=1			
HMD with body	1.926 < p<0.001	1.723 < p<0.005	1.521 < p<0.025	1 p=1		
HMD+tracking w/o body	2.708 < p<0.001	2.422 < p<0.001	2.138 < p<0.001	1.406 < p<0.05	1 p=1	
HMD+tracking with body	2.736 < p<0.001	2.447 < p<0.001	2.160 < p<0.001	1.420 < p<0.05	1.010 < p>0.1	1 p=1

Table A.11 - Velocity Error: F-Tests Between Configurations

A.1.3 Individual Post Times

There is a very wide range between subjects in the average time to reach each post: from nineteen seconds to nearly forty seconds (Table A.12). Taking all subjects, the configurations which had the largest time for each subject are spread among the first five configurations; the HMD with head-tracking and the vehicle body did not result in the largest mean time for any subject.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	25.35	12.16	32.71	12.47	32.71	14.21	32.04	13.57
monitor+body	28.77	13.78	33.87	13.72	32.37	14.12	33.34	12.67
HMD	31.67	18.49	31.70	12.69	37.04	12.78	33.48	16.77
HMD+body	29.59	13.09	32.02	9.67	42.30	17.85	41.53	18.87
HMD+track	46.08	30.56	40.02	16.19	51.78	21.40	34.76	16.09
HMD+track+body	38.32	21.29	36.51	15.99	43.58	17.68	34.77	18.81
all configurations	33.29	19.31	34.47	13.64	39.96	16.60	34.99	16.30

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	18.07	6.61	25.51	10.75	20.42	7.48	28.02	9.71	26.85	11.17
monitor+body	19.14	6.94	36.04	16.66	17.77	5.61	28.04	12.59	28.67	12.52
HMD	23.37	5.92	31.45	12.07	17.96	6.85	28.61	9.86	29.41	12.61
HMD+body	22.34	6.36	30.50	17.89	18.74	7.34	30.95	6.27	31.00	13.20
HMD+track	19.95	7.98	32.43	21.01	20.12	7.65	30.83	11.79	34.49	18.08
HMD+track+body	20.58	8.98	23.45	13.18	19.66	6.45	31.68	9.33	31.07	14.82
all configurations	20.57	7.21	29.90	15.67	19.11	6.93	29.69	10.13	30.25	13.91

Table A.12 - Post Time (in seconds) by Subject and Configuration

The time to reach each post is nearly normally-distributed (Fig. A.4), and so is an appropriate variable to use in the statistical analysis. In order to speed computation time, two ANOVAs were performed on the post times with some different factors included in each (Tables A.13, A.14). The first ANOVA included all relevant independent variables as factors plus first-order interactions involving the subject and body variables and the day x runday interaction. The second ANOVA, which was a refinement of the first, tested all factors indicated as significant in the first ANOVA plus first-order interactions involving the post-angle variable. The second ANOVA shows the subject, display, track, day, post number, and post-angle variables and the subject x track and track x body interactions to all be highly significant.

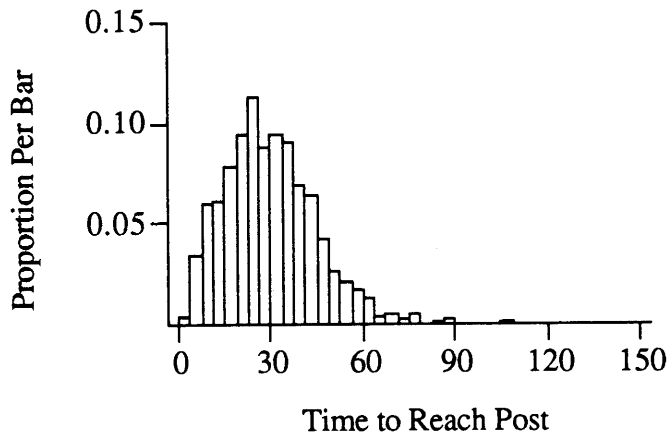

Figure A.4 - Distribution of Post Times (in seconds)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**35257.293**	**7**	**5036.756**	**35.247**	**0.000**
Display	**1083.391**	**1**	**1083.391**	**7.582**	**0.006**
Track	**1227.815**	**1**	**1227.815**	**8.592**	**0.003**
Body	97.425	1	97.425	0.682	0.409
Day	**8171.887**	**2**	**4085.944**	**28.593**	**0.000**
Runday	545.556	5	109.111	0.764	0.576
Postnum	**6696.459**	**7**	**956.637**	**6.695**	**0.000**
Postang	**40457.483**	**7**	**5779.640**	**40.446**	**0.000**
Subject*Display	1106.726	7	158.104	1.106	0.357
Subject*Track	**3963.157**	**7**	**566.165**	**3.962**	**0.000**
Subject*Body	874.858	7	124.980	0.875	0.526
Day*Runday	2093.110	10	209.311	1.465	0.147
Display*Body	0.535	1	0.535	0.004	0.951
Track*Body	**1195.758**	**1**	**1195.758**	**8.368**	**0.004**
Error	153615.608	1075	142.898		

Table A.13 - Post Time ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**53264.672**	**7**	**7609.239**	**53.001**	**0.000**
Display	**1130.404**	**1**	**1130.404**	**7.874**	**0.005**
Track	**1268.939**	**1**	**1268.939**	**8.839**	**0.003**
Day	**8230.346**	**2**	**4115.173**	**28.664**	**0.000**
Postnum	**6696.534**	**7**	**956.648**	**6.663**	**0.000**
Postang	**28862.011**	**7**	**4123.144**	**28.719**	**0.000**
Subject*Track	**7387.292**	**7**	**1055.327**	**7.351**	**0.000**
Track*Body	**1446.806**	**1**	**1446.806**	**10.078**	**0.002**
Postang*Display	472.073	7	67.439	0.470	0.857
Postang*Track	1244.741	7	177.820	1.239	0.278
Postang*Body	54.371	7	7.767	0.054	1.000
Error	155770.209	1085	143.567		

Table A.14 - Post Time Revised ANOVA

Averaging over all subjects, it took approximately ten percent longer to reach each post with the HMD than with the monitor (Table A.15). Six subjects took longer with the HMD, while two took longer with the monitor. Although the ANOVA indicated that the display was highly statistically significant in its effect on the post times, the effects on each subject, as well as all subjects averaged together, are not large enough in practical terms to be important.

	subject 1 mean	subject 1 stdev	subject 2 mean	subject 2 stdev	subject 3 mean	subject 3 stdev	subject 4 mean	subject 4 stdev
monitor	27.06	12.97	33.29	12.98	32.54	14.02	32.69	13.00
HMD	30.63	15.88	31.86	11.16	39.67	15.58	37.33	18.07
both	28.84	14.50	32.57	12.11	36.11	14.82	35.01	15.74

	subject 5 mean	subject 5 stdev	subject 6 mean	subject 6 stdev	subject 7 mean	subject 7 stdev	subject 8 mean	subject 8 stdev	all subjects mean	all subjects stdev
monitor	18.60	6.73	30.55	14.73	19.04	6.63	28.03	11.12	27.72	11.90
HMD	22.83	6.10	30.97	15.11	18.35	7.04	29.78	8.26	30.18	12.89
both	20.72	6.42	30.76	14.92	18.69	6.84	28.91	9.79	28.95	12.40

Table A.15 - Post Time (in seconds) by Subject and Display

Grouping the data by the presence of absence of head-tracking yields a table that looks very similar to Table A.15 above (Table A.16). The first three subjects took much longer to reach each post with tracking than without it, but the differences in means between the two cases for the rest of the subjects are small enough to be of no practical significance. The overall mean is less than ten percent greater for the tracking case than the no-tracking case. Head-tracking had a significant effect according to the ANOVA, but that effect turned out to be insubstantial.

	subject 1 mean	subject 1 stdev	subject 2 mean	subject 2 stdev	subject 3 mean	subject 3 stdev	subject 4 mean	subject 4 stdev
HMD	30.63	15.88	31.86	11.16	39.67	15.58	37.33	18.07
HMD+track	42.20	26.35	38.34	16.01	47.50	19.76	34.77	17.31
both	36.41	21.75	35.10	13.80	43.59	17.80	36.05	17.69

	subject 5 mean	subject 5 stdev	subject 6 mean	subject 6 stdev	subject 7 mean	subject 7 stdev	subject 8 mean	subject 8 stdev	all subjects mean	all subjects stdev
HMD	22.83	6.10	30.97	15.11	18.35	7.04	29.78	8.26	30.18	12.89
HMD+track	20.26	8.41	27.94	17.93	19.89	7.00	31.25	10.53	32.77	16.56
both	21.55	7.35	29.46	16.58	19.12	7.02	30.52	9.46	31.47	14.84

Table A.16 - Post Time (in seconds) by Subject and Head-Tracking

Six of the individual subjects, as well as all subjects grouped together, had mean post times that were strictly-decreasing over the three days on which the random posts task was performed (Table A.17, Figure A.5). From the first day to the last the overall mean decreased by almost twenty percent. Given the highly-significant effect of the day variable listed in the ANOVA, we conclude that the trend of decreasing means over the days is meaningful and important.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
day 1	32.68	19.37	38.52	15.90	38.21	15.49	39.78	16.76
day 2	38.00	25.03	34.95	11.49	45.19	19.96	33.29	15.76
day 3	29.21	14.17	29.65	11.96	35.83	15.80	31.47	15.31
all days	33.29	20.02	34.37	13.27	39.74	17.21	34.85	15.95

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
day 1	23.51	7.81	35.99	20.72	22.20	6.82	31.86	10.39	32.84	14.98
day 2	19.83	6.82	30.53	12.85	17.81	6.25	30.03	9.50	31.20	14.77
day 3	18.17	6.32	22.61	9.02	17.19	6.56	27.18	9.92	26.41	11.68
all days	20.50	7.01	29.71	15.01	19.07	6.55	29.69	9.94	30.15	13.89

Table A.17 - Post Time (in seconds) by Subject and Day

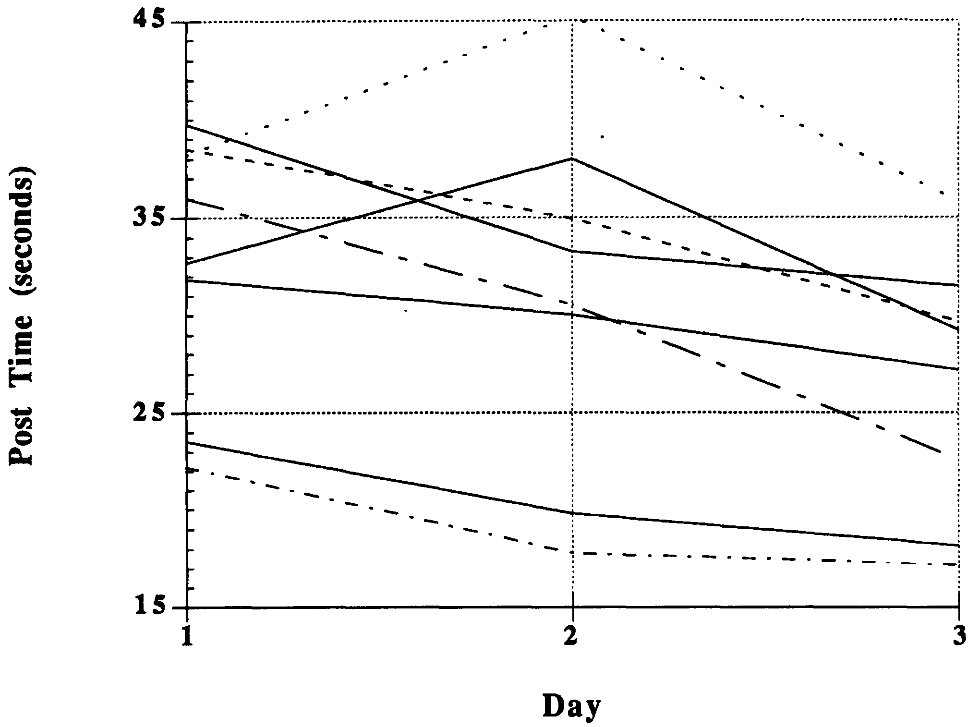

Figure A.5 - Post Time (in seconds) by Day for all Subjects

The ANOVA on post times indicated that the post number and post angle had highly-significant effects on post times. Arranging the data by post number (Table A.18) and graphing the mean post times for each subject by post number (Fig. A.6) reveals the trend that was detected by the ANOVA. The subjects generally had a relatively short time for the first post, larger times for the second through fifth posts, and shorter times for the last three. Examining the data grouped by the post-angle variable (Table A.19, Fig. A.7) shows a trend as well: having the next post directly ahead resulted in the least time to reach the post, and the more the subject had to turn the vehicle to get to the next post the longer it took to reach that post. Also, most subjects showed a directional bias: that is, they reached posts with a particular magnitude of angle in one direction faster than when they had to turn through the same angle in the opposite direction.

	subject 1		subject 2		subject 3		subject 4	
	mean	**stdev**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
post #1	22.75	8.56	27.47	7.96	39.37	15.12	26.78	8.39
post #2	33.86	15.80	39.77	17.83	39.88	17.49	40.52	17.24
post #3	38.14	21.81	33.56	11.72	43.89	20.87	40.41	15.01
post #4	34.89	28.86	37.11	13.49	44.31	17.15	37.13	18.10
post #5	36.71	18.82	35.87	12.32	40.86	12.88	44.49	16.18
post #6	30.78	23.61	30.35	13.71	37.57	23.45	29.13	16.81
post #7	38.52	18.02	38.18	15.77	34.70	16.21	33.69	15.29
post #8	30.70	19.15	33.08	12.57	37.73	16.73	27.21	13.92
all posts	33.29	20.11	34.42	13.45	39.79	17.76	34.92	15.38

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	**stdev**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
post #1	19.44	5.71	25.84	14.39	17.06	5.68	23.47	7.49	25.27	9.77
post #2	22.89	5.33	36.36	16.64	21.67	6.43	30.14	9.27	33.14	14.16
post #3	20.32	8.58	33.13	15.46	20.66	7.49	34.31	12.04	33.05	14.95
post #4	22.39	5.44	33.01	14.17	18.97	6.33	31.88	12.04	32.46	16.01
post #5	20.64	7.29	31.30	21.66	20.17	8.19	30.01	7.34	32.51	14.04
post #6	18.45	8.21	31.54	16.12	17.01	6.00	26.04	10.62	27.61	16.02
post #7	18.54	7.14	20.92	12.34	19.11	7.64	29.88	9.92	29.19	13.37
post #8	21.51	9.77	26.56	12.74	18.04	6.82	31.78	8.18	28.33	13.08
all posts	20.52	7.34	29.83	15.68	19.09	6.87	29.69	9.77	30.19	14.05

Table A.18 - Post Time (in seconds) by Subject and Post Number

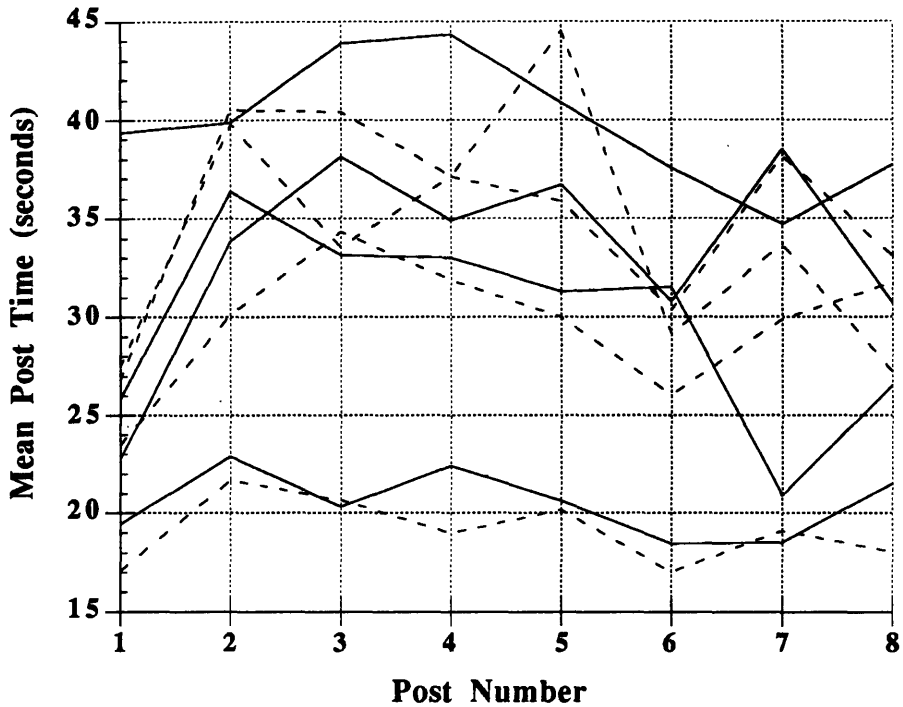

Figure A.6 - Post Time (in seconds) versus Post Number for All Subjects

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
angle = -180°	39.10	12.72	45.49	18.49	47.29	18.65	45.19	10.05
angle = -135°	47.17	29.38	39.29	7.86	49.96	14.66	45.43	12.80
angle = -90°	36.17	14.71	33.20	10.23	42.57	12.02	36.62	11.23
angle = -45°	29.51	14.23	33.04	15.15	36.92	21.81	23.07	14.22
angle = 0°	22.12	25.68	22.10	10.60	21.61	13.20	19.62	11.45
angle = 45°	24.66	13.75	30.18	11.89	37.44	11.49	29.18	20.68
angle = 90°	34.54	21.32	35.37	11.77	41.37	16.81	40.12	12.11
angle = 135°	33.10	14.55	36.67	9.77	41.19	16.26	39.90	14.53
all angles	33.29	19.23	34.42	12.38	39.79	15.95	34.89	13.74

