An Investigation into the Cognitive Effects of Delayed Visual Feedback

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Thesis submitted
for the
Degree of Doctor of Philosophy

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February 2003

Abstract

The purpose of this thesis is to investigate the cognitive effects that delays in visual feedback have on real-time system users, especially operators of remote vehicles. Pilot work was carried out and then hypotheses were formed regarding the cognitive nature of visual delay effects; namely visual delays cause disruption to working memory. These hypotheses were then investigated with virtual reality based driving experiments.

Results from these experiments supported this hypothesis. Further experiments were then performed using a control system model to evaluate whether a system that made use of a mechanism analagous to working memory would behave in a similar manner to human operators. This system did indeed behave in a similar manner, with the same pattern of instability in tracking performance with the introduction of visual delays and additional interpolated tasks (similar to visual interference tasks). It is suggested that the control system model that was derived may well have use in further investigations regarding how to compensate for visual delays.

The thesis achieved the following goals: (1) previous work was replicated in showing the detrimental effects of delayed visual feedback, (2) past work was extended by investigating the cognitive nature of these effects and highlighting which cognitive mechanisms appear to be failing; namely by demonstrating a link between visual delays and working memory disruption, (3) a virtual environment was created to enable the investigation of complex tasks in a measurable manner thus demonstrating the use of immersive virtual reality in conducting complex experiments, (4) a model is proposed that introduces variable delay dependent on task complexity and demonstrates similar results to human performance when using delayed feedback.

To my son, Joel, for teaching me more about life, and to my father, John, for showing me the way.

Acknowledgments

I would like to acknowledge the efforts of the following during the preparation of this thesis: Dr. Patrik O'Brian Holt for supervising and answering many questions; Prof. George Russell for setting goals and for the invaluable help with modelling; Dr. Gus Ferguson for the loan of the laptop allowing work to continue even after the birth of my son; Alistair Houstin for the technical help and procurement; Hugh Connor for the advice and help in getting the VR system to an operational state, Alan Wilson and Tom Marshall for their work on developing the delay hardware; David Inglis and Lyndsey McKenzie for collecting the data for pilot studies 2 and 3; my wonderful wife for encouraging and bearing with all my faults; and finally, God, for whom and through whom all this was done.

> *"Now to him who is able to do immeasurably more than all we ask or imagine, according to his power that is at work within us, to him be glory in the church and in Christ Jesus throughout all generations, for ever and ever! Amen."* (Ephesians 3:20-21)

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List of Abbreviations

DAF	Delayed Auditory Feedback.
df	Degrees of freedom. The number of possible options for variation which exist in the data set. (Hayes, 2000)
DSF	Delayed Sensory Feedback.
DVF	Delayed Visual Feedback.
fps	Frames per second (of video).
ISE	Integral of Squared (tracking) Error, $\int \epsilon^2$. A measure of (tracking) performance.
PC	Personal Computer.
RF	Radio Frequency.
ROV	Remotely Operated Vehicle.
RT	Reaction Time. The amount of time taken by a subject in responding to a stimulus. (Eysenck et al., 1975)
SD	Standard Deviation. Defined as $s = \sqrt{\frac{\sum(x-\bar{x})^2}{N-1}}$. A statistical measure which describes how a set of scores are spread out around a mean. (Hayes, 2000)
VR	Virtual Reality.
WM	Working Memory.
wrt	With respect to.

Chapter 1

Introduction

1.1 Overview

This investigation into the effects of delayed visual feedback was commenced as a result of these effects being well known in the use of remotely operated vehicles (ROVs). The problem, that delayed visual feedback adversely affects any remote operation task with a human operator in the loop, has been known for many years. Delays can range from a few milliseconds (as is the case for delays introduced by computer processing) to many minutes (where there are large distances between the operator and vehicle, for example in space robotics applications such as the Mars Rover). However, there has been little work in attempting to define the cognitive nature of this problem.

For this reason pilot studies were carried out to measure the effect on performance of delayed visual feedback. A model of the system, with an operator controlling the vehicle with delayed feedback, was then produced and in-depth experiments designed and performed using custom-written virtual reality (VR) software. From the results gained from these experiments a control systems model was designed and implemented in order to further test hypotheses regarding the cognitive nature of delayed feedback effects. An overview of this experimental and modelling work is given in Section 1.4 of this chapter.

1.2 Research Aims

The research described in this thesis has the following major aims:

- To replicate previous work in showing the detrimental effects of delayed visual feedback on operator performance.
- To investigate the cognitive nature of this effect and highlight which cognitive mechanisms appear to be failing.
- To create a virtual environment to enable the investigation of complex tasks in a measurable manner and allow interpolated tasks to be incorporated in a natural way.
- To create a model that performs in a similar manner to human operators when using delayed feedback.