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
angle = -180°	24.43	4.57	36.64	13.62	24.12	4.71	35.87	10.90	37.27	12.75
angle = -135°	23.13	5.13	36.24	10.55	22.88	4.64	35.40	6.32	37.44	13.71
angle = -90°	22.14	6.36	30.87	10.14	20.12	5.27	33.14	5.95	31.85	9.99
angle = -45°	17.64	7.97	14.53	7.71	15.36	8.60	25.00	6.79	24.38	13.00
angle = 0°	13.60	8.18	15.38	9.81	11.98	6.02	22.32	12.20	18.59	13.35
angle = 45°	18.19	6.62	34.21	21.65	15.83	4.97	24.83	12.13	26.81	14.03
angle = 90°	22.39	7.71	37.07	14.53	22.77	4.71	30.86	6.13	33.06	13.00
angle = 135°	22.73	5.43	34.20	16.11	19.72	5.52	30.09	9.10	32.20	12.17
all angles	20.53	6.62	29.89	13.67	19.10	5.69	29.69	9.06	30.20	12.80

Table A.19 - Post Time (in seconds) by Subject and Post Angle

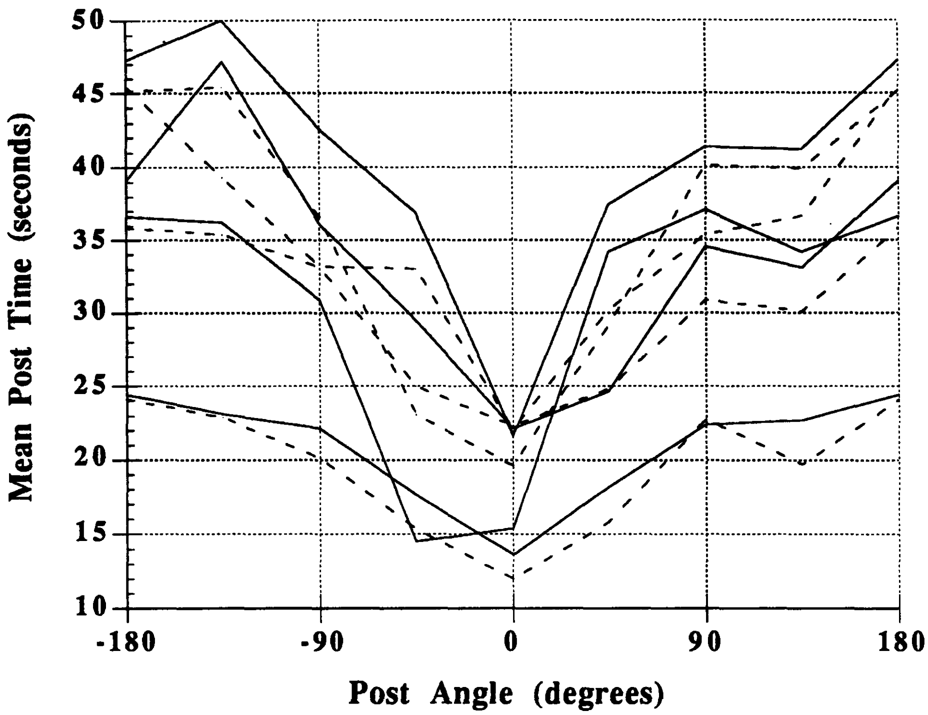

Figure A.7 - Post Time (in seconds) by Post Angle

Lastly, the track x body interaction is examined (Table A.20). When the vehicle body was absent, adding head-tracking significantly increased both the mean and standard deviation of the times to reach each post. When the vehicle body was displayed, however, the mean increased only very slightly and the standard deviation slightly increased when head-tracking was added.

	HMD		HMD+track	
	mean	stdev	mean	stdev
without body	29.47	13.67	34.31	20.60
with body	30.89	14.96	31.01	16.76

Table A.20 - Post Time (in seconds) by Head-Tracking and Body

A.1.4 Total Distance Travelled

The mean total distances traveled per run were in the 250 to 350 meter range for all subjects except subject one; subject number one's mean was more than twice that of the subject with the next highest mean (Table A.21). Subject one's standard deviations were also significantly larger than those of any other subject. There are differences between the means, averaged over all subjects, for the different configurations, but it is not immediately clear whether these differences are statistically significant. For the HMD both with and without head-tracking, the overall standard deviation is much larger with the vehicle body absent than with it displayed. F-tests performed on these data showed that the body reduced the variance of the completion times by a statistically significant amount for the HMD both with and without head-tracking (Table A.22).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	457.1	197.1	202.9	20.8	273.6	47.3	295.3	37.5
monitor+body	546.6	283.3	234.1	22.7	254.8	46.7	287.4	2.9
HMD	901.1	447.6	237.9	39.1	247.6	73.2	352.8	53.9
HMD+body	596.6	159.9	200.2	26.8	250.2	32.1	520.5	202.6
HMD+track	1226.	983.5	356.6	67.5	296.0	75.3	326.4	110.6
HMD+track+body	810.1	129.6	300.9	87.9	236.3	44.6	309.3	22.0
all configurations	756.2	470.6	255.4	50.8	259.8	55.5	348.6	98.4

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	257.0	17.2	260.5	31.3	295.6	91.9	284.5	72.1	290.8	85.0
monitor+body	330.8	53.2	372.7	88.5	242.9	10.2	327.7	28.2	324.6	108.7
HMD	404.7	109.8	273.6	61.0	240.0	24.0	363.0	157.3	377.6	177.2
HMD+body	359.7	100.4	290.5	148.3	294.6	48.7	243.5	24.5	344.5	113.7
HMD+track	282.4	18.2	496.4	472.8	252.8	34.5	425.7	139.4	457.8	392.8
HMD+track+body	356.8	75.7	308.8	118.7	270.8	20.9	466.0	230.9	382.4	112.1
all configurations	331.9	72.2	333.8	213.0	266.1	46.8	351.7	131.7	362.9	195.9

Table A.21 - Total Distance (in meters) by Subject and Configuration

	mean	variance	F	p
monitor	290.81	9964.52		
monitor+body	324.63	17712.96	1.78	p<0.1
HMD	377.59	66422.88	2.44	p<0.025
HMD+body	344.48	27264.56		
HMD+track	457.76	201098.80	4.99	p<0.001
HMD+track+body	382.37	40283.30		

Table A.22 - Total Distance: F-Tests by Body

The distribution of total distances has a grouping that looks nearly normally-distributed centered around 300 meters, plus a number of outliers at much larger distances (Fig. A.8). It turns out that most of the outliers were points from the data of subject number one, and removing that subject's data results in a more normal distribution (Fig. A.9).

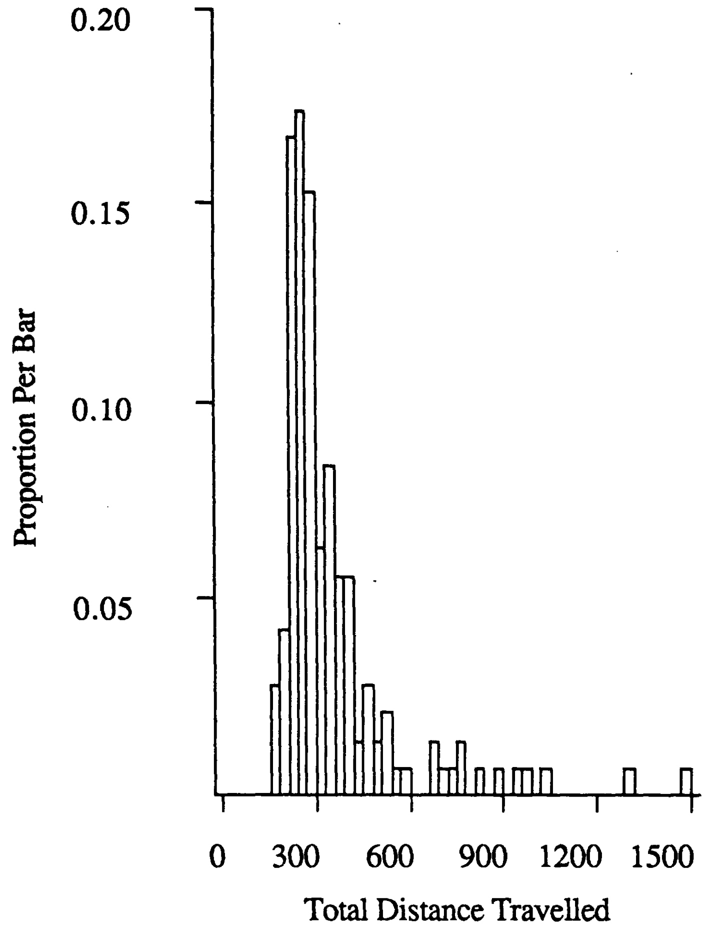

Figure A.8 - Distribution of Total Distances (in meters) for all Subjects

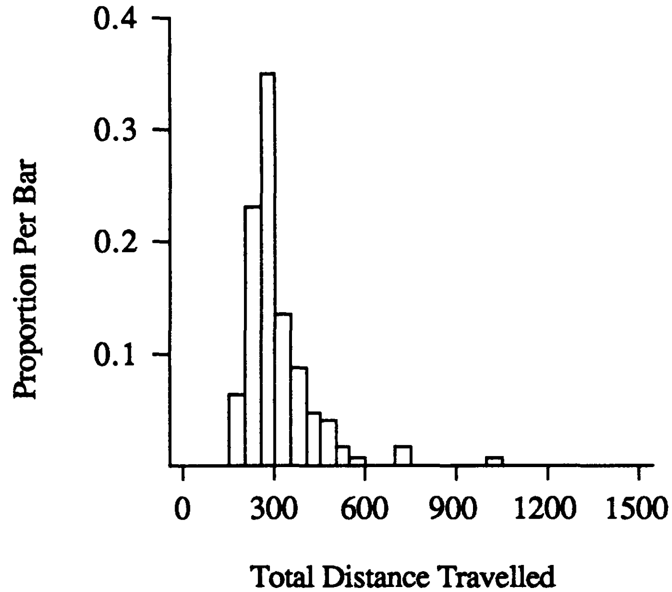

Figure A.9 - Distribution of Total Distances (in meters) for Subjects 2-8

An ANOVA performed on the data for subjects two through eight indicated that only the day variable and subject x track interaction were significant (Table A.23). Because the total distance variable was only sampled once per run, rather than eight times per run as the previous three variables analyzed were, the number of DOF which make up the error term is much lower than for those previous variables. For each variable which was only sampled once per run, a second ANOVA was performed, removing all factors which had p>.20 in the first ANOVA. This was done to get a better estimate of the residual mean-square. In the case of total distance, the second ANOVA showed only the subject and day variables to be significant (Table A.24).

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	133907.672	6	22317.945	1.916	0.088
Display	17204.044	1	17204.044	1.477	0.228
Track	18972.754	1	18972.754	1.629	0.206
Body	894.764	1	894.764	0.077	0.782
Day	**177634.267**	**2**	**88817.133**	**7.624**	**0.001**
Runday	13026.409	5	2605.282	0.224	0.951
Subject*Display	80382.413	6	13397.069	1.150	0.342
Subject*Track	**169410.714**	**6**	**28235.119**	**2.424**	**0.033**
Subject*Body	9597.001	6	1599.500	0.137	0.991
Day*Runday	61564.292	10	6156.429	0.528	0.865
Display*Body	963.352	1	963.352	0.083	0.774
Track*Body	7539.810	1	7539.810	0.647	0.424
Error	920316.267	79	11649.573		

Table A.23 - Total Distance ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**205640.481**	**6**	**34273.413**	**3.246**	**0.006**
Day	**177634.267**	**2**	**88817.133**	**8.411**	**0.000**
Subject*Track	132158.829	6	22026.471	2.086	0.060
Error	1172098.006	111	10559.441		

Table A.24 - Total Distance Revised ANOVA

Most subjects had significantly greater total distances for the first day than for the second or third days (Table A.25, Fig. A.10). With all subjects taken together, there is a slight decrease from days one to two and days two to three. With subject one's data removed, however, there is a large decrease in both the mean and standard deviation after the first day.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
day 1	595.2	204.6	238.2	39.4	306.5	50.0	415.6	174.2
day 2	938.9	740.5	228.5	65.9	242.6	25.9	303.7	27.9
day 3	734.6	334.3	299.6	89.7	230.2	39.7	326.6	81.5
all days	756.2	483.7	255.4	68.2	259.8	39.8	348.6	112.2

	subject 5		subject 6		subject 7		subject 8	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
day 1	388.2	97.0	473.3	287.1	267.4	47.7	429.8	164.2
day 2	298.9	39.8	285.0	51.9	255.1	27.0	341.5	143.7
day 3	308.7	68.2	243.0	106.2	275.9	62.0	283.9	48.5
all days	331.9	72.2	333.8	179.3	266.1	47.8	351.7	129.0

	subj.s 2-8		all subjects	
	mean	stdev	mean	stdev
day 1	359.8	149.0	389.3	157.1
day 2	279.3	67.0	361.8	269.2
day 3	281.1	74.1	337.8	137.0
all days	306.8	103.6	362.9	196.6

Table A.25 - Total Distance (in meters) by Subject and Day

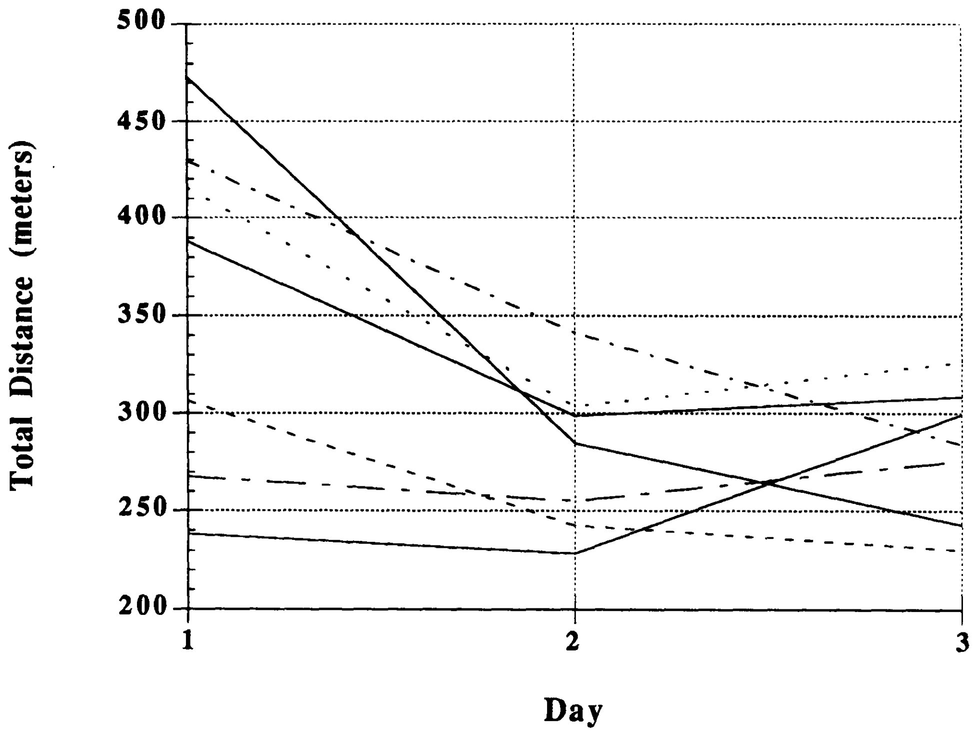

Figure A.10 - Total Distance (in meters) by Day for Subjects Two through Eight

A.1.5 Total Time

Looking at the total time taken per run, broken down by subject and configuration, reveals no obvious trends (Table A.26). Figure A.11 shows the distribution of run times. Both ANOVAs show the subject, display, track, and day variables and the subject x track and track x body interactions to be significant (Tables A.27, A.28).

	subject 1 mean	subject 1 stdev	subject 2 mean	subject 2 stdev	subject 3 mean	subject 3 stdev	subject 4 mean	subject 4 stdev
monitor	202.8	22.9	261.6	61.5	261.7	30.7	256.3	44.7
monitor+body	230.1	48.1	270.9	34.1	259.0	64.3	266.7	29.6
HMD	253.3	68.9	253.6	45.9	296.3	8.3	267.8	22.4
HMD+body	236.7	46.1	256.1	4.3	338.4	92.1	331.8	94.0
HMD+track	368.6	165.3	320.2	32.8	421.5	87.8	278.1	87.1
HMD+track+body	306.6	24.5	291.9	43.1	348.7	35.4	278.1	53.7
all configurations	266.3	79.2	275.7	40.8	320.9	61.4	279.8	61.5

	subject 5 mean	subject 5 stdev	subject 6 mean	subject 6 stdev	subject 7 mean	subject 7 stdev	subject 8 mean	subject 8 stdev	all subjects mean	all subjects stdev
monitor	144.5	14.1	204.1	38.6	165.9	35.9	224.2	40.6	215.1	38.5
monitor+body	153.2	23.0	284.9	59.8	142.1	18.2	224.3	5.9	228.9	40.2
HMD	184.7	31.6	251.6	38.7	143.6	18.1	228.9	29.3	235.0	37.3
HMD+body	178.7	33.3	244.0	68.7	149.9	31.3	247.6	3.4	247.9	57.3
HMD+track	159.6	32.3	259.4	101.3	161.0	23.4	246.6	17.7	276.9	83.6
HMD+track+body	164.6	19.1	187.6	63.7	157.2	10.2	253.4	27.8	248.5	38.6
all configurations	164.2	26.6	238.6	65.3	153.3	24.4	237.5	24.6	242.0	52.0

Table A.26 - Total Time (in seconds) by Subject and Configuration

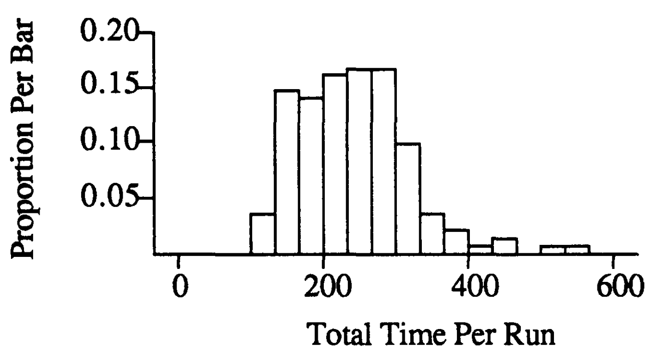

Figure A.11 - Distribution of Total Times (in seconds)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**286142.768**	**7**	**40877.538**	**18.837**	**0.000**
Display	**8634.248**	**1**	**8634.248**	**3.979**	**0.049**
Track	**10674.852**	**1**	**10674.852**	**4.919**	**0.029**
Body	959.527	1	959.527	0.442	0.508
Day	**61609.202**	**2**	**30804.601**	**14.196**	**0.000**
Runday	4369.286	5	873.857	0.403	0.846
Subject*Display	9657.931	7	1379.704	0.636	0.725
Subject*Track	**33129.298**	**7**	**4732.757**	**2.181**	**0.043**
Subject*Body	7674.720	7	1096.389	0.505	0.828
Day*Runday	16644.498	10	1664.450	0.767	0.660
Display*Body	3.969	1	3.969	0.002	0.966
Track*Body	**10088.101**	**1**	**10088.101**	**4.649**	**0.034**
Error	201811.117	93	2170.012		

Table A.27 - Total Time ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**439691.677**	**7**	**62813.097**	**32.030**	**0.000**
Display	**9067.594**	**1**	**9067.594**	**4.624**	**0.033**
Track	**10818.383**	**1**	**10818.383**	**5.517**	**0.020**
Day	**61609.202**	**2**	**30804.601**	**15.708**	**0.000**
Subject*Track	**64146.493**	**7**	**9163.785**	**4.673**	**0.000**
Track*Body	**12112.837**	**1**	**12112.837**	**6.177**	**0.014**
Error	243173.833	124	1961.079		

Table A.28 - Total Time Revised ANOVA

Six of the subjects had longer run times with the HMD than with the monitor (Table A.29). The mean over all subjects was ten percent larger and the standard deviation was slightly larger for the HMD than the monitor. Although only five subjects took longer with the HMD with head-tracking than without, the mean time with head-tracking was nearly ten percent greater and the standard deviation was about 25 percent greater (Table A.30). The fact that although three subjects took significantly longer with tracking, two took only slightly longer and three took less time with tracking, accounts for the significance of the subject x track interaction in the ANOVA.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	216.4	36.9	266.3	44.8	260.3	45.1	261.5	34.4
HMD	245.0	53.2	254.9	29.2	317.4	62.9	299.8	70.4
both	230.7	45.8	260.6	37.8	288.8	54.7	280.7	55.4

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	148.8	17.7	244.5	63.1	154.0	28.6	224.3	26.0	222.0	39.4
HMD	181.7	29.2	247.8	50.1	146.8	23.1	238.3	21.3	241.5	46.1
both	165.3	24.2	246.1	57.0	150.4	26.0	231.3	23.7	231.7	42.9

Table A.29 - Total Time (in seconds) by Subject and Display

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	245.0	53.2	254.9	29.2	317.4	62.9	299.8	70.4
HMD+track	337.6	111.0	306.0	37.6	385.1	71.9	278.1	64.7
both	291.3	87.1	280.5	33.6	351.2	67.6	289.0	67.6

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	181.7	29.2	247.8	50.1	146.8	23.1	238.3	21.3	241.5	46.1
HMD+track	162.1	23.9	223.5	85.3	159.1	16.3	250.0	21.2	262.7	63.0
both	171.9	26.7	235.6	69.9	152.9	20.0	244.1	21.2	252.1	55.2

Table A.30 - Total Time (in seconds) by Subject and Head-Tracking

Six subjects had run times which were strictly-decreasing over the three days on which the random task was performed (Table A.31, Fig. A.12). Assuming the null hypothesis, the chances of finding six or more subjects with strictly-decreasing means over the three days would be:

$$p = \text{probability} = (1/6)^8 + 8(1/6)^7(5/6) + 28(1/6)^6(5/6)^2 = 0.000441$$

Therefore, in addition to the statistically-significant difference between days in the means averaged over across all subjects indicated by the ANOVA, there is a highly-significant trend when the subjects are taken independently.

	subject 1 mean	subject 1 stdev	subject 2 mean	subject 2 stdev	subject 3 mean	subject 3 stdev	subject 4 mean	subject 4 stdev		
day 1	261.4	73.0	308.2	37.3	305.7	29.1	318.3	78.1		
day 2	303.9	122.6	279.6	20.9	361.5	103.8	266.3	31.4		
day 3	233.7	52.8	239.5	36.2	295.6	76.6	254.8	37.3		
all	266.3	87.8	275.7	32.3	320.9	76.4	279.8	53.2		
	subject 5 mean	**subject 5 stdev**	**subject 6 mean**	**subject 6 stdev**	**subject 7 mean**	**subject 7 stdev**	**subject 8 mean**	**subject 8 stdev**	**all subjects mean**	**all subjects stdev**
day 1	188.1	24.6	287.9	71.6	177.6	18.2	254.8	18.2	262.7	50.1
day 2	158.6	18.4	244.2	38.4	142.5	16.0	240.3	19.7	249.6	60.9
day 3	146.0	18.2	183.6	31.5	139.8	7.6	217.4	20.0	213.8	40.5
all	164.2	20.6	238.6	50.3	153.3	14.6	237.5	19.3	242.0	51.2

Table A.31 - Total Time (in seconds) by Subject and Day

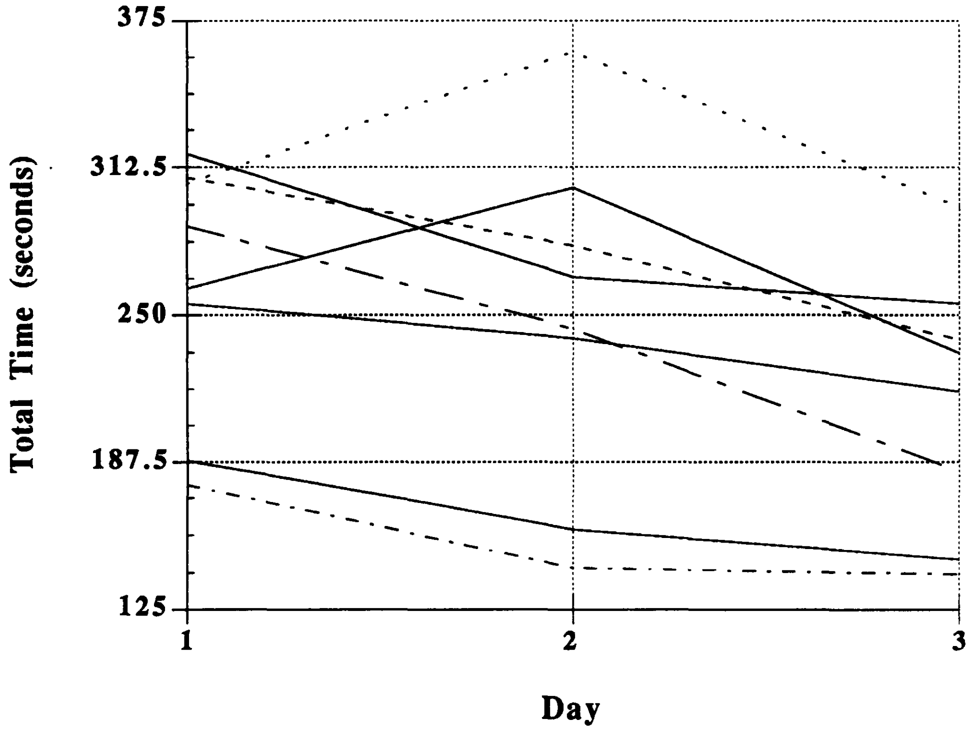

Figure A.12 - Total Time (in seconds) by Day for all Subjects

Looking at total times arranged by the presence or absence of head-tracking and the presence or absence of the vehicle body reveals the reason for the significant body x track interaction in the ANOVAs (Table A.32). When using the HMD without head-tracking, displaying the vehicle body increased both the mean and standard deviation of the total times. With the HMD with head-tracking, however, adding the vehicle body decreased the mean and standard deviation.

	HMD		HMD+track	
	mean	stdev	mean	stdev
without body	234.98	56.08	276.85	112.41
with body	247.92	78.59	248.51	75.07

Table A.32 - Total Time (in seconds) by Head-Tracking and Body

A.1.6 Integrated X-Axis Force Command

The values of total integrated force-command in the X-axis direction do not vary much within subjects, and there appears to be no correlation of the variation to configuration (Table A.33). The means for the different configurations averaged over all subjects are grouped closely together. Although it appears that there are significant differences in standard deviation with and without the vehicle body for the HMD with and without head-tracking, F-tests reveal that the differences are not statistically significant because of the small number of samples (Table A.34).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	20280	9089	9931	2448	15356	2923	7268	1709
monitor+body	21863	12568	10833	3463	12646	560	6989	145
HMD	32358	16813	10336	2145	15795	9141	8854	3758
HMD+body	27016	4419	9854	2618	12960	3973	12251	5827
HMD+track	36456	21849	13041	5345	10308	4490	7009	3616
HMD+track+body	28295	8460	11026	3766	9050	3326	6496	1276
all configurations	27711	13489	10837	3469	12686	4821	8144	3310

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	26080	3939	17863	5828	22432	6461	19978	106	17398	4890
monitor+body	28955	2223	22166	6613	22317	4266	20749	3197	18315	5561
HMD	30920	8029	18468	4996	18491	2154	23739	3368	19870	7829
HMD+body	32580	5933	18003	2606	23439	3685	16966	1947	19134	4115
HMD+track	26389	2412	25110	18851	18429	5151	23060	5298	19975	10926
HMD+track+body	30020	3265	17847	4422	19153	1576	26241	2992	18516	4185
all configurations	29157	4771	19909	8985	20710	4227	21789	3224	18868	6708

Table A.33 - Integrated X-Command (in 20*N·s) by Subject and Configuration

	mean	variance	F	p
monitor	17398.3	52953100		
monitor+body	18314.7	70938800	1.340	p>0.1
HMD	19870.3	111215000	1.611	p>0.1
HMD+body	19133.6	69047700		
HMD+track	19975.2	169218000	1.930	p<0.1
HMD+track+body	18515.9	87664400		

Table A.34 - Integrated X-command: F-Tests by Body

Figure A.13 shows that the distribution of total X-axis command forces is near-normal with a few outliers at large values of total force. The ANOVAs both show that the subject is the only variable which had a significant effect on X-axis force (Tables A.35, A.36).

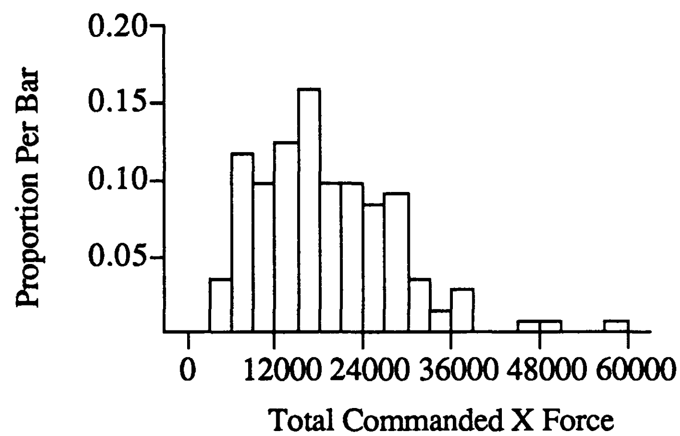

Figure A.13 - Distribution of Integrated X-Commands (in 20*N·s)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**4961820000.**	**7**	**708831000.**	**17.616**	**0.000**
Display	66195000.	1	66195000.	1.645	0.203
Track	533741.632	1	533741.632	0.013	0.909
Body	57677.574	1	57677.574	0.001	0.970
Day	64244300.	2	32122200.	0.798	0.453
Runday	393229000.	5	78645700.	1.954	0.093
Subject*Display	259348000.	7	37049600.	0.921	0.494
Subject*Track	150686000.	7	21526600.	0.535	0.806
Subject*Body	104145000.	7	14877900.	0.370	0.918
Day*Runday	392171000.	10	39217100.	0.975	0.471
Display*Body	15592200.	1	15592200.	0.387	0.535
Track*Body	4193121.262	1	4193121.262	0.104	0.748
Error	3742170000.	93	40238300.		

Table A.35 - Integrated X-Command ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**7466290000.**	**7**	**1066610000.**	**27.362**	**0.000**
Display	59741400.	1	59741400.	1.533	0.218
Runday	413754000.	5	82750700.	2.123	0.067
Error	5067530000.	130	38981000.		

Table A.36 - Integrated X-Command Revised ANOVA

A.1.7 Integrated Y-Axis Force Command

Most of the subjects followed the same general pattern of integrated Y-axis commanded force versus configuration: they used the least Y-axis command with the monitor, slightly more with the HMD without head-tracking, and significantly more with the HMD with head-tracking (Table A.37). The presence or absence of the vehicle body seems to have little influence on the means for each of the three cases.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	11875	1067	4420	2338	6226	1334	6325	604
monitor+body	9357	1974	5793	486	7198	4582	6312	1855
HMD	14419	4535	8259	2805	4587	1686	8600	977
HMD+body	15073	628	7929	798	6620	2424	9267	2530
HMD+track	16464	4648	9917	5637	6306	4297	9994	3929
HMD+track+body	17585	4428	11778	5417	4903	2525	10733	2336
all configurations	14129	3347	8016	3543	5973	3064	8538	2311

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	7591	670	9764	5590	9508	3102	4087	1353	7475	2547
monitor+body	7693	1025	9784	3174	8540	2547	5591	2756	7533	2593
HMD	8826	1352	10574	2031	9033	237	4304	2159	8575	2316
HMD+body	8059	1819	6701	2007	9982	2505	4267	940	8487	1864
HMD+track	9050	1813	18170	10388	13064	1466	7856	2970	11352	5117
HMD+track+body	10341	3095	14207	3908	12231	4611	6247	1195	11003	3680
all configurations	8593	1803	11533	5364	10393	2765	5392	2050	9071	3209

Table A.37 - Integrated Y-Command (in 20*N·m·s) by Subject and Configuration

The total Y-axis commands are fairly normally-distributed (Fig. A.14), and the ANOVAs reveal only the subject and track factors to be statistically-significant (Tables A.38, A.39). Every one of the eight subjects applied more total Y-axis command using the HMD without head-tracking than the HMD with tracking, and the mean across all subjects is about thirty percent higher in the latter case (Table A.40).