1.3 Structure of the report

The structure that this report will take is as follows.

A review of the literature relevant to this thesis is given in Chapter 2 including a detailed description of the cognitive element of this investigation (namely human memory and its role in visuo-spatial cognition). Initial pilot work that was carried out in order to better understand and specify the problem is described in Chapter 3 along with the results obtained from these studies.

The knowledge gained from this pilot work was then incorporated into the main experimental design as described in Chapters 4 and 5. As these experiments made use of virtual reality (VR) the software design and implementation was a major undertaking (approximately 12 months work) and is therefore described separately in Chapters 6 and 7. Delays were introduced electronically into the VR system using a device designed and manufactured by technicians in the Department of Computing and Electrical Engineering at Heriot-Watt University. The design and implementation of this system is included in Chapter 8 for reference in order to aid replication of these experiments. Results from the main experiments are then presented and briefly discussed in Chapters 9 and 10.

Once these results were obtained a control system model was designed and implemented to define further the cognitive nature of the problems with delayed feedback. This model is presented along with results of the system navigating around a bend in Chapter 11. The thesis is then concluded with an in-depth discussion of all the factors considered in this study presented in Chapter 12.

1.4 Experimental Framework

The main findings of this thesis are from three major pieces of work; namely pilot work, main experiments and then deriving and testing a control system model. This section explains the interactions and links between these three areas.

As has been mentioned pilot experiments were performed in order to measure, under controlled laboratory conditions, the effects of delays on operator performance (measured by task times and errors). A general model of the experimental system used in all cases was proposed and is presented in Figure 1.1. All pilot studies made use of physical vehicles and conventional measurement techniques (for example timings were measured using a stopwatch, errors in position were measured with a tape measure). The main experiments however were performed using VR with virtual vehicles driving along virtual tracks and measurements being captured automatically by the computer system.

The first pilot study measured the effect on performance of inserting delays into the visual feedback from a camera on-board the vehicle being controlled. This ex-