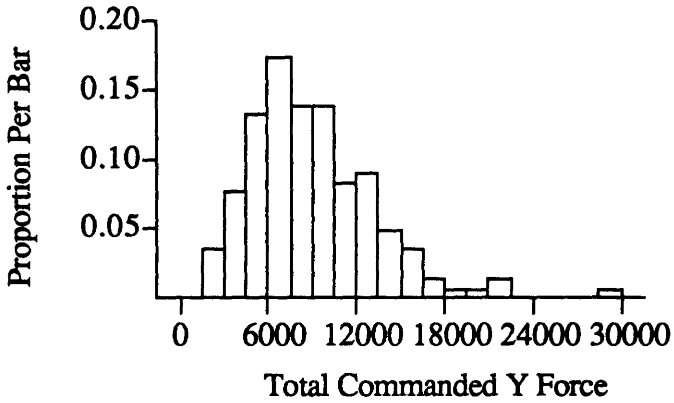

Figure A.14 - Distribution of Integrated Y-Commands (in 20*N·s)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**688000000.**	**7**	**98285700.**	**9.939**	**0.000**
Display	31806800.	1	31806800.	3.217	0.076
Track	**165496000.**	**1**	**165496000.**	**16.736**	**0.000**
Body	375928.599	1	375928.599	0.038	0.846
Day	6231328.329	2	3115664.164	0.315	0.731
Runday	57219000.	5	11443800.	1.157	0.336
Subject*Display	81624200.	7	11660600.	1.179	0.322
Subject*Track	92797800.	7	13256800.	1.341	0.240
Subject*Body	30138800.	7	4305542.057	0.435	0.878
Day*Runday	58046800.	10	5804681.463	0.587	0.821
Display*Body	837453.371	1	837453.371	0.085	0.772
Track*Body	52960.607	1	52960.607	0.005	0.942
Error	919626000.	93	9888453.350		

Table A.38 - Integrated Y-Command ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**1046650000.**	**7**	**149522000.**	**15.399**	**0.000**
Display	25321200.	1	25321200.	2.608	0.109
Track	**168117000.**	**1**	**168117000.**	**17.314**	**0.000**
Error	1301090000.	134	9709636.410		

Table A.39 - Integrated Y-Command Revised ANOVA

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	14746	2918	8094	1853	5603	2174	8933	1754
HMD+track	17024	4106	10848	5049	5604	3245	10363	2919
both	15885	3562	9471	3803	5604	2762	9648	2408

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	8442	1494	8638	2786	9508	1674	4285	1489	8531	2085
HMD+track	9695	2377	16188	7347	12648	3094	7051	2208	11178	4115
both	9069	1985	12413	5556	11078	2488	5668	1883	9855	3262

Table A.40 - Integrated Y-Command (in 20*N·m·s) by Subject and Head-Tracking

A.1.8 Integrated Z-Axis Torque Command

There appears to be no trend to the integrated Z-axis torque command data other than a large difference between subjects in mean total Z-commands averaged over all configurations (Table A.41). Taking all the subjects together, it is not clear whether the differences in the mean torque command between configurations are significant, and the differences in standard deviation do not appear significant. The data are approximately normally distributed (Fig. A.15). Although the initial ANOVA shows only the subject variable to be statistically-significant (Table A.42), when the DOF of the estimate of the residual are increased the subject x display and subject x track interactions become significant as well.

	subject 1 mean	subject 1 stdev	subject 2 mean	subject 2 stdev	subject 3 mean	subject 3 stdev	subject 4 mean	subject 4 stdev		
monitor	15277	2735	18974	770	18634	3120	12092	1366		
monitor+body	16352	2383	17947	3306	18167	1074	11427	3842		
HMD	20077	6436	14750	5604	21366	6274	12176	5195		
HMD+body	18934	4125	15745	4790	17090	3065	12504	1491		
HMD+track	24503	10839	19625	3866	15634	4442	10063	1135		
HMD+track+body	17716	2140	15234	1088	16057	2791	8741	1539		
all configurations	18810	5681	17046	3697	17825	3811	11167	2872		
	subject 5 mean	**subject 5 stdev**	**subject 6 mean**	**subject 6 stdev**	**subject 7 mean**	**subject 7 stdev**	**subject 8 mean**	**subject 8 stdev**	**all subjects mean**	**all subjects stdev**
monitor	22244	2325	10689	1478	25494	1522	20582	1098	17998	1962
monitor+body	21980	1422	12895	6908	22940	3292	17812	4468	17440	3759
HMD	31526	5708	14985	5171	21874	1943	17970	1270	19340	5048
HMD+body	27865	7602	13981	847	23283	5406	17530	2535	18366	4268
HMD+track	19530	1395	19248	7173	19649	1324	17774	1275	18253	5126
HMD+track+body	21875	4965	17986	2019	21014	1051	19921	2931	17318	2606
all configurations	24170	4553	14964	4706	22376	2858	18598	2564	18119	3974

Table A.41 - Integrated Z-Command (in 20*N·m·s) by Subject and Configuration

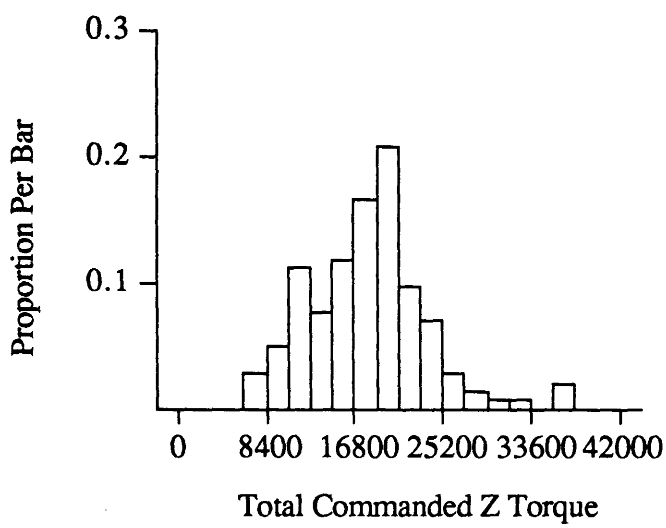

Figure A.15 - Distribution of Integrated Z-Commands (in 20*N·m·s)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**1118250000.**	**7**	**159751000.**	**9.752**	**0.000**
Display	29627000.	1	29627000.	1.809	0.182
Track	26305100.	1	26305100.	1.606	0.208
Body	10181300.	1	10181300.	0.622	0.432
Day	5472738.161	2	2736369.080	0.167	0.846
Runday	57235900.	5	11447200.	0.699	0.626
Subject*Display	203817000.	7	29116700.	1.777	0.101
Subject*Track	218762000.	7	31251600.	1.908	0.077
Subject*Body	29542700.	7	4220388.653	0.258	0.968
Day*Runday	93717500.	10	9371745.937	0.572	0.833
Display*Body	2051151.991	1	2051151.991	0.125	0.724
Track*Body	85358.824	1	85358.824	0.005	0.943
Error	1523420000.	93	16380800.		

Table A.42 - Integrated Z-Command ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**1131340000.**	**7**	**161620000.**	**11.152**	**0.000**
Display	11535800.	1	11535800.	0.796	0.374
Subject*Display	**252577000.**	**7**	**36082400.**	**2.490**	**0.020**
Subject*Track	**367474000.**	**7**	**52496200.**	**3.622**	**0.001**
Error	1753610000.	121	14492700.		

Table A.43 - Integrated Z-Command Revised ANOVA

Comparing the two displays, three subjects used significantly more integrated yaw torque with the HMD, two subjects used significantly more with the monitor, and three subjects had no significant difference (Table A.44), explaining the significance of the subject x display interaction. Overall there was little difference in the means between the two displays. Two subjects applied significantly more total torque with the HMD with head-tracking, four applied significantly more using the HMD without tracking, and two had only small differences between the two cases (Table A.45). The overall averages were about the same for the HMD with and without head-tracking.

	subject 1		subject 2		subject 3		subject 4			
	mean	stdev	mean	stdev	mean	stdev	mean	stdev		
monitor	15815	2369	18460	2219	18401	2103	11759	2604		
HMD	20307	6323	16338	4108	17537	4416	10871	2930		
both	18061	4774	17399	3302	17969	3459	11315	2772		
	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	22112	1730	11792	4628	24217	2687	19197	3282	17719	2832
HMD	25199	6775	16550	4484	21455	2902	18299	2074	18320	4523
both	23655	4944	14171	4557	22836	2797	18748	2745	18019	3773

Table A.44 - Integrated Z-Command (in 20*N·m·s) by Subject and Display

	subject 1		subject 2		subject 3		subject 4			
	mean	stdev	mean	stdev	mean	stdev	mean	stdev		
HMD	19505	4875	15248	4694	19228	4999	12340	3423		
HMD+track	21109	7915	17429	3498	15846	3326	9402	1410		
both	20307	6573	16338	4140	17537	4245	10871	2618		
	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	29695	6338	14483	3359	22579	3714	17750	1809	18853	4345
HMD+track	20703	3505	18617	4763	20331	1305	18848	2339	17786	4032
both	25199	5121	16550	4121	21455	2784	18299	2091	18320	4192

Table A.45 - Integrated Z-Command (in 20*N·m·s) by Subject and Head-Tracking

A.2 Square of Posts Task Analysis

For this task, the only parameter measured for each individual post was the closest the simulated vehicle came to each post during the run. Parameters measured for each run of one circumnavigation of the square of posts were the same as for the random posts task: the total time, distance travelled, and integrated X-axis and Y-axis forces and Z-axis torque commands. All variables were analyzed using ANOVA.

A.2.1 Individual Post Distances

For most of the subjects, displaying the vehicle body reduced their mean post distances for the monitor and the HMD with and without head-tracking (Table A.46). Adding the body tended to increase the standard deviations of post distances more often than decrease them, however. Figure A.16 shows the near-normal distribution of post distances. Although the first ANOVA shows the subject, display, track, body, and post number variables and the subject x display and display x body interactions to be statistically-significant (Table A.47), the revised ANOVA also indicated the runday variable and subject x track and day x runday interactions to be significant, and the display x body interaction to be not significant (Table A.48).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	3.059	1.044	1.592	0.625	1.731	0.398	2.929	0.759
monitor+body	2.495	0.806	1.232	0.520	2.012	1.763	2.223	0.910
HMD	1.909	0.721	1.460	0.680	1.897	1.040	2.242	0.724
HMD+body	2.112	0.927	1.274	0.475	2.042	1.105	2.012	0.651
HMD+track	3.003	0.796	1.358	0.606	1.904	0.798	2.239	0.675
HMD+track+body	2.798	0.903	1.448	0.676	1.879	1.679	1.858	0.761
all configurations	2.563	0.873	1.394	0.602	1.911	1.226	2.251	0.751

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	2.318	0.944	1.201	0.633	1.994	0.885	2.332	0.570	2.145	0.760
monitor+body	1.929	0.768	1.186	0.616	1.870	0.888	2.175	0.464	1.890	0.924
HMD	2.332	0.682	1.520	0.772	1.660	0.763	2.387	0.635	1.926	0.761
HMD+body	2.322	1.137	1.514	0.998	1.555	0.744	2.360	0.452	1.899	0.850
HMD+track	2.680	0.812	1.706	1.660	1.917	0.900	2.382	0.551	2.149	0.910
HMD+track+body	2.301	1.151	1.685	0.586	1.873	0.880	2.361	0.606	2.025	0.967
all configurations	2.314	0.933	1.469	0.955	1.812	0.846	2.333	0.551	2.006	0.866

Table A.46 - Post Distance (in meters) by Subject and Configuration

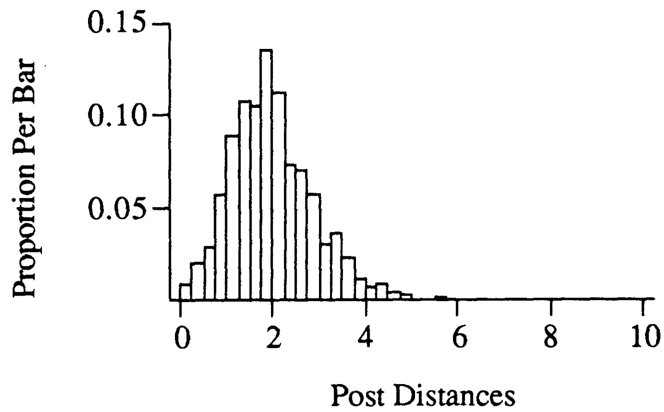

Figure A.16 - Distribution of Post Distances (in meters)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**149.603**	**7**	**21.372**	**30.488**	**0.000**
Display	**3.631**	**1**	**3.631**	**5.179**	**0.023**
Track	**5.663**	**1**	**5.663**	**8.079**	**0.005**
Body	**7.677**	**1**	**7.677**	**10.952**	**0.001**
Sqdir	0.001	1	0.001	0.001	0.974
Pnum	**40.284**	**7**	**5.755**	**8.210**	**0.000**
Day	2.305	2	1.152	1.644	0.194
Runday	6.406	5	1.281	1.828	0.105
Subject*Display	**20.036**	**7**	**2.862**	**4.083**	**0.000**
Subject*Track	10.333	7	1.476	2.106	0.040
Subject*Body	2.494	7	0.356	0.486	0.829
Day*Runday	11.906	10	1.191	1.698	0.076
Display*Body	**2.688**	**1**	**2.688**	**3.835**	**0.050**
Track*Body	0.414	1	0.414	0.590	0.443
Pnum*Body	7.631	7	1.090	1.555	0.145
Pnum*Display	4.006	7	0.572	0.816	0.574
Pnum*Track	3.471	7	0.496	0.707	0.666
Error	751.451	1072	0.701		

Table A.47 - Post Distance ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**150.041**	**7**	**21.434**	**30.754**	**0.000**
Display	**3.486**	**1**	**3.486**	**5.002**	**0.026**
Track	**5.570**	**1**	**5.570**	**7.993**	**0.005**
Body	**7.982**	**1**	**7.982**	**11.453**	**0.001**
Pnum	**43.774**	**7**	**6.253**	**8.973**	**0.000**
Runday	**7.835**	**5**	**1.567**	**2.248**	**0.048**
Subject*Display	**20.743**	**7**	**2.963**	**4.252**	**0.000**
Subject*Track	**10.629**	**7**	**1.518**	**2.179**	**0.034**
Day*Runday	**15.060**	**10**	**1.506**	**2.161**	**0.018**
Display*Body	2.270	1	2.270	3.257	0.071
Pnum*Body	7.631	7	1.090	1.564	0.142
Error	764.568	1097	0.697		

Table A.48 - Post Distance Revised ANOVA

Three subjects passed significantly closer to the posts when using the monitor, two passed significantly closer with the HMD, and three had no significant difference (Table A.49). Overall, subjects passed slightly closer to the posts using the HMD than the monitor. With the HMD, three subjects passed significantly closer to the posts without head-tracking than with tracking, while the rest had no significant difference with or without tracking (Table A.50). Including all three display setups, three subjects had significantly smaller mean post distances with the vehicle body displayed, while the presence of the body had no significant effect on the post distances for the other subjects (Table A.51).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	2.777	0.966	1.412	0.597	1.871	1.272	2.576	0.902
HMD	2.010	0.828	1.367	0.587	1.970	1.064	2.127	0.691
both	2.394	0.900	1.390	0.592	1.921	1.173	2.352	0.803

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	2.124	0.873	1.194	0.618	1.932	0.879	2.253	0.520	2.017	0.859
HMD	2.327	0.927	1.517	0.883	1.607	0.748	2.373	0.545	1.912	0.801
both	2.226	0.900	1.356	0.762	1.770	0.816	2.313	0.533	1.965	0.831

Table A.49 - Post Distance (in meters) by Subject and Display

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	2.010	0.828	1.367	0.587	1.970	1.064	2.127	0.691
HMD+track	2.901	0.849	1.403	0.637	1.892	1.301	2.048	0.737
both	2.456	0.839	1.385	0.613	1.931	1.188	2.088	0.714

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
HMD	2.327	0.927	1.517	0.883	1.607	0.748	2.373	0.545	1.912	0.801
HMD+track	2.491	1.004	1.695	1.231	1.895	0.881	2.371	0.573	2.087	0.935
both	2.409	0.966	1.606	1.071	1.751	0.817	2.372	0.559	2.000	0.871

Table A.50 - Post Distance (in meters) by Subject and Head-Tracking

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
without body	2.657	1.006	1.470	0.636	1.844	0.784	2.470	0.782
with body	2.469	0.913	1.318	0.564	1.978	1.523	2.031	0.785
both	2.563	0.961	1.394	0.601	1.911	1.211	2.251	0.784

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
without body	2.443	0.825	1.476	1.122	1.857	0.852	2.367	0.579	2.073	0.840
with body	2.184	1.035	1.462	0.775	1.766	0.842	2.298	0.512	1.938	0.917
both	2.314	0.936	1.469	0.964	1.812	0.847	2.333	0.547	2.006	0.879

Table A.51 - Post Distance (in meters) by Subject and Body

From Table A.52 and Figure A.17 it is evident that the there is a correlation between the post numbers and how close, on average, subjects came to each post. Distances from post number one were generally smaller, as were distances from the even-numbered posts, while the odd-numbered posts other than number one had relatively large distances.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
post #1	1.849	0.385	1.652	0.216	1.573	0.330	1.660	0.280
post #2	2.500	0.957	1.311	0.536	1.847	0.743	2.017	0.584
post #3	2.523	1.067	1.551	0.620	2.451	2.594	2.418	1.008
post #4	2.819	0.808	0.966	0.353	1.658	0.905	2.289	0.704
post #5	3.026	0.902	1.397	0.806	1.846	1.105	2.360	1.013
post #6	2.734	1.133	1.438	0.660	2.133	1.115	2.093	0.735
post #7	2.682	1.179	1.602	0.763	1.953	0.961	2.781	0.882
post #8	2.369	0.713	1.235	0.427	1.827	0.360	2.386	0.666
all posts	2.563	0.925	1.394	0.580	1.911	1.211	2.251	0.768

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
post #1	1.778	0.241	1.152	0.426	1.569	0.391	1.974	0.089	1.651	0.313
post #2	2.159	0.552	1.238	0.397	1.550	0.662	2.616	0.567	1.905	0.644
post #3	2.780	0.771	1.627	0.697	2.057	1.010	2.677	0.569	2.261	1.209
post #4	1.677	0.798	1.771	1.177	2.034	0.867	2.175	0.575	1.924	0.806
post #5	2.869	0.990	1.784	1.808	1.834	0.759	2.396	0.511	2.228	1.049
post #6	2.201	1.256	1.397	0.970	1.764	0.975	2.197	0.437	1.911	0.848
post #7	2.961	0.911	1.494	0.789	1.938	0.981	2.419	0.696	2.229	0.906
post #8	2.085	0.809	1.287	0.544	1.748	0.938	2.207	0.404	1.893	0.638
all posts	2.314	0.839	1.469	0.958	1.812	0.846	2.333	0.510	2.006	0.770

Table A.52 - Post Distance (in meters) by Subject and Post Number

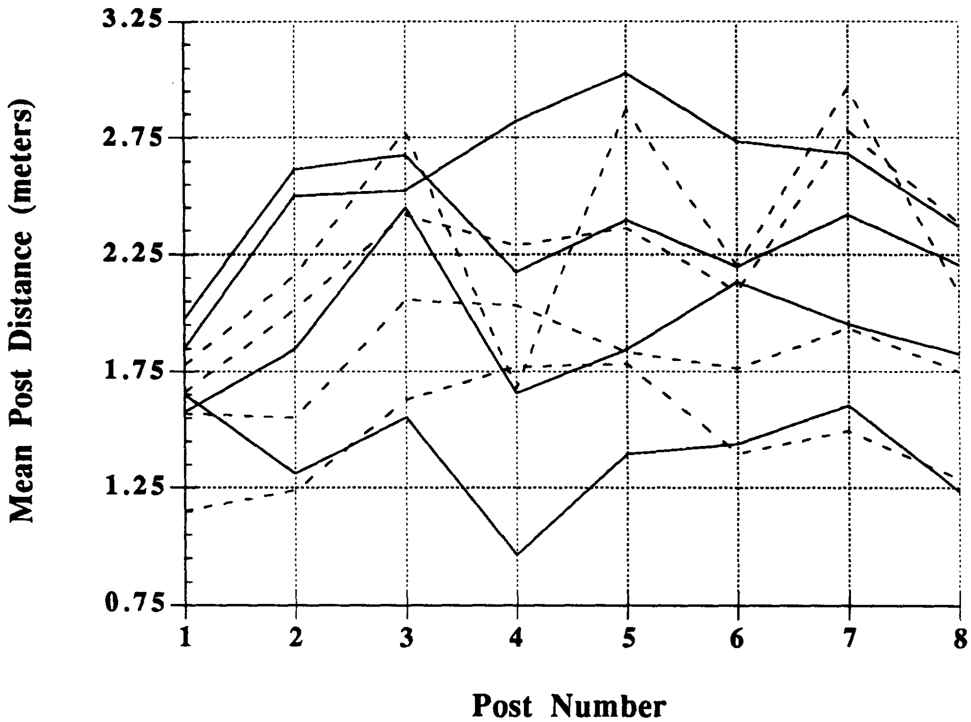

Figure A.17 - Post Distance (in meters) versus Post Number for all Subjects

Table A.53 and Figure A.18 show the dependence of post distance on on which run of the day the data were taken from. Although the means averaged across all subjects increase strictly over the six runs, and subject #1 shows this same trend, there seems to be no general trend based on the run number that is common to many subjects.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
runday = 1	1.867	0.842	1.130	0.428	1.958	1.107	2.033	0.897
runday = 2	2.097	0.651	1.631	0.691	2.052	0.901	2.397	0.605
runday = 3	2.671	0.928	1.237	0.535	1.865	1.682	2.263	0.800
runday = 4	2.626	0.927	1.451	0.689	1.563	0.769	2.136	0.852
runday = 5	3.012	0.985	1.411	0.549	1.794	0.550	2.137	0.765
runday = 6	3.103	0.814	1.503	0.609	2.234	1.747	2.537	0.883
all runs	2.563	0.865	1.394	0.591	1.911	1.212	2.251	0.806

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
runday = 1	2.282	1.113	1.357	1.087	1.556	0.692	2.239	0.495	1.803	0.871
runday = 2	2.223	0.917	1.410	0.692	1.496	0.673	2.498	0.556	1.976	0.721
runday = 3	2.212	1.030	1.632	1.415	1.897	0.949	2.217	0.589	1.999	1.056
runday = 4	2.442	0.983	1.539	0.694	1.957	1.037	2.412	0.570	2.016	0.829
runday = 5	2.329	0.915	1.514	0.663	1.904	0.696	2.354	0.585	2.057	0.730
runday = 6	2.394	0.725	1.361	1.046	2.060	0.878	2.274	0.470	2.183	0.967
all runs	2.314	0.955	1.469	0.973	1.812	0.833	2.332	0.546	2.006	0.871

Table A.53 - Post Distance (in meters) by Subject and Run of Day

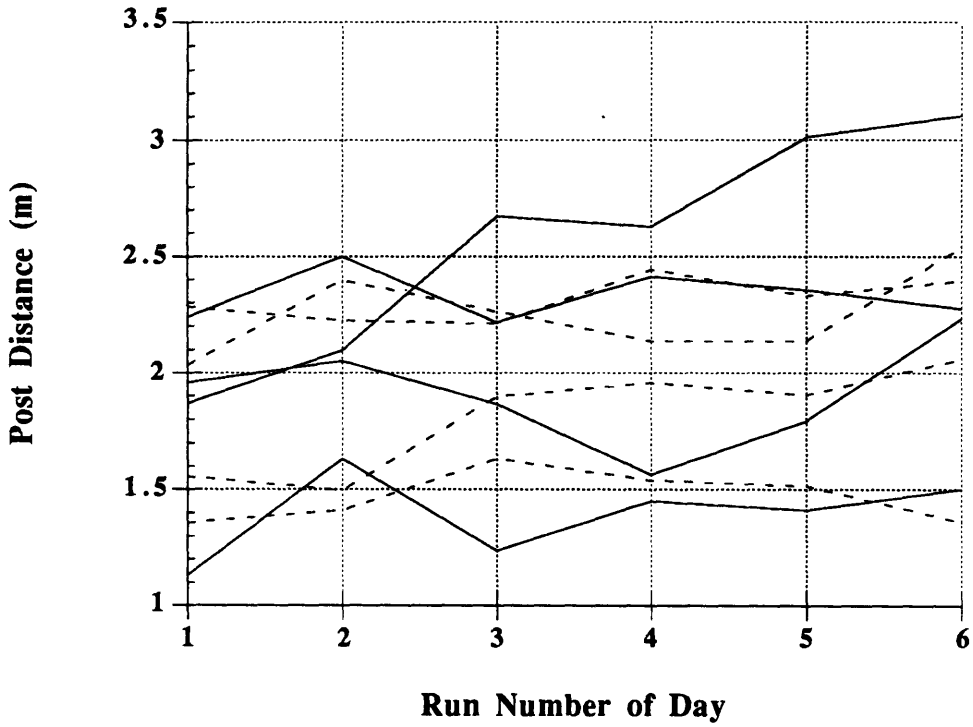

Figure A.18 - Post Distance (in meters) versus Run Number of Day for all Subjects

Although the day variable alone had no significant effect on post distances, Table A.54 and Figure A.19 show the interaction between the day number and run number of the day. On the first and second days there is significant variation in mean post distance among the six runs, but on day three the differences between runs are much smaller.

	day 1 mean	day 1 stdev	day 2 mean	day 2 stdev	day 3 mean	day 3 stdev	all days mean	all days stdev
runday = 1	1.883	1.213	1.547	0.728	1.978	0.756	1.803	0.926
runday = 2	2.088	0.911	1.813	0.773	2.026	0.712	1.976	0.803
runday = 3	2.019	1.316	1.940	1.094	2.039	0.917	1.999	1.121
runday = 4	1.768	0.979	2.199	0.919	2.081	0.817	2.016	0.907
runday = 5	2.000	0.892	2.111	0.903	2.059	0.810	2.057	0.869
runday = 6	2.397	1.320	2.052	1.021	2.102	0.841	2.184	1.079
all runs	2.026	1.120	1.944	0.915	2.048	0.811	2.006	0.958

Table A.54 - Post Distance (in meters) by Day and Run of Day

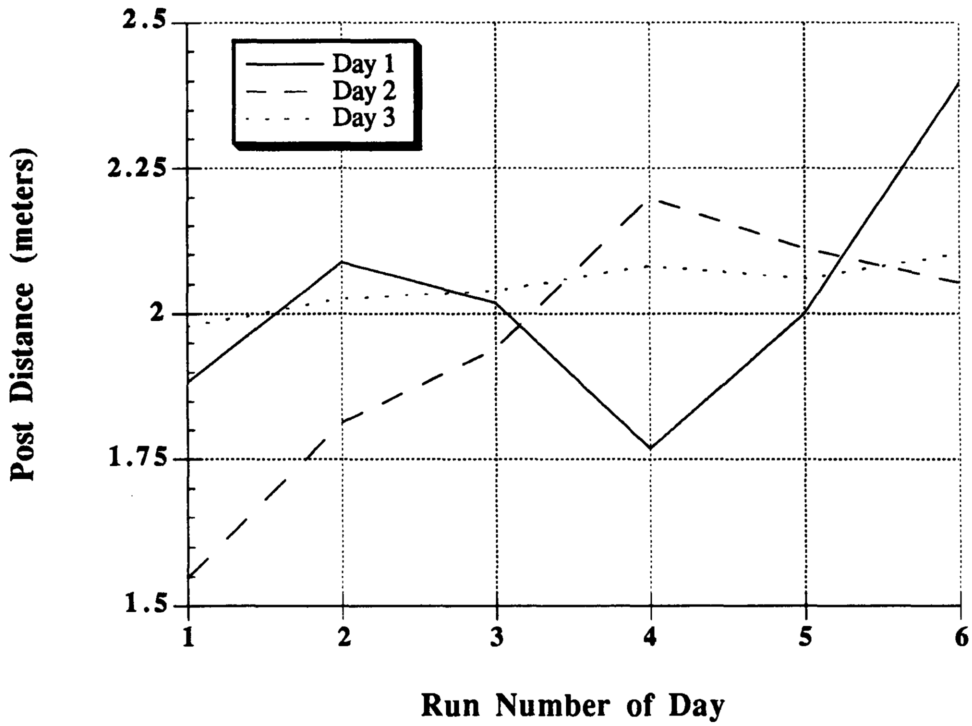

Figure A.19 - Post Distance (in meters) versus Run Number of Day for all Days

A.2.2 Total Distance Travelled

There is no discernable relationship between configuration and the total distance travelled for this task (Table A.55). There is very little difference between subjects in mean distances averaged over all configurations, although there is a wide range of standard deviations between subjects. The data are mostly normally-distributed, with a few outliers at large distances (Fig. A.20). The initial ANOVA reveals only the subject and day factors to be statistically-significant (Table A.56); the revised ANOVA adds the subject x body interaction (Table A.57).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	177.0	6.1	154.5	0.5	154.6	7.0	191.3	10.9
monitor+body	178.2	7.4	147.9	4.3	176.6	50.9	201.0	11.4
HMD	172.6	17.9	152.4	3.0	169.5	16.0	172.6	6.3
HMD+body	174.8	5.9	158.8	10.1	171.7	20.3	177.7	2.7
HMD+track	179.4	6.8	169.6	4.3	163.9	11.0	166.8	4.1
HMD+track+body	183.2	8.2	169.5	11.7	213.5	92.1	173.4	3.8
all configurations	177.5	9.7	158.8	6.9	175.0	44.6	180.5	7.4

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	174.0	23.6	153.5	6.9	168.2	9.6	162.6	9.2	167.0	11.1
monitor+body	162.7	17.1	154.6	10.6	158.5	5.2	175.6	21.3	169.4	21.5
HMD	165.6	8.4	164.6	16.9	189.2	45.3	157.8	0.7	168.0	19.5
HMD+body	171.6	16.6	170.9	23.3	153.7	4.3	163.1	9.3	167.8	13.6
HMD+track	164.9	5.6	181.2	21.3	168.4	8.1	166.7	1.0	170.1	9.7
HMD+track+body	167.1	0.8	170.6	25.8	172.6	24.1	161.8	8.4	176.5	35.4
all configurations	167.6	14.3	165.9	18.7	168.4	21.7	164.6	10.8	169.8	20.4

Table A.55 - Total Distance (in meters) by Subject and Configuration

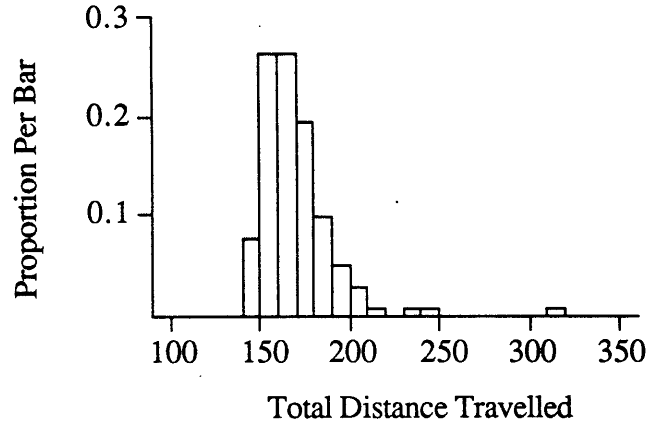

Figure A.20 - Distribution of Total Distances (in meters)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**5559.239**	**7**	**794.177**	**2.699**	**0.014**
Display	0.445	1	0.445	0.002	0.969
Track	413.597	1	413.597	1.405	0.239
Body	472.697	1	472.697	1.606	0.208
Sqdir	121.231	1	121.231	0.412	0.523
Day	**10509.866**	**2**	**5254.933**	**17.857**	**0.000**
Runday	1240.152	5	248.030	0.843	0.523
Subject*Display	2676.567	7	382.367	1.299	0.260
Subject*Track	1585.799	7	226.543	0.770	0.614
Subject*Body	4116.035	7	588.005	1.998	0.064
Day*Runday	4208.970	10	420.897	1.430	0.180
Display*Body	56.466	1	56.466	0.192	0.662
Track*Body	288.198	1	288.198	0.979	0.325
Error	27073.411	92	294.276		

Table A.56 - Total Distance ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**6680.658**	**7**	**954.380**	**3.070**	**0.005**
Day	**10509.866**	**2**	**5254.933**	**16.902**	**0.000**
Subject*Body	**4836.794**	**7**	**690.971**	**2.222**	**0.037**
Day*Runday	4387.459	10	438.746	1.411	0.184
Error	36376.299	117	310.909		

Table A.57 - Total Distance Revised ANOVA

The mean total distances of seven of the eight individual subjects, as well as the average over all subjects, decreased monotonically over the three days (Table A.58, Fig. A.21). The standard deviations averaged over all subjects also decreased monotonically over the days.

	subject 1		subject 2		subject 3		subject 4			
	mean	stdev	mean	stdev	mean	stdev	mean	stdev		
day 1	182.5	7.4	163.9	12.1	212.6	58.0	177.6	8.7		
day 2	175.6	11.9	157.3	8.0	158.0	7.0	182.0	15.7		
day 3	174.5	4.9	155.2	10.0	154.4	6.5	181.8	17.4		
all days	177.5	8.6	158.8	10.2	175.0	33.9	180.5	14.4		
	subject 5		**subject 6**		**subject 7**		**subject 8**		**all subjects**	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
day 1	179.8	14.2	184.6	17.3	180.7	34.7	172.5	14.4	181.8	26.3
day 2	162.9	7.0	159.8	13.8	162.6	7.7	163.8	3.5	165.2	10.1
day 3	160.3	5.2	153.3	6.1	162.0	7.7	157.5	5.8	162.4	8.8
all days	167.6	9.6	165.9	13.3	168.4	21.0	164.6	9.2	169.8	17.1