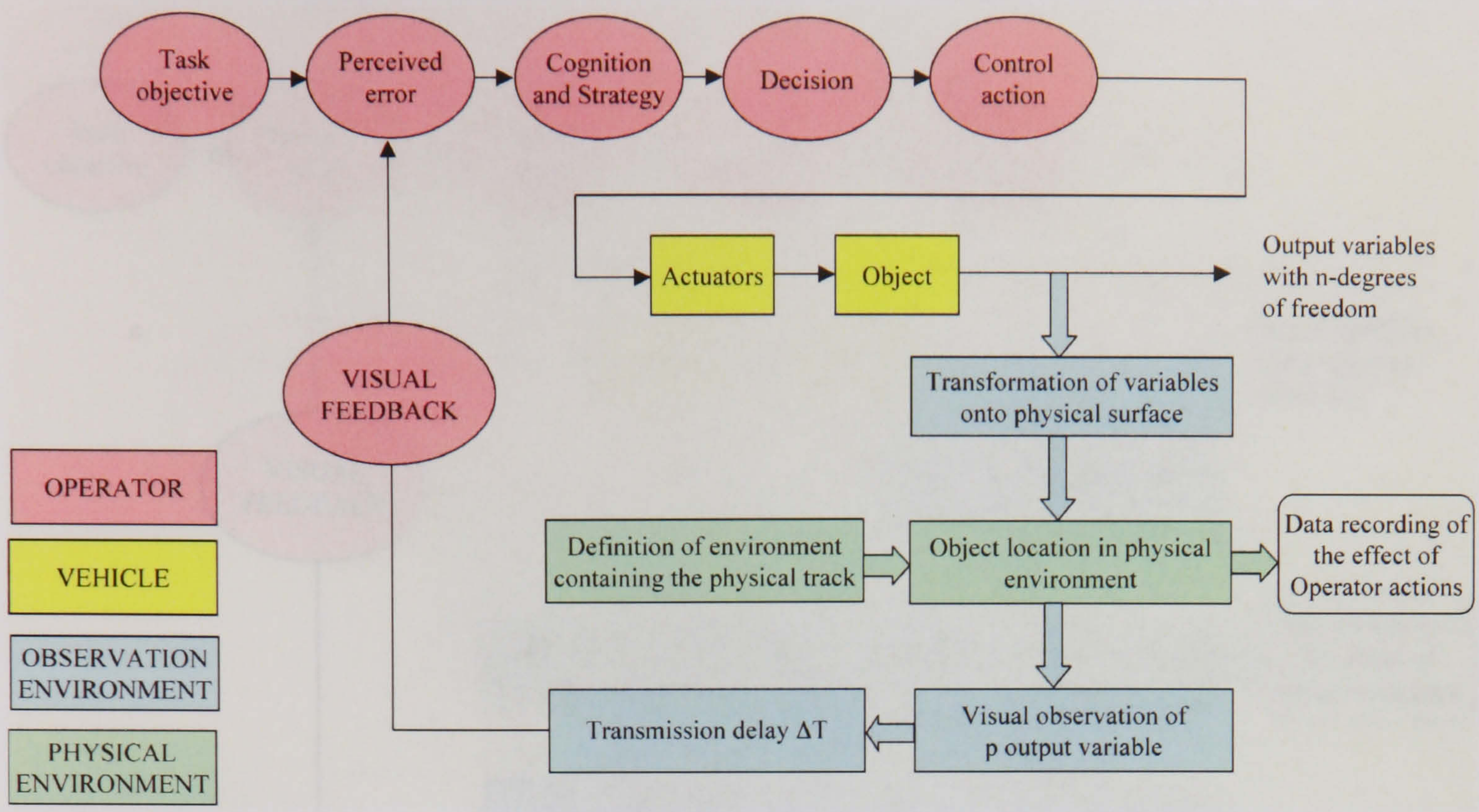


Figure 1.1: General Model of Experimental System

perimental system is summarised in Figure 1.2. However, as a result of the software that was used to insert delays into the feedback, the video was degraded to low frame rates.

In order to understand better the results obtained from the first pilot study, a second study was performed in which the delays inserted into the video were solely a degradation of frame rate (i.e. slow scan feedback) as is described in Figure 1.3.

This work was originally designed to be extended into a consideration of track complexity and low frame rates as summarised in Figure 1.4. However, the complexity of the tracks was later removed (i.e. only one track was used for the experiments) and so in effect the third pilot experiment replicated the results of the second.

Finally, using the knowledge gained from the pilot work a generic model was derived to describe the system processes (including the cognition of the human operator as an integral part of the whole system) as is shown in Figure 1.5. This model was later formalised into a control system model which demonstrated similar results to human operators, in particular, being similarly affected by visual delay,

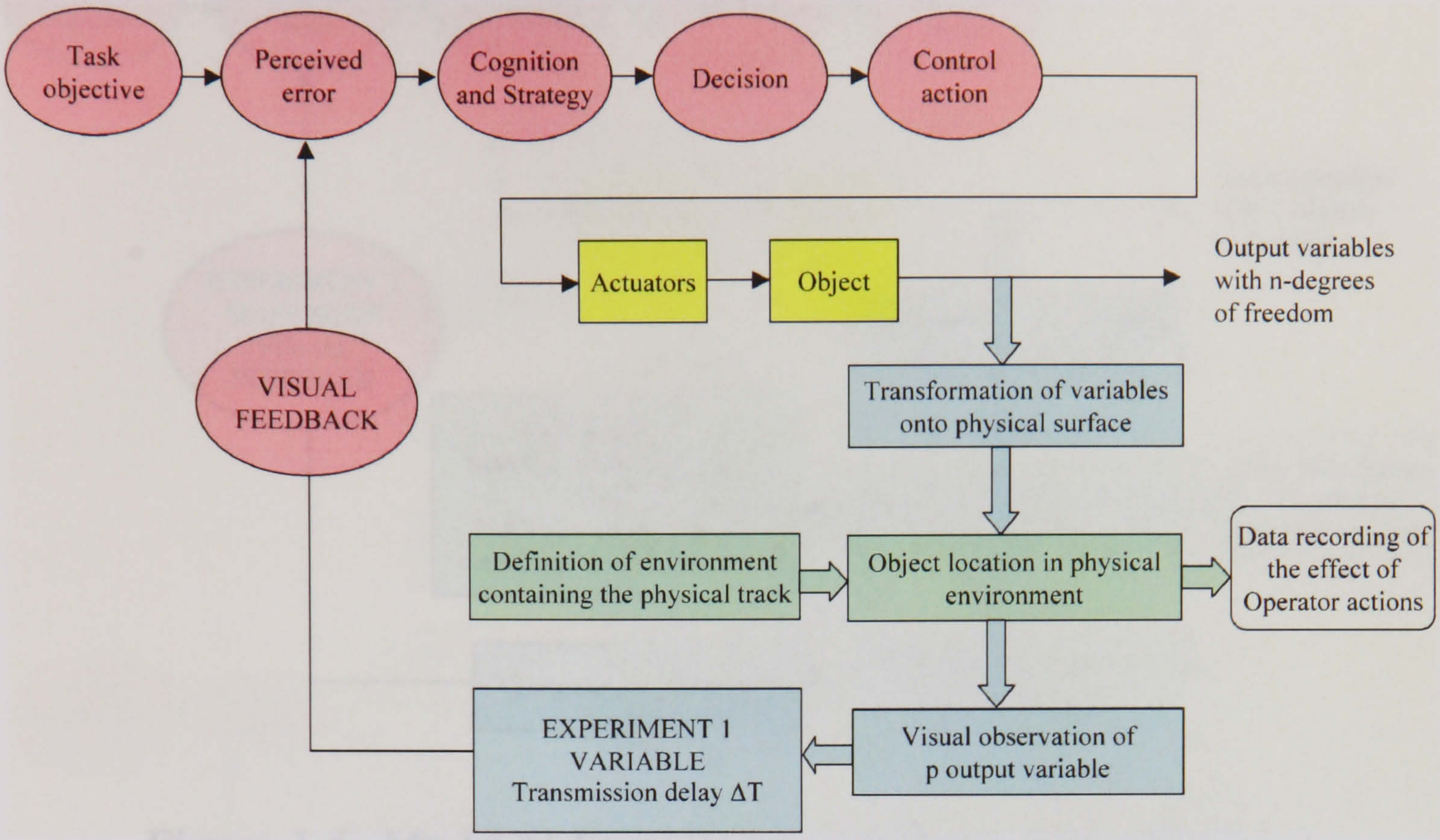


Figure 1.2: Model of Experimental System - Pilot Study 1

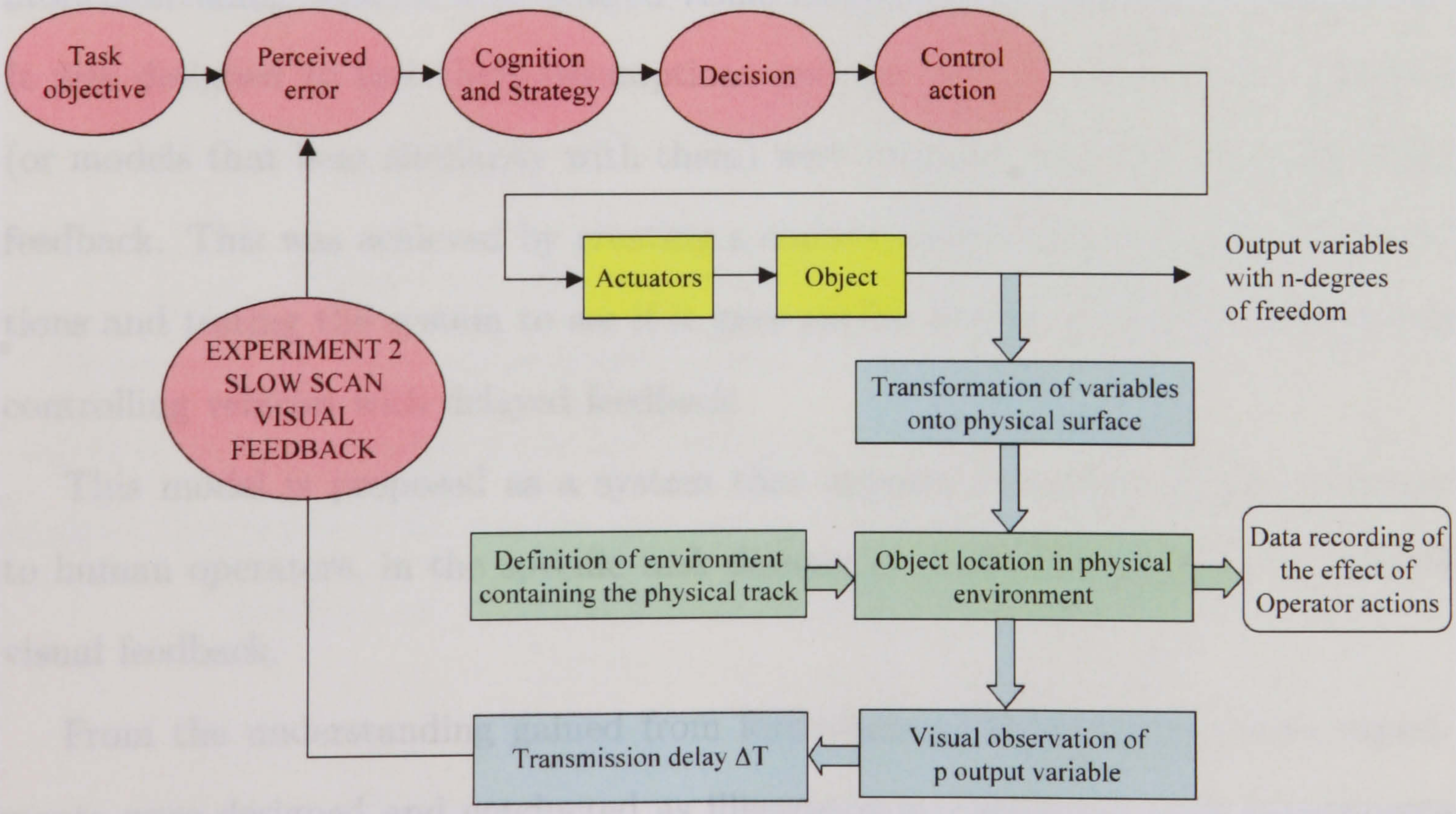


Figure 1.3: Model of Experimental System - Pilot Study 2

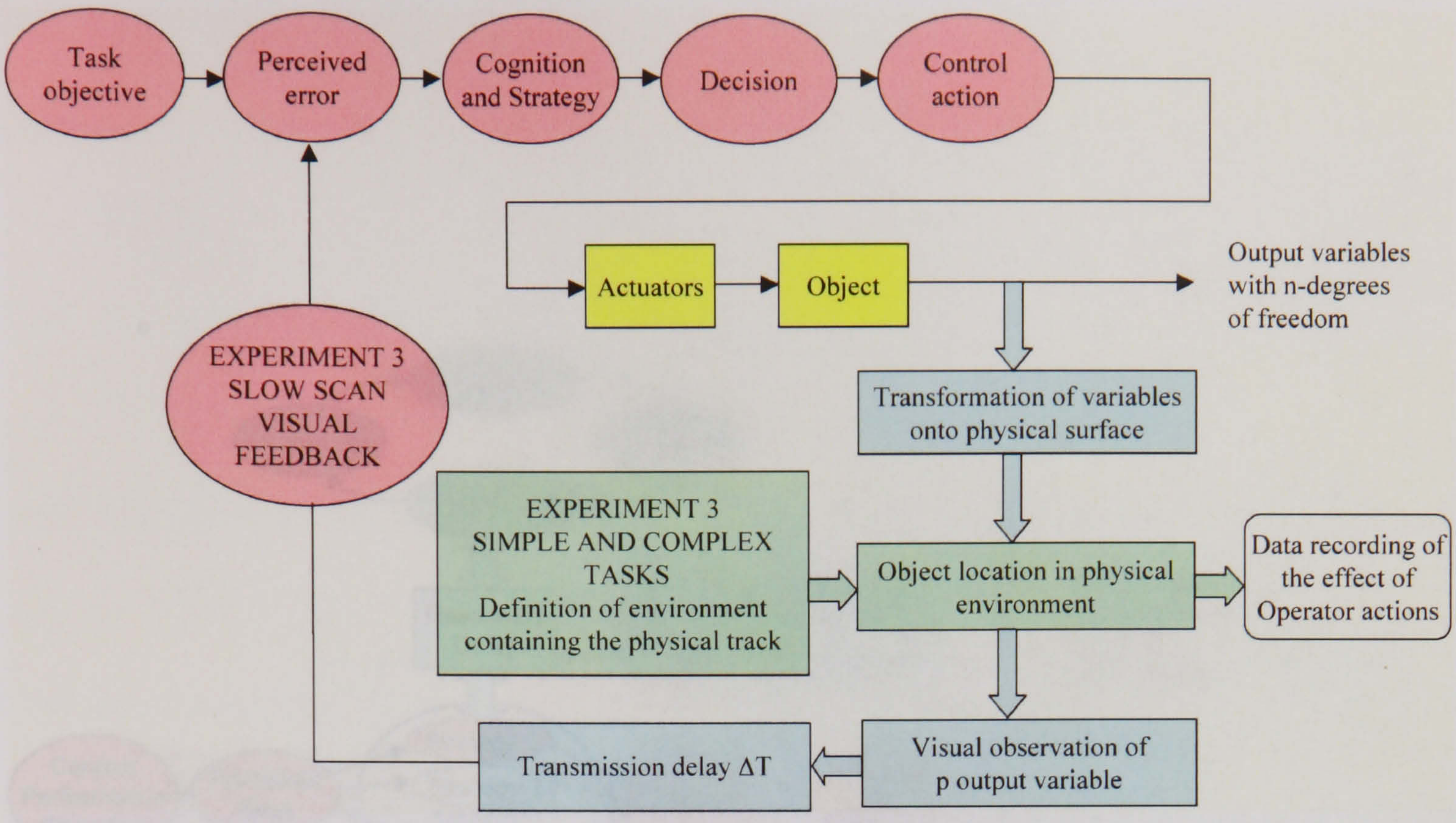


Figure 1.4: Model of Experimental System - Pilot Study 3

and is presented in Chapter 11.

The model was derived from assumptions regarding the cognition of human operators controlling vehicles with delayed visual feedback and is therefore task specific. It was designed to test these assumptions and see if these cognitive mechanisms (or models that bear similarity with them) were being disrupted by delayed visual feedback. This was achieved by creating a control system that used these assumptions and testing the system to see if it gave similar results as human operators in controlling vehicles with delayed feedback.