Table A.58 - Total Distance (in meters) by Subject and Day

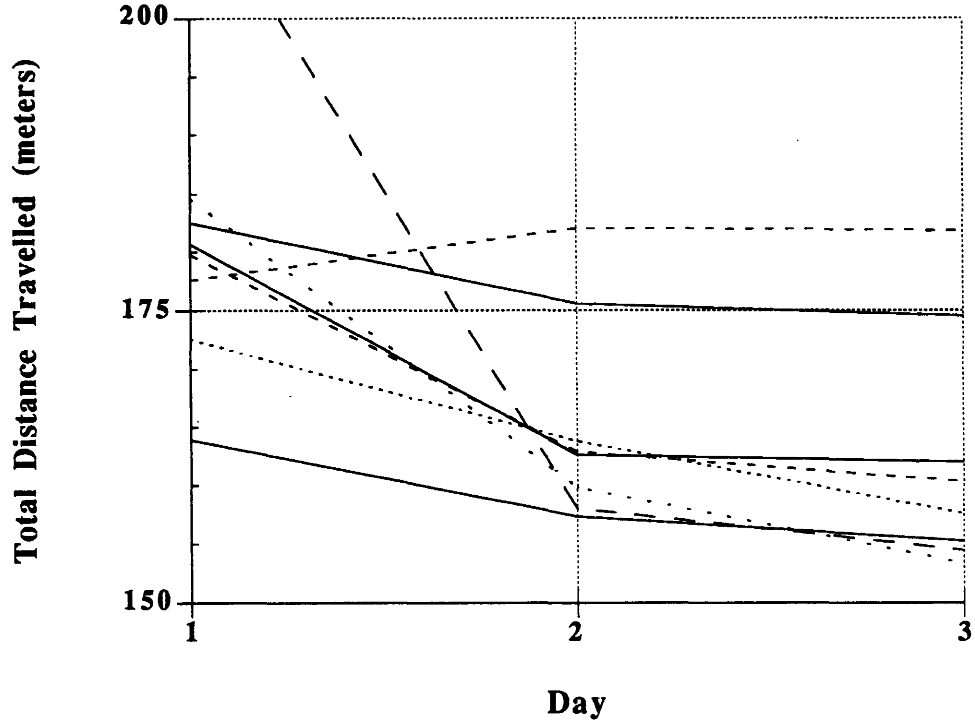

Figure A.21 - Total Distance Travelled (in meters) by Day for all Subjects

Adding the vehicle body considerably increased the mean distances for two subjects, considerably decreased the mean for one, and had no significant difference for the others (Table A.59), which is the basis for the significance of the subject x body factor in the ANOVA.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
without body	176.3	10.5	158.8	8.5	162.7	12.2	176.9	12.9
with body	178.7	7.2	158.7	12.3	187.3	57.1	184.0	14.3
both	177.5	9.0	158.8	10.6	175.0	41.3	180.5	13.6

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
without body	168.1	13.6	166.4	18.5	175.3	25.7	162.4	6.0	168.4	14.7
with body	167.1	12.5	165.3	19.9	161.6	15.1	166.8	14.0	171.2	24.1
both	167.6	13.1	165.9	19.2	168.4	21.1	164.6	10.8	169.8	20.0

Table A.59 - Total Distance (in meters) by Subject and Body

A.2.3 Total Time

There is more variation between subjects of the total time per run than there was for the total distance, and there is again a wide range of average standard deviations between subjects (Table A.60). There is no apparent relationship between configuration and total time, however, that is consistent across many subjects. Figure A.22 shows that the distribution of total times is approximately normal, and the ANOVAs indicate that only the subject and day variables are statistically-significant (Tables A.61, A.62).

	subject 1 mean	subject 1 stdev	subject 2 mean	subject 2 stdev	subject 3 mean	subject 3 stdev	subject 4 mean	subject 4 stdev
monitor	168.6	11.3	189.5	23.6	223.6	120.8	191.0	7.0
monitor+body	148.9	41.8	203.6	20.3	178.4	70.3	210.8	43.2
HMD	152.9	22.8	179.7	51.1	280.8	81.3	186.5	31.7
HMD+body	155.8	21.6	180.2	69.2	214.4	49.5	183.4	13.2
HMD+track	144.2	15.7	192.8	45.4	222.5	82.3	166.6	28.2
HMD+track+body	161.8	30.5	198.5	47.0	209.6	48.4	167.5	6.5
all configurations	155.4	25.9	190.7	45.9	221.5	79.3	184.3	25.6

	subject 5 mean	subject 5 stdev	subject 6 mean	subject 6 stdev	subject 7 mean	subject 7 stdev	subject 8 mean	subject 8 stdev	all subjects mean	all subjects stdev
monitor	83.2	19.4	239.3	54.6	90.9	12.2	132.1	38.7	164.8	50.4
monitor+body	102.3	32.0	210.1	90.8	93.2	15.2	128.4	21.0	159.5	48.6
HMD	87.8	15.5	215.0	94.8	109.2	14.7	126.5	16.2	167.3	50.5
HMD+body	108.9	24.3	208.3	94.8	97.0	11.7	114.5	3.1	157.8	46.9
HMD+track	86.9	7.5	275.7	205.5	89.3	7.2	140.9	9.8	164.9	80.9
HMD+track+body	91.0	4.3	217.5	128.2	92.2	13.3	128.8	14.4	158.4	52.9
all configurations	93.4	19.6	227.6	121.0	95.3	12.7	128.5	20.5	162.1	56.3

Table A.60 - Total Time (in seconds) by Subject and Configuration

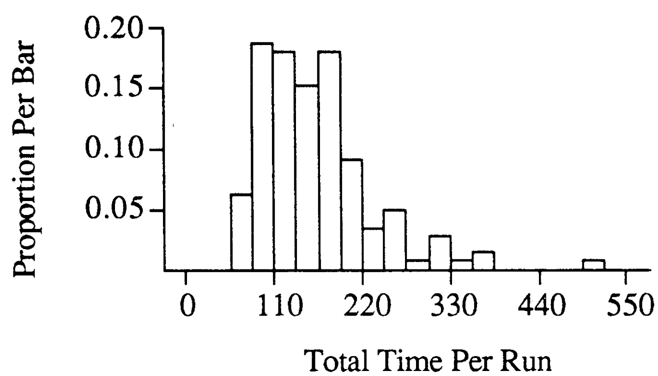

Figure A.22 - Distribution of Total Times (in seconds)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**216309.326**	**7**	**30901.332**	**13.280**	**0.000**
Display	95.061	1	95.061	0.041	0.840
Track	0.347	1	0.347	0.000	0.990
Body	1012.750	1	1012.750	0.435	0.511
Sqdir	845.515	1	845.515	0.363	0.548
Day	**71110.300**	**2**	**35555.150**	**15.280**	**0.000**
Runday	13434.977	5	2686.995	1.155	0.338
Subject*Display	4739.590	7	677.084	0.291	0.956
Subject*Track	5157.310	7	736.759	0.317	0.945
Subject*Body	7158.030	7	1022.576	0.439	0.875
Day*Runday	10085.808	10	1008.581	0.433	0.927
Display*Body	12.054	1	12.054	0.005	0.943
Track*Body	0.341	1	0.341	0.000	0.990
Error	214068.652	92	2326.833		

Table A.61 - Total Time ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**350967.543**	**7**	**50138.220**	**24.907**	**0.000**
Day	**71110.300**	**2**	**35555.150**	**17.663**	**0.000**
Error	269744.885	134	2013.022		

Table A.62 - Total Time Revised ANOVA

The total time means for seven of the eight subjects, as well as the means over all subjects, decrease steadily from day one to day three (Table A.63, Fig. A.23). This decreasing trend occurs in the standard deviations for four of the subjects and the average standard deviation over all subjects as well.

	subject 1 mean	subject 1 stdev	subject 2 mean	subject 2 stdev	subject 3 mean	subject 3 stdev	subject 4 mean	subject 4 stdev		
day 1	180.1	14.1	236.5	17.5	173.7	56.7	200.4	24.0		
day 2	151.0	16.7	173.2	25.4	304.6	46.0	188.6	24.4		
day 3	135.0	10.9	162.4	23.0	186.3	24.1	164.0	19.6		
all days	155.4	14.1	190.7	22.3	221.5	44.4	184.3	22.8		
	subject 5 mean	**subject 5 stdev**	**subject 6 mean**	**subject 6 stdev**	**subject 7 mean**	**subject 7 stdev**	**subject 8 mean**	**subject 8 stdev**	**all subjects mean**	**all subjects stdev**
day 1	106.0	15.8	350.1	81.7	106.1	11.4	143.0	19.0	187.0	38.2
day 2	93.5	22.8	193.2	34.7	96.4	8.5	129.8	12.7	166.3	26.5
day 3	80.6	8.5	139.6	24.1	83.4	5.6	112.9	12.5	133.0	17.5
all days	93.4	16.7	227.6	53.1	95.3	8.8	128.5	15.1	162.1	28.7

Table A.63 - Total Time (in seconds) by Subject and Day

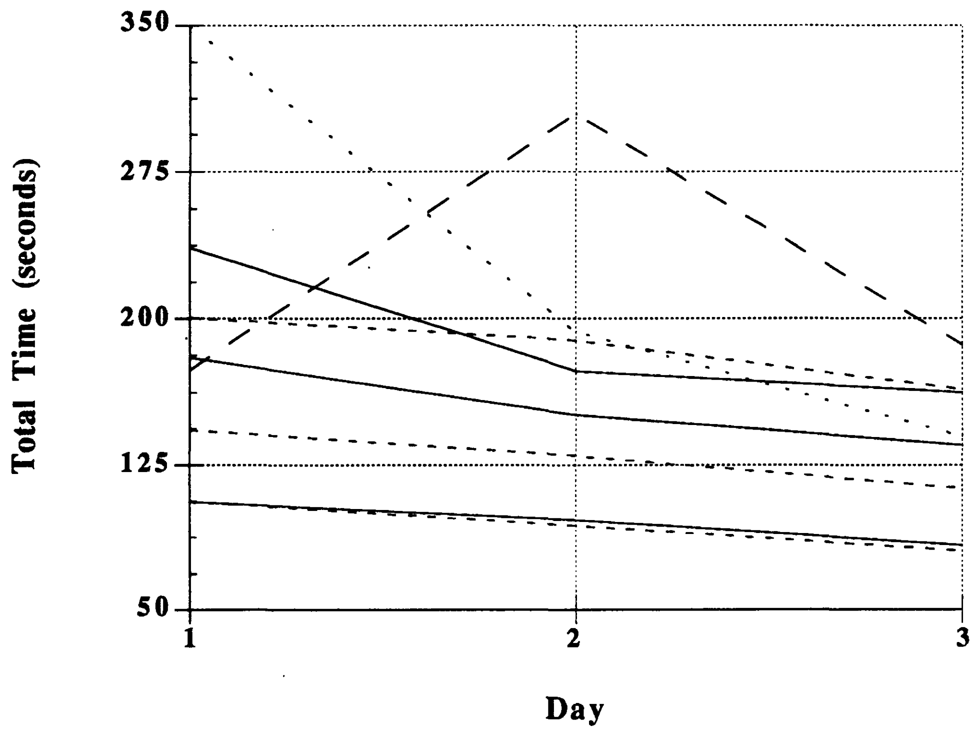

Figure A.23 - Total Time (in seconds) by Day for all Subjects

A.2.4 Integrated X-Axis Force Command

Although there is a large range in overall means and standard deviations of the integrated X-axis command between subjects, there is no apparent correlation between either means or standard deviations and configuration (Table A.64). The X-command data are approximately normally-distributed (Fig. A.24), and the ANOVAs reveal that only the subject and day variables are statistically-significant (Tables A.65, A.66).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	7939	718	5985	1539	4331	1511	3884	497
monitor+body	9477	1289	5071	1781	5553	5116	4253	1082
HMD	6770	648	6023	2011	4087	1545	2855	251
HMD+body	9738	2068	6476	1385	4937	2755	2712	555
HMD+track	6887	631	6085	2636	3458	1283	3045	628
HMD+track+body	8006	1841	6954	3011	7398	6113	2822	492
all configurations	8136	1333	6099	2141	4961	3593	3262	636

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	14334	6608	5047	902	10916	3763	7265	513	7463	2836
monitor+body	12553	4969	5014	1193	7528	2162	7482	1371	7116	2847
HMD	12920	3654	6009	1564	14162	7355	6483	1748	7414	3160
HMD+body	13776	4130	7810	321	8844	372	6901	1228	7649	2028
HMD+track	13290	1774	7967	2170	11783	2087	6906	2239	7428	1824
HMD+track+body	15139	767	8504	2969	11043	2458	6390	739	8282	2874
all configurations	13669	4133	6725	1747	10713	3730	6904	1430	7559	2640

Table A.64 - Integrated X-Command (in 20*N·s) by Subject and Configuration

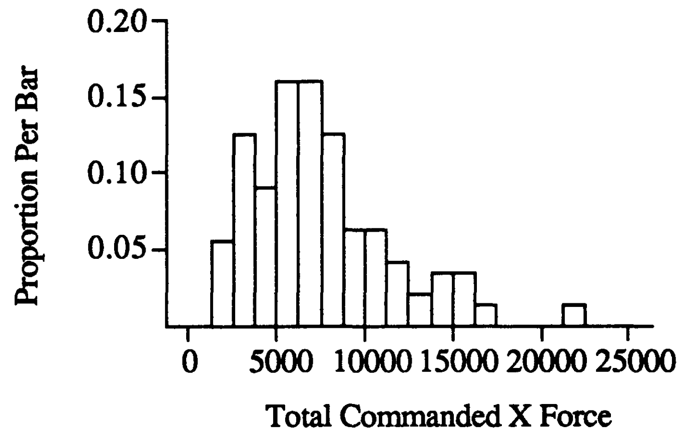

Figure A.24 - Distribution of Integrated X-Commands (in 20*N·s)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**740356000.**	**7**	**105765000.**	**16.332**	**0.000**
Display	125130.551	1	125130.551	0.019	0.890
Track	1788734.870	1	1788734.870	0.276	0.600
Body	1128387.901	1	1128387.901	0.174	0.677
Sqdir	413828.400	1	413828.400	0.064	0.801
Day	36974200.	2	18487100.	2.855	0.063
Runday	16469100.	5	3293815.438	0.509	0.769
Subject*Display	43400200.	7	6200028.650	0.957	0.467
Subject*Track	13603200.	7	1943317.813	0.300	0.952
Subject*Body	72866900.	7	20509700.	1.607	0.143
Day*Runday	50240000.	10	5023995.954	0.776	0.652
Display*Body	2009152.711	1	2009152.711	0.310	0.579
Track*Body	2455135.120	1	2455135.120	0.379	0.540
Error	595787000.	92	6475942.166		

Table A.65 - Integrated X-Command ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**1369440000.**	**7**	**195635000.**	**33.092**	**0.000**
Day	**36974200.**	**2**	**18487100.**	**3.127**	**0.047**
Subject*Body	79473100.	7	11353300.	1.920	0.071
Error	750810000.	127	5911887.800		

Table A.66 - Integrated X-Command Revised ANOVA

Unlike previous variables, the X-command means do not generally decrease or increase over the three days. For four of the subjects, as well as the mean across all subjects, X-command decreases from day one to day two and then increases from day two to day three (Table A.67, Fig. 5.25). Of the remaining subjects, two have mean X-commands which increase steadily over the three days and two have means which increase from day one to two and then drop again on the last day. Although the mean over all subjects is much higher for the first day than the other days, this is due to only three individual subjects. Similarly, although the ANOVA shows large variation by day of experiment, there is no important relationship between the day number and mean X-command.

	subject 1 mean	subject 1 stdev	subject 2 mean	subject 2 stdev	subject 3 mean	subject 3 stdev	subject 4 mean	subject 4 stdev		
day 1	8009	1717	4239	696	7699	4284	3033	480		
day 2	9042	1964	6697	2057	2477	744	3135	783		
day 3	7358	660	7361	982	4706	1191	3618	1067		
all days	8136	1554	6099	1376	4961	2603	3262	813		
	subject 5		**subject 6**		**subject 7**		**subject 8**		**all subjects**	
	mean	**stdev**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
day 1	16657	2775	6634	2244	12724	5557	6730	1342	8216	2903
day 2	11693	3399	7285	2563	9310	2975	6220	653	6982	2141
day 3	12656	2802	6256	1533	10105	1447	7763	1319	7478	1500
all days	13669	3006	6725	2157	10713	3734	6904	1150	7559	2255

Table A.67 - Integrated X-Command (in 20*N·s) by Subject and Day

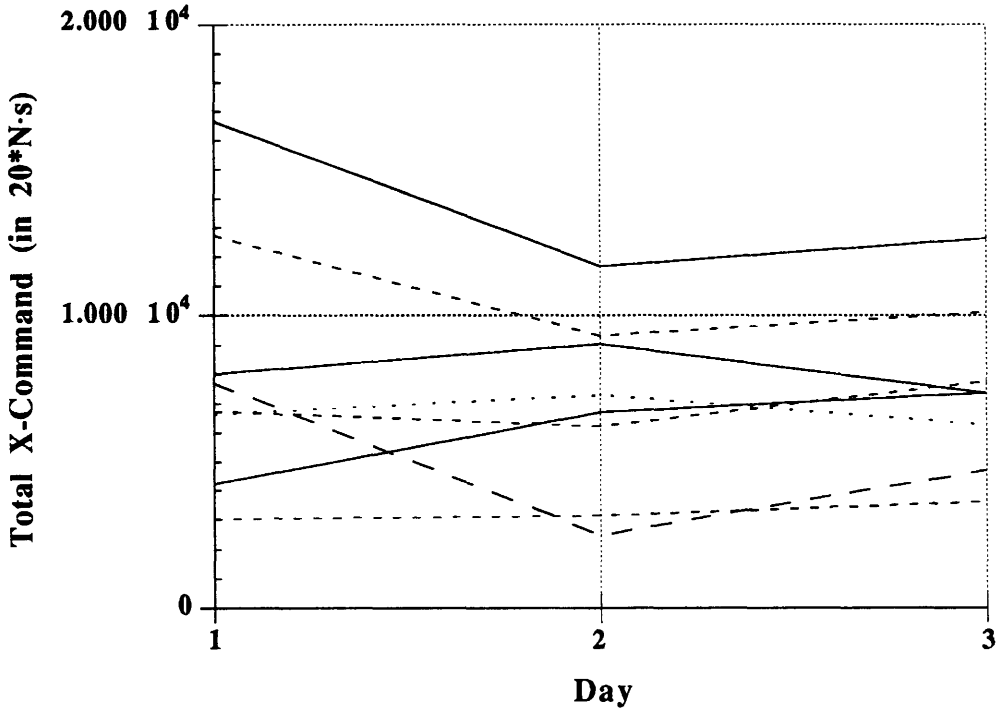

Figure A.25 - Integrated X-Command (in 20*N·s) by Day for all Subjects

A.2.5 Integrated Y-Axis Force Command

Referring to Table A.68, it is evident that there is a wide range of means and standard deviations between subjects, when averaged over all configurations for each subject. There is little difference between configurations, however, in the means averaged over all subjects, and there seems to be no correlation between configuration and integrated Y-command. The Y-command data are reasonably normally-distributed (Fig. A.26), and the first ANOVA shows the subject, display, and runday factors to be statistically-significant (Table A.69). The second ANOVA shows subject and runday as significant also, but the display variable falls just below the p=.05 level of significance (Table A.70).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	11500	1725	6414	1551	10164	4008	12184	1483
monitor+body	12107	933	5729	691	12523	7301	12415	1606
HMD	10363	1057	6666	957	9648	1513	11509	1879
HMD+body	10706	1837	7910	949	9157	2267	11358	958
HMD+track	11677	2633	7314	1086	7808	69	11169	2299
HMD+track+body	12960	871	8325	1464	10205	1329	13724	1123
all configurations	11552	1634	7060	1156	9917	3619	12060	1621