This model is proposed as a system that appears to act in a similar manner to human operators, in the specific task domain of remote operation with delayed visual feedback.

From the understanding gained from formulating this model the main experiments were designed and conducted as illustrated in Figure 1.6. The experiments tested the following hypotheses (see Chapter 4 for more details):

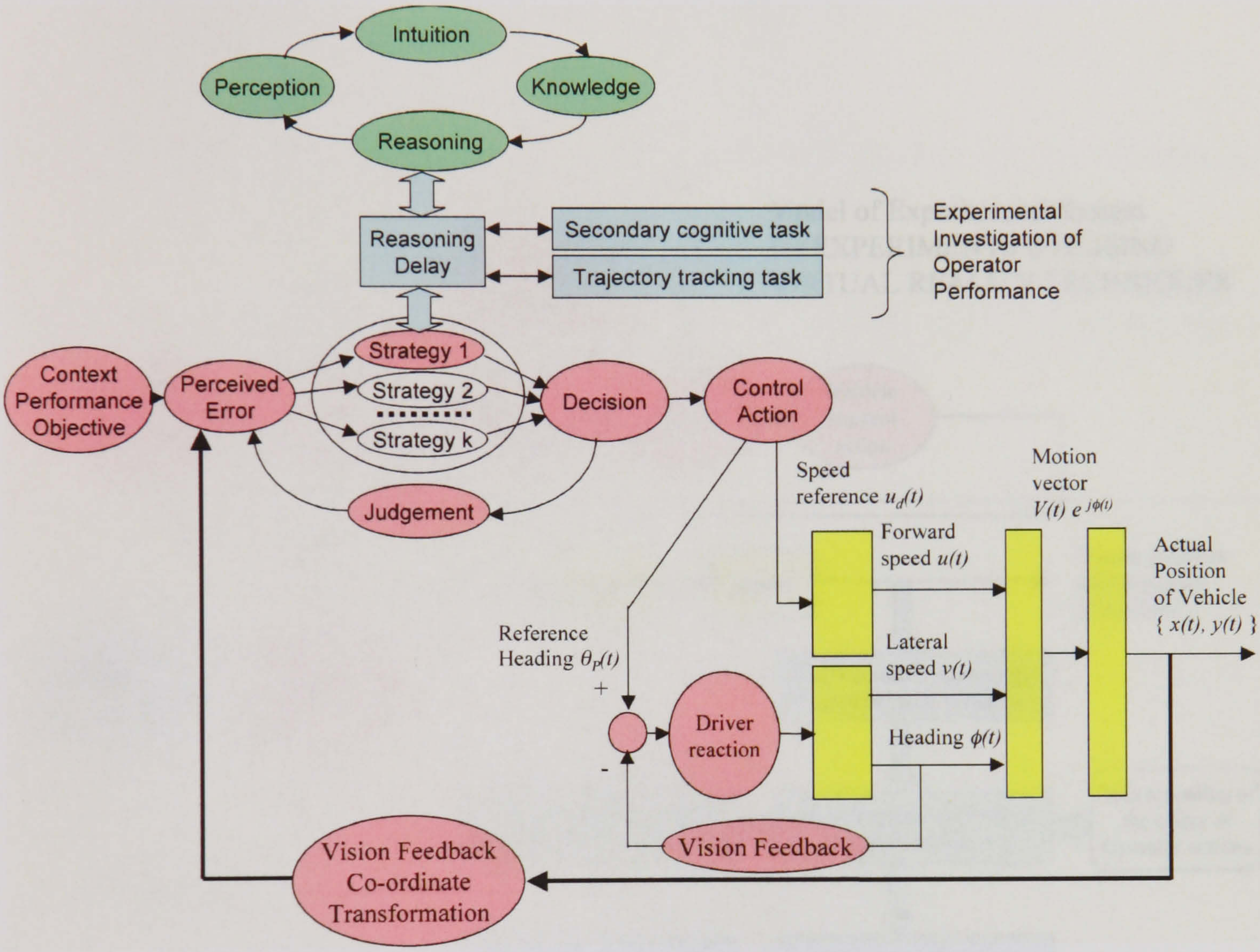


Figure 1.5: Experimental System Structure

Please note, the inner vision feedback loop (from heading to reference heading) refers to the actual heading i.e. not relative to current position. The outer vision feedback loop refers to the relative measure of current position compared to required position, i.e. the vehicle position within the environment.