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	17007	3760	5790	703	14004	531	9973	476	10880	2202
monitor+body	13208	4164	7094	1664	15233	1558	11458	1619	11221	3209
HMD	14023	887	7740	1749	13133	2074	9776	1323	10357	1489
HMD+body	12211	1061	8833	1379	11041	1610	10474	596	10211	1428
HMD+track	14742	2299	7307	3746	13213	3791	9941	644	10396	2437
HMD+track+body	13561	1675	9341	4126	13457	981	11531	533	11638	1837
all configurations	14125	2629	7684	2559	13347	2039	10525	971	10784	2188

Table A.68 - Integrated Y-Command (in 20*N·s) by Subject and Configuration

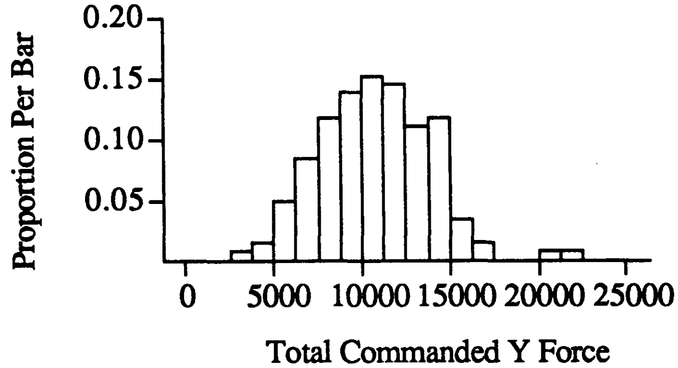

Figure A.26 - Distribution of Integrated Y-Commands (in 20*N·s)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**567497000.**	**7**	**81071000.**	**20.539**	**0.000**
Display	**23555400.**	**1**	**23555400.**	**5.968**	**0.016**
Track	14341900.	1	14341900.	3.633	0.060
Body	12356500.	1	12356500.	3.130	0.080
Sqdir	5893787.158	1	5893787.158	1.493	0.225
Day	21259300.	2	10629700.	2.693	0.073
Runday	**58324500.**	**5**	**11664900.**	**2.955**	**0.016**
Subject*Display	29063200.	7	4151887.013	1.052	0.401
Subject*Track	17775800.	7	2539399.414	0.643	0.719
Subject*Body	21508900.	7	3072701.504	0.778	0.607
Day*Runday	34017500.	10	3401749.543	0.862	0.571
Display*Body	1436540.343	1	1436540.343	0.364	0.548
Track*Body	14355500.	1	13255500.	3.358	0.070
Error	363139000.	92	3947160.164		

Table A.69 - Integrated Y-Command ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**796437000.**	**7**	**113777000.**	**28.446**	**0.000**
Display	15552200.	1	15552200.	3.888	0.051
Track	15181200.	1	15181200.	3.796	0.054
Body	13651500.	1	13651500.	3.413	0.067
Day	21259300.	2	10629700.	2.658	0.074
Runday	**81063600.**	**5**	**16212600.**	**4.053**	**0.002**
Track*Body	10885600.	1	10885600.	2.722	0.102
Error	499963000.	125	3999703.072		

Table A.70 - Integrated Y-Command Revised ANOVA

The effects of the display are examined since the display variable is clearly significant in the first ANOVA and nearly significant at the p=.05 level in the second. Six of the subjects applied a greater total Y-command when using the monitor than when using the HMD, and the mean over all subjects is greater with the monitor than the HMD (Table A.71).

	subject 1		**subject 2**		**subject 3**		**subject 4**			
	mean	**stdev**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**		
monitor	11803	1284	6072	1138	11343	5424	12300	1388		
HMD	10535	1353	7288	1091	9402	1745	11433	1336		
both	11169	1319	6680	1115	10373	4029	11866	1362		
	subject 5		**subject 6**		**subject 7**		**subject 8**		**all subjects**	
	mean	**stdev**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
monitor	15108	4113	6442	1347	14619	1240	10716	1342	11050	2654
HMD	13117	1323	8287	1531	12087	2018	10125	994	10284	1458
both	14112	3055	7364	1442	13353	1674	10420	1181	10667	2141

Table A.71 - Integrated Y-Command (in 20*N·s) by Subject and Display

Although the means over all subjects increase steadily between the first and last runs of the day, none of the individual subjects' means follows this same trend (Table A.72).

Examining Figure A.27 it appears that there is indeed some upward trend in integrated Y-command over the run numbers, but it is not at clear exactly what the form of this trend is.

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
runday = 1	11720	637	6156	904	8833	1460	12168	290
runday = 2	11769	1721	7684	1138	10356	1368	12236	3150
runday = 3	10386	1389	7304	1112	9364	1811	12471	1993
runday = 4	10690	1743	7607	1615	7467	631	11969	2370
runday = 5	11593	2285	7163	1367	10414	3761	12099	1319
runday = 6	13155	1415	6444	2088	13069	6929	11417	484
all runs	11552	1610	7060	1425	9917	3412	12060	1896

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
runday = 1	11638	3288	4668	1541	12113	1844	10422	1884	9715	1717
runday = 2	13351	1637	6602	1958	11705	2133	10174	1910	10484	1961
runday = 3	15411	5188	8128	2328	13268	789	10512	961	10855	2353
runday = 4	14092	1227	7947	1784	12992	3463	10486	486	10406	1890
runday = 5	14591	1080	8544	881	14142	458	10443	180	11124	1774
runday = 6	15670	1453	10217	3063	15859	1139	11116	1078	12118	2927
all runs	14125	2744	7684	2040	13347	1918	10525	1262	10784	2145

Table A.72 - Integrated Y-Command (in 20*N·s) by Subject and Runday

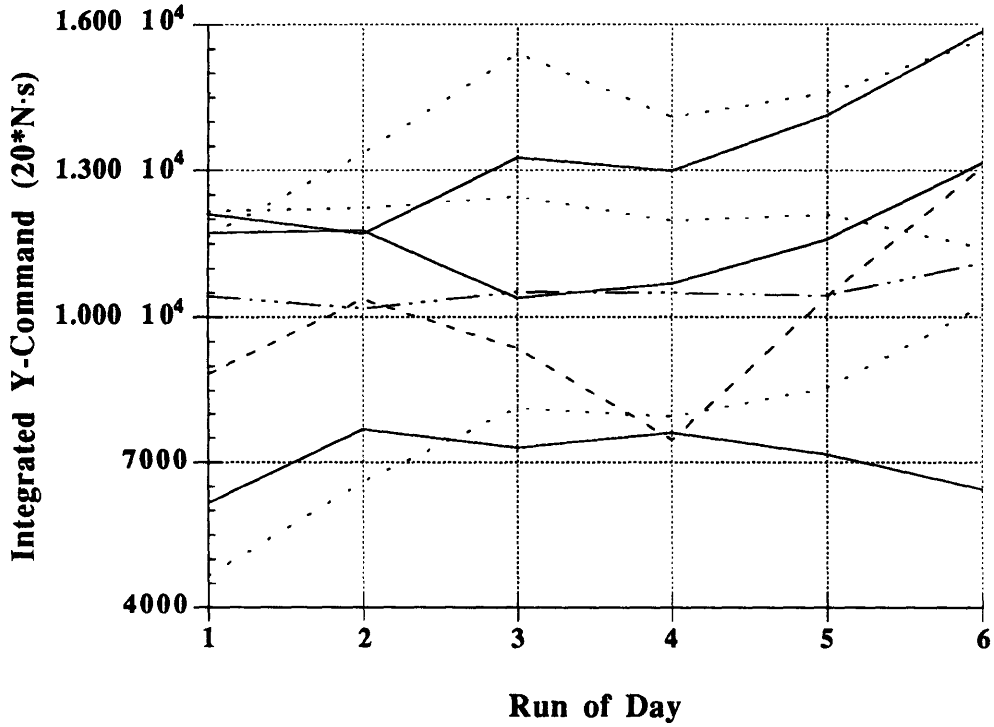

Figure A.27 - Integrated Y-Command (in 20*N·s) by Run of Day for all Subjects

A.2.6 Integrated Z-Axis Torque Command

The HMD without head-tracking, without the vehicle body configuration resulted in the largest mean integrated Z-axis commanded torque over all subjects, and was significantly larger than the same setup with the vehicle body displayed (Table A.73). With the monitor and the HMD with head-tracking, the presence or absence of the vehicle body made little difference. Like previous variables, the Z-command data are nearly normally-distributed with several large-valued outliers (Fig. A.28). The ANOVAs indicated that the subject, display, and day variables and the display x body and track x body interactions were statistically-significant (Tables A.74, A.75).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	6717	451	5750	1698	5209	2022	6194	799
monitor+body	6682	1956	6264	1926	7179	4172	5537	910
HMD	7150	797	5612	1149	8505	3195	7766	1864
HMD+body	8127	2538	5627	730	8617	2419	6021	1464
HMD+track	7403	1140	5062	2952	5898	1379	5212	1377
HMD+track+body	7462	1575	4889	1815	8868	4364	6579	2550
all configurations	7257	1575	5534	1846	7379	3123	6218	1606

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	7965	501	5564	1506	10457	2977	5774	677	6704	1567
monitor+body	6350	3258	6836	1145	9433	1198	6504	796	6848	2230
HMD	7733	982	13946	8628	12350	4162	6316	2047	8672	3751
HMD+body	6108	1927	6831	1674	7928	1911	5620	593	6860	1785
HMD+track	8043	2011	12108	5330	9498	3794	6999	899	7528	2772
HMD+track+body	7324	828	9451	3759	10095	2345	6207	1032	7610	2567
all configurations	7254	1838	9123	4534	9960	2920	6237	1118	7370	2548

Table A.73 - Integrated Z-Command (in 20*N·m·s) by Subject and Configuration

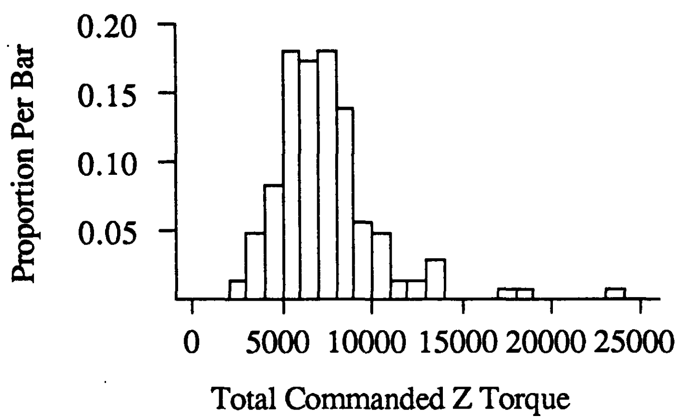

Figure A.28 - Distribution of Integrated Z-Commands (in 20*N·m·s)

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**153464000.**	**7**	**21923500.**	**3.589**	**0.002**
Display	20728000.	1	20728000.	3.393	0.069
Track	381916.551	1	381916.551	0.063	0.803
Body	218841.140	1	218841.140	0.036	0.850
Sqdir	3322892.490	1	3322892.490	0.544	0.463
Day	**64194300.**	**2**	**32097200.**	**5.254**	**0.007**
Runday	5305614.035	5	1061122.807	0.174	0.972
Subject*Display	48709100.	7	6958436.867	1.139	0.346
Subject*Track	11474200.	7	1639176.477	0.268	0.965
Subject*Body	64670700.	7	9238662.659	1.512	0.173
Day*Runday	40472900.	10	4047290.798	0.663	0.756
Display*Body	19579500.	1	19579500.	3.205	0.077
Track*Body	17215700.	1	17215700.	2.818	0.097
Error	562021000.	92	6108919.732		

Table A.74 - Integrated Z-Command ANOVA

Source	Sum-of-Squares	DOF	Mean-Square	F-Ratio	p
Subject	**284203000.**	**7**	**40600500.**	**7.163**	**0.000**
Display	**25435400.**	**1**	**25435400.**	**4.488**	**0.036**
Day	**64194300.**	**2**	**32097200.**	**5.663**	**0.004**
Subject*Body	59788600.	7	8541235.169	1.507	0.171
Display*Body	**27190300.**	**1**	**27190300.**	**4.797**	**0.030**
Track*Body	**25371500.**	**1**	**25371500.**	**4.476**	**0.036**
Error	702820000.	124	5667900.822		

Table A.75 - Integrated Z-Command Revised ANOVA

Although only five of the eight subjects have Z-command means which are larger for the HMD without head-tracking than for the monitor, the average mean over all subjects is about fifteen percent larger with the HMD than with the monitor and the average standard deviation is seventy percent greater (Table A.76).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	6699	1270	6007	1648	6194	3125	5865	846
HMD	7638	1765	5619	861	8561	2535	6893	1778
both	7169	1538	5813	1315	7377	2845	6379	1392

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
monitor	7157	2265	6200	1385	9945	2106	6139	773	6776	1833
HMD	6920	1632	10389	6789	10139	3775	5968	1401	7766	3131
both	7039	1974	8294	4899	10042	3057	6053	1131	7271	2565

Table A.76 - Integrated Z-Command (in 20*N·m·s) by Subject and Display

Looking at the data arranged by day, it is apparent that the general trend, as well as the trend for four of the subjects, is a decrease in integrated Z-command from first day to the second and then an increase between the second and third days (Table A.77, Fig. A.29).

	subject 1		subject 2		subject 3		subject 4	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
day 1	8317	1565	4579	1123	9227	3652	7210	892
day 2	7363	893	6205	1443	6925	1468	4749	808
day 3	6090	764	5818	1961	5986	2901	6696	1769
all days	7257	1130	5534	1548	7379	2823	6218	1235

	subject 5		subject 6		subject 7		subject 8		all subjects	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
day 1	7077	1235	12870	6871	11037	3533	6154	807	8309	3157
day 2	6591	2592	6882	1809	9996	2642	5780	964	6811	1717
day 3	8093	739	7616	2554	8848	2118	6776	1251	6990	1907
all days	7254	1712	9123	4359	9960	2825	6237	1024	7370	2349

Table A.77 - Integrated Z-Command (in 20*N·m·s) by Subject and Day

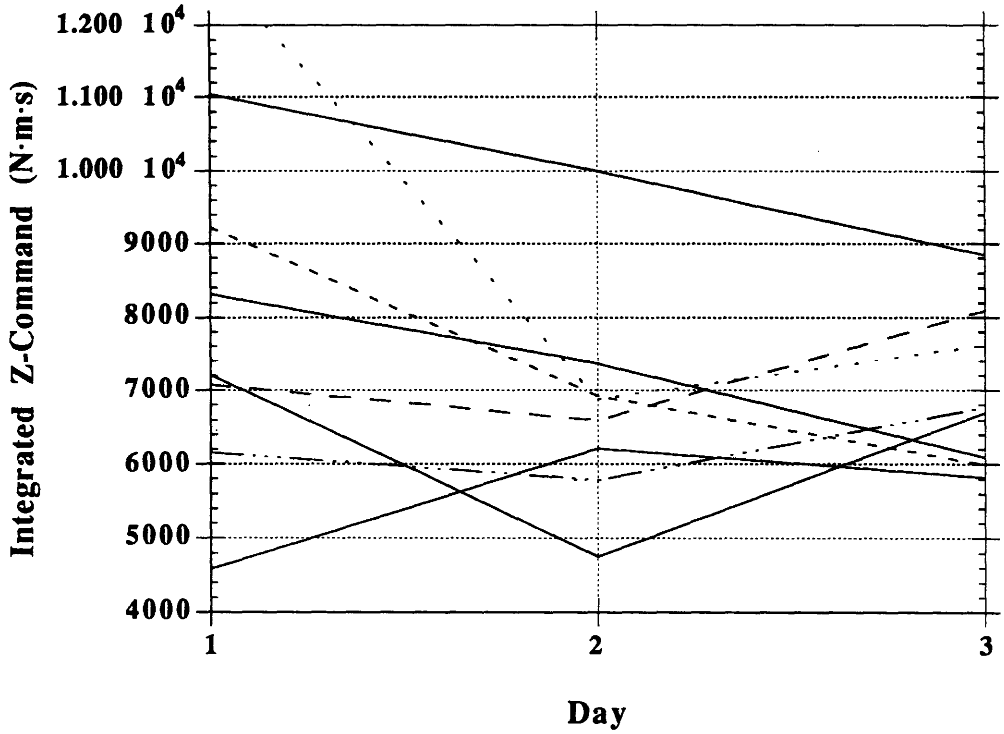

Figure A.29 - Integrated Z-Command (in N·m·s) by Day for all Subjects

Table A.78 is arranged to examine the display x body interaction. When the vehicle body was not displayed, replacing the monitor with the HMD significantly increased the mean and standard deviation of the integrated Z-commands. With the vehicle-body image shown, however, the monitor and HMD had nearly identical mean integrated Z-commands and similar standard deviations.

	monitor		HMD	
	mean	stdev	mean	stdev
without body	6703.5	2116.6	8672.2	4201.7
with body	6848.0	2159.6	6859.9	1882.0

Table A.78 - Integrated Z-Command (in 20*N·m·s) by Display and Body

With the HMD without head-tracking, adding the vehicle body significantly decreased the mean and standard deviation of integrated Z-command (Table A.79). When using the HMD with head-tracking, however, adding the vehicle body made little difference in the mean or standard deviation. Because of this interaction between the vehicle body and head-tracking, when the vehicle body was absent the HMD with tracking configuration resulted in less total Z-command, but with the vehicle body present the HMD without head-tracking showed the lower total.

	HMD		HMD+track	
	mean	stdev	mean	stdev
without body	8672.2	4201.7	7527.7	3240.3
with body	6859.9	1882.0	7609.5	2722.4

Table A.79 - Integrated Z-Command (in 20*N·m·s) by Head-Tracking and Body

Appendix B Text of Experimental Introduction

"In this set of experiments, you will be controlling a simulation of a remotely-operated vehicle. You will use a pair of joysticks to command inputs to the vehicle, and you will get video feedback which represents the signal coming from a video camera mounted on the vehicle you are controlling. The vehicle will be free to move and rotate in two dimensions. You will use the joysticks to command accelerations of the vehicle. You will be able to command accelerations in the forward, backward, right, and left directions, and you will be able to command rotational accelerations: rotate to the right and rotate to the left. Because you will be commanding accelerations, and since there are no external forces on the vehicle, the vehicle will act like a puck with thrusters mounted on it sliding on a surface of ice. For example, if you command a short forward acceleration the vehicle will begin moving forward in a straight line. It will continue to move forward at a constant speed until you command a backward acceleration to stop the motion. The same holds for rotational motion: if you command a short rotational acceleration to the right, the vehicle will begin rotating to the right. It will continue to do so at constant angular velocity until you counter the motion with a rotational acceleration to the left.

"You will be given video feedback from a fixed monitor or a head-mounted display. The head-mounted display will sometimes be used with head-tracking, where the orientation of your head will be used to transform the image you see. When the image you see moves with the motion of your head, this represents motion of the camera with respect to the vehicle it is mounted on, and not motion of the vehicle itself. This is like having a camera mounted on the vehicle with a set of motors and gears which can point the camera in different directions based on the orientation of your head. Again, moving your head to look in different directions does not affect the motion of the vehicle or how your joystick commands move the vehicle. For example, if you are looking directly to the right and you command a forward acceleration, you will see the environment begin moving from left to right across the screen, just as if you were driving a car and turned to look at buildings going by on the right side of the street. Please note that the head tracker has a slightly limited range, so you cannot quite look directly behind you.

"In all cases the environment, or terrain, in which the vehicle operates will consist of a grid below the vehicle, representing the ground, and stars in the distance. In some cases the images you see will be the environment around the vehicle exactly as it would be seen by a camera moving through space. In other cases, you will see the environment, and you will also see a representation of the body of the vehicle you are controlling. This body representation will be the outline of a car, and you will be looking out through the car frame at the environment. You will see a windshield in front of you and a hood stretching out in front of you.

"Two different tasks will be run repeatedly. The first task is a set of randomly-appearing columns, with one column visible at a time. You must locate each column and navigate the vehicle directly to the column. Your objective in this task is to navigate to the columns as accurately as possible. The vehicle's velocity as you approach the column should be pointing directly at the column. Also, the vehicle should be oriented so that the front of the vehicle is pointing directly at the column. As you are performing the task, remember that the most important thing is to minimize misalignment of the velocity and orientation of the vehicle with respect to the columns. Fly as fast as you feel comfortable such that your accuracy is not reduced. As you reach each column, that column will disappear and another will appear somewhere on the grid. If the next column is not within your immediate field of view, you may have to search for it.

"The second task will be consist of a square of columns. You must slalom in and out through the columns as shown in the diagram, which is a top view of the environment. You will start out at one of the two endpoints in the lower left corner of the diagram and must circumnavigate the square once. You must fly to the outside of the corner columns and the inside of the side columns. You will be going around the square in different directions on different runs. When you begin a run, if the column nearest you is offset to the right, you must fly to the left of it, and will be moving around the square in the clockwise direction on the diagram. If the nearest column is offset to the left, you must fly to the right of it and you will be moving around in the counterclockwise direction. Try to navigate at a speed such that you are always under control, and it is very unlikely that you will ever accidentally pass on the wrong side of a column. However, if you do go through or pass to the wrong side of a column, continue on with the task, maneuvering around the correct side of the next column.

"Each half-hour session will consist of six runs. The screen will go blank when you have completed each run. Before each run you will be told which video device you will be using, whether there will be head tracking if you're using the helmet-mounted display, and whether the vehicle body will be displayed or not. At the beginning of each session you will be told which task you will be performing for the six runs in that session. If you ever feel you must stop the experiment for any reason, please let me know immediately."

Appendix C Test Subject Questionnaire Data

All questions on this form are optional -- answer only those you wish. For each question, fill in the blank or circle your choice as appropriate. If you have any questions, please feel free to ask. Thank you.

Subject number: __1__
Sex: (**M** / F)
Age: __23__

1. Do you know how to drive a car? (**yes** / no)
   If yes:
      Do you drive (daily / regularly / **rarely**)?

2. Do you have any aircraft piloting experience? (yes / **no**)
   If yes:
      Do you fly (weekly / monthly / rarely)?
      How many total hours have you logged? ______

3. Do you play video or computer games? (**yes** / no)
   If yes:
      Do you play these games (**daily** / regularly / rarely)?

4. Do you play flight- or driving-simulation video games? (**yes** / no)
   If yes:
      Do you play these games (daily / **regularly** / rarely)?

5. About how good is your vision (e.g. 20/50)? 20/250

6. Do you have any vision irregularities (e.g. astigmatism)? (**yes** / no)
   If yes:
      Please describe: **astigmatism, nearsighted**

7. Do you wear corrective lenses? (**yes** / no)
   If yes:
      Will you be wearing them during the experiment? (yes / **no**)
      What is your corrected vision (e.g. 20/50)? 20/20

8. Are you color-blind? (yes / **no**)

9. Are you dyslexic? (yes / **no**)

10. Are you (**right-handed** / left-handed / ambidextrous)?

11. Are you (very / **slightly** / not at all) susceptible to motion sickness?

All questions on this form are optional -- answer only those you wish. For each question, fill in the blank or circle your choice as appropriate. If you have any questions, please feel free to ask. Thank you.

Subject number: 2
Sex: (M / **F**)
Age: 22

1. Do you know how to drive a car? (**yes** / no)
   If yes:
   Do you drive (daily / regularly / **rarely**)?

2. Do you have any aircraft piloting experience? (yes / **no**)
   If yes:
   Do you fly (weekly / monthly / rarely)?
   How many total hours have you logged? ______

3. Do you play video or computer games? (**yes** / no)
   If yes:
   Do you play these games (daily / **regularly** / rarely)?

4. Do you play flight- or driving-simulation video games? (yes / **no**)
   If yes:
   Do you play these games (daily / regularly / rarely)?

5. About how good is your vision (e.g. 20/50)? 20/20

6. Do you have any vision irregularities (e.g. astigmatism)? (yes / **no**)
   If yes:
   Please describe: ______________________________

7. Do you wear corrective lenses? (yes / **no**)
   If yes:
   Will you be wearing them during the experiment? (yes / no)
   What is your corrected vision (e.g. 20/50)? ______

8. Are you color-blind? (yes / **no**)

9. Are you dyslexic? (yes / **no**)

10. Are you (**right-handed** / left-handed / ambidextrous)?

11. Are you (very / **slightly** / not at all) susceptible to motion sickness?

All questions on this form are optional -- answer only those you wish. For each question, fill in the blank or circle your choice as appropriate. If you have any questions, please feel free to ask. Thank you.

Subject number: 3
Sex: (**M** / F)
Age: 23

1. Do you know how to drive a car? (**yes** / no)
   If yes:
   Do you drive (daily / **regularly** / rarely)?

2. Do you have any aircraft piloting experience? (yes / **no**)
   If yes:
   Do you fly (weekly / monthly / rarely)?
   How many total hours have you logged? ______

3. Do you play video or computer games? (**yes** / no)
   If yes:
   Do you play these games (daily / regularly / **rarely**)?

4. Do you play flight- or driving-simulation video games? (yes / **no**)
   If yes:
   Do you play these games (daily / regularly / rarely)?

5. About how good is your vision (e.g. 20/50)? 20/80

6. Do you have any vision irregularities (e.g. astigmatism)? (yes / **no**)
   If yes:
   Please describe: ______________________

7. Do you wear corrective lenses? (yes / **no**)
   If yes:
   Will you be wearing them during the experiment? (yes / no)
   What is your corrected vision (e.g. 20/50)? ______

8. Are you color-blind? (yes / **no**)

9. Are you dyslexic? (yes / **no**)

10. Are you (**right-handed** / left-handed / ambidextrous)?

11. Are you (very / slightly / **not at all**) susceptible to motion sickness?

All questions on this form are optional -- answer only those you wish. For each question, fill in the blank or circle your choice as appropriate. If you have any questions, please feel free to ask. Thank you.

Subject number: 4
Sex: (M / **F**)
Age: 22

1. Do you know how to drive a car? (**yes** / no)
   If yes:
   Do you drive (**daily** / regularly / rarely)?

2. Do you have any aircraft piloting experience? (yes / **no**)
   If yes:
   Do you fly (weekly / monthly / rarely)?
   How many total hours have you logged? ______

3. Do you play video or computer games? (**yes** / no)
   If yes:
   Do you play these games (daily / regularly / **rarely**)?

4. Do you play flight- or driving-simulation video games? (yes / **no**)
   If yes:
   Do you play these games (daily / regularly / rarely)?

5. About how good is your vision (e.g. 20/50)? 20/1000?

6. Do you have any vision irregularities (e.g. astigmatism)? (**yes** / no)
   If yes:
   Please describe: **slight astigmatism**

7. Do you wear corrective lenses? (**yes** / no)
   If yes:
   Will you be wearing them during the experiment? (**yes** / no)
   What is your corrected vision (e.g. 20/50)? 20/20

8. Are you color-blind? (yes / **no**)

9. Are you dyslexic? (yes / **no**)

10. Are you (**right-handed** / left-handed / ambidextrous)?

11. Are you (very / **slightly** / not at all) susceptible to motion sickness?

All questions on this form are optional -- answer only those you wish. For each question, fill in the blank or circle your choice as appropriate. If you have any questions, please feel free to ask. Thank you.

Subject number: 5
Sex: (**M** / F)
Age: 24

1. Do you know how to drive a car? (**yes** / no)
   If yes:
   Do you drive (**daily** / regularly / rarely)?

2. Do you have any aircraft piloting experience? (**yes** / no)
   If yes:
   Do you fly (weekly / **monthly** / rarely)?
   How many total hours have you logged? 1700

3. Do you play video or computer games? (**yes** / no)
   If yes:
   Do you play these games (daily / regularly / **rarely**)?

4. Do you play flight- or driving-simulation video games? (**yes** / no)
   If yes:
   Do you play these games (daily / regularly / **rarely**)?

5. About how good is your vision (e.g. 20/50)? 20/50

6. Do you have any vision irregularities (e.g. astigmatism)? (**yes** / no)
   If yes:
   Please describe: **astigmatism, both eyes - strong**

7. Do you wear corrective lenses? (**yes** / no)
   If yes:
   Will you be wearing them during the experiment? (**yes** / no)
   What is your corrected vision (e.g. 20/50)? 20/20

8. Are you color-blind? (yes / **no**)

9. Are you dyslexic? (yes / **no**)

10. Are you (**right-handed** / left-handed / ambidextrous)?

11. Are you (very / **slightly** / not at all) susceptible to motion sickness?

All questions on this form are optional -- answer only those you wish. For each question, fill in the blank or circle your choice as appropriate. If you have any questions, please feel free to ask. Thank you.

Subject number: 6
Sex: (**M** / F)
Age: 27

1. Do you know how to drive a car? (**yes** / no)
   If yes:
   Do you drive (daily / **regularly** / **rarely**)?

2. Do you have any aircraft piloting experience? (yes / **no**)
   If yes:
   Do you fly (weekly / monthly / rarely)?
   How many total hours have you logged? ______

3. Do you play video or computer games? (yes / **no**)
   If yes:
   Do you play these games (daily / regularly / rarely)?

4. Do you play flight- or driving-simulation video games? (yes / **no**)
   If yes:
   Do you play these games (daily / regularly / rarely)?

5. About how good is your vision (e.g. 20/50)? ?

6. Do you have any vision irregularities (e.g. astigmatism)? (**yes** / no)
   If yes:
   Please describe: have some sort of astigmatism

7. Do you wear corrective lenses? (**yes** / no)
   If yes:
   Will you be wearing them during the experiment? (yes / **no**)
   What is your corrected vision (e.g. 20/50)? ______

8. Are you color-blind? (yes / **no**)

9. Are you dyslexic? (yes / **no**)

10. Are you (**right-handed** / left-handed / ambidextrous)?

11. Are you (very / **slightly** / not at all) susceptible to motion sickness?

All questions on this form are optional -- answer only those you wish. For each question, fill in the blank or circle your choice as appropriate. If you have any questions, please feel free to ask. Thank you.

Subject number: 7
Sex: (**M** / F)
Age: 23

1. Do you know how to drive a car? (**yes** / no)
   If yes:
   Do you drive (daily / **regularly** / rarely)?

2. Do you have any aircraft piloting experience? (yes / **no**)
   If yes:
   Do you fly (weekly / monthly / rarely)?
   How many total hours have you logged? ______

3. Do you play video or computer games? (**yes** / no)
   If yes:
   Do you play these games (daily / **regularly** / rarely)?

4. Do you play flight- or driving-simulation video games? (**yes** / no)
   If yes:
   Do you play these games (daily / **regularly** / rarely)?

5. About how good is your vision (e.g. 20/50)? 20/50

6. Do you have any vision irregularities (e.g. astigmatism)? (**yes** / no)
   If yes:
   Please describe: **yes, astigmatism, left eye slow to focus**

7. Do you wear corrective lenses? (**yes** / no)
   If yes:
   Will you be wearing them during the experiment? (**yes** / no)
   What is your corrected vision (e.g. 20/50)? 20/20

8. Are you color-blind? (yes / **no**)

9. Are you dyslexic? (yes / **no**)

10. Are you (**right-handed** / left-handed / ambidextrous)?

11. Are you (very / **slightly** / not at all) susceptible to motion sickness?

All questions on this form are optional -- answer only those you wish. For each question, fill in the blank or circle your choice as appropriate. If you have any questions, please feel free to ask. Thank you.

Subject number: __8__
Sex: (**M** / F)
Age: __24__

1. Do you know how to drive a car? (**yes** / no)
   If yes:
   Do you drive (daily / **regularly** / rarely)?

2. Do you have any aircraft piloting experience? (yes / **no**)
   If yes:
   Do you fly (weekly / monthly / rarely)?
   How many total hours have you logged? ______

3. Do you play video or computer games? (**yes** / no)
   If yes:
   Do you play these games (daily / **regularly** / rarely)?

4. Do you play flight- or driving-simulation video games? (**yes** / no)
   If yes:
   Do you play these games (daily / **regularly** / rarely)?

5. About how good is your vision (e.g. 20/50)? ______

6. Do you have any vision irregularities (e.g. astigmatism)? (yes / **no**)
   If yes:
   Please describe: ____
   ____

7. Do you wear corrective lenses? (**yes** / no)
   If yes:
   Will you be wearing them during the experiment? (yes / **no**)
   What is your corrected vision (e.g. 20/50)? ______

8. Are you color-blind? (yes / **no**)

9. Are you dyslexic? (yes / **no**)

10. Are you (right-handed / **left-handed** / ambidextrous)?

11. Are you (very / **slightly** / not at all) susceptible to motion sickness?