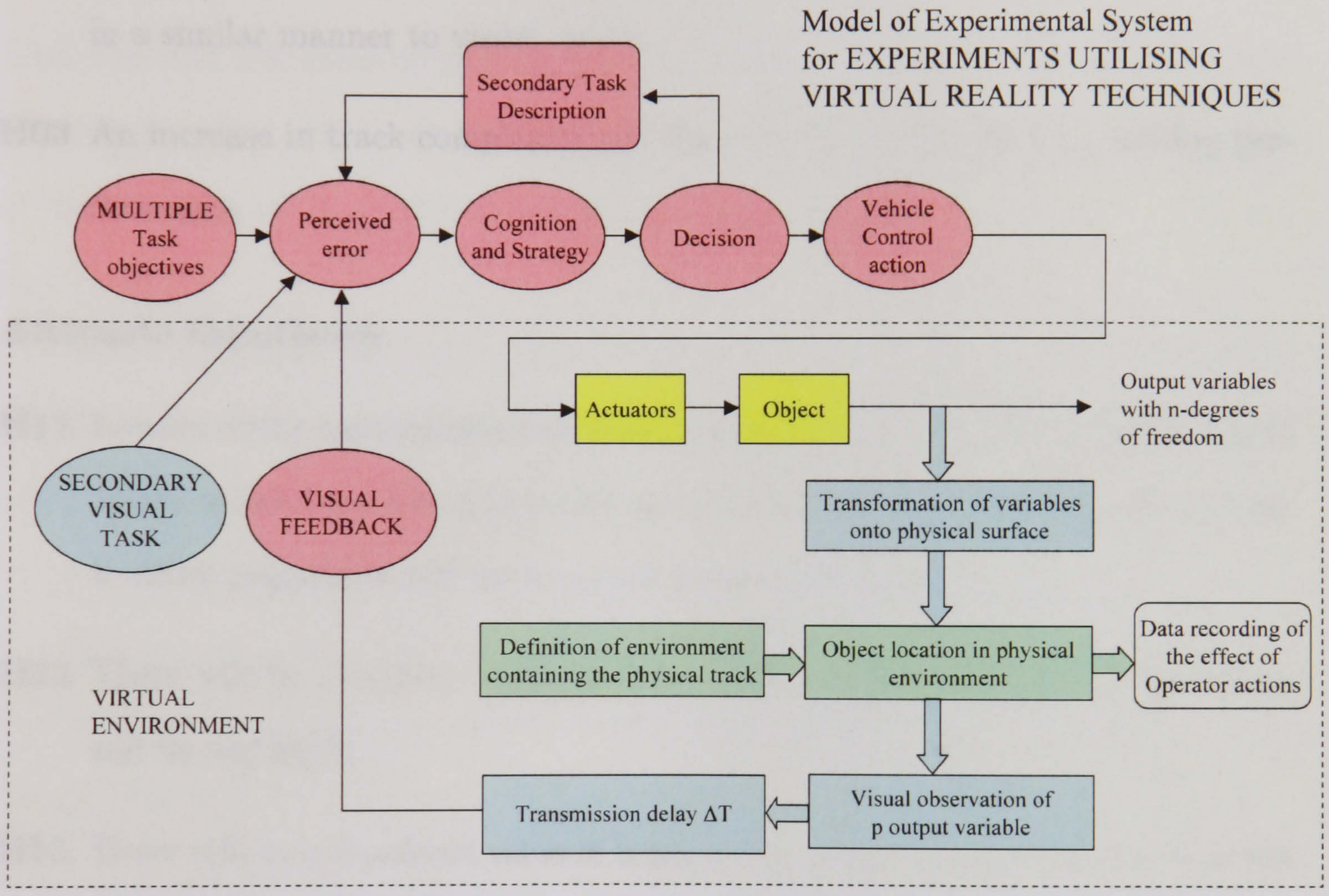


Figure 1.6: Model of Experimental System - experiments with VR

Null hypotheses

H00 An increase in visual delay magnitude will have no effect on driving performance.

H01 The presence of visual interference tasks will have no significant effect on driving performance.

H02 The presence of visual interference tasks will not affect driving performance in a similar manner to visual delays.

H03 An increase in track complexity will have no significant effect on driving performance.

Alternate hypotheses

H11 Results of the experiments will show a similar performance decrement due to delays as has been found in preliminary experiments, namely that an increase in delay magnitude will cause a performance decrement.

H12 There will be threshold value of delay below which the effects of the delays will be negligible.

H13 There will be a threshold value of delay above which the performance does not decrease any more (complete failure).

H14 The spatial letter-processing task will disrupt tracking (driving) performance, i.e. Baddeley's findings will be replicated.

H15 Delays in visual feedback cause confusion due to disruptions in visuo-spatial working memory, therefore visual interference which also disrupts visuo-spatial working memory will give a similar performance decrement to visual delays.

H16 An increase in track complexity will cause a performance decrement.

Chapter 2

Literature Review

2.1 Introduction

This research continues on from work carried out by the author as part of a MSc dissertation (Day, 1998). In this work it was discovered that operator performance is degraded by visual delays to a point, and then the level of degradation appears to tail off.

When this study was begun, it was envisaged as an investigation into the effects of delays on real-time system operators such as those controlling remotely operated vehicles. For this reason, it was expected that the majority of the literature would be from the fields of robotics and tele-operation.

However, on further investigation, it was discovered that there was relevant information to be found in a diverse number of areas of study. The main areas of study that were found to be useful are as follows:

- Robotics and teleoperation
- Experimental psychology
- Simulation (in particular flight simulators)
- Cybernetics
- Virtual reality
- Neuroscience including neurophysiology and neuropsychology

- Ergonomics and human factors
- Speech, acoustics and hearing studies
- Opthalmics and optometry
- Biological physics
- Video-mediated communication

For ease of reference, these areas are broadly grouped into 3 distinct fields:

1. Psychological: experimental and applied psychology
2. Physiological: neuroscience, biological physics, optometry, acoustics and ergonomics
3. Engineering: robotics, teleoperation, simulation, instruments, cybernetics, video-mediated communcication and virtual reality (VR)

Each field will be discussed individually in order to present effectively the main findings with the addition of human memory, which is discussed separately due to its importance to the thesis.

2.2 Psychological Literature

2.2.1 Structure

This section will describe the classic psychological findings on the perception of movement, will then discuss the general effects of delayed sensory feedback (particularly auditory feedback) before finally discussing the effects of delayed visual feedback.

2.2.2 Introduction

Initial investigations into the problems of delayed feedback, as part of an MSc dissertation (Day, 1998), uncovered technical difficulties in delaying video. Due to these difficulties of producing experimental equipment suitable for introducing controlled delays into full-motion (25 or greater frames per second or *fps*) video, it was decided that the cognitive effects of low frame rates should be investigated. For this reason, classical studies on the perception of movement were reviewed.

In order to understand properly the effect that delays in visual feedback have one must first understand the effect that low frame rates have on performance.

2.2.3 Effects of Low Frame Rates

It was Wertheimer (1912) who first rigorously explored the perception of movement. He investigated stroboscopic movement whereby successions of discrete visual stimuli are perceived as a single continuous image. In doing so, he discovered a condition known as *pure phi*; at an interval longer than that required for optimal stroboscopic movement, the two objects are seen only at their terminal positions, and yet there is a clear impression of movement from one to the other. At some shorter interval (60 ms in Wertheimer's experiments) the stroboscopic movement is seen, with the two objects being perceived as a single object moving through space (from one terminal position to another). If we take this figure of 60 ms and apply it to video, we have a useful rule that adequate perception of movement (i.e. 'smooth' video) occurs at frame rates of 16 fps and above.

Osgood (1953) reports on these findings and includes further details. Of particular interest are the time intervals (between the two visual stimuli being shown) that Osgood states. For instance, he states that *'if the interval is too long (more than about 200 ms), the two objects are seen in succession without apparent movement* *between them'.* Taking this figure of 200 ms gives us the guideline that movement is unlikely to be perceived in frame rates of less than 5 frames a second (fps). In addition to this, the comment is made that the optimum time interval for stroboscopic movement (Wertheimer's figure was 60 ms) is variable with many conditions such as exposure time, distance and intensity of the objects in addition to training and attitude of the participants.

Osgood also notes that at an interval of 30 ms, both objects appear simultaneously. Again applying this to video gives us the rule of thumb that smooth perception of movement occurs at frame rates of approximately 33 fps or above. This compares favourably with the fact that conventional analogue video uses either 25 or 30 fps.

Woodworth and Schlosberg (1954) also made similar comments on the findings of Wertheimer with the same figures being quoted. In addition to this, mention is made of Korte's work (1915) of drawing up what has become known as *Korte's Laws.* Postman and Egan (1949) also note these findings and give the following summary of Korte's Laws:

- If the intensity remains constant, the time interval for optimal movement varies directly with the distance between stimuli.
- If the time interval remains constant, the distance for optimal movement varies directly with intensity.
- If the distance between stimuli remains constant, the intensity for optimal movement varies inversely with the time interval.

Postman also elaborated on some of the conditions that can affect the perception of stroboscopic movement. Some of his main points are as follows. If the second flash is brighter than the first, perceived direction may be reversed. This is known as *delta movement.* An increase or decrease in the illumination of a figure results in a corresponding increase or decrease in the perceived size of figure. This is known as *gamma movement*.

The spatial framework in which a stimulus is perceived influences the perception of movement. For example, if one stares at a point source of light in a dark room, the light appears to move from one side to another; so called *autokinetic movement*. When two light sources are in a dark room, and one is in motion, an observer might perceive the other to be in motion; so called *induced movement*. Perception of movement depends on the relative spacing of objects and other factors of spatial organisation (such as sizes and organisation). More detail on perception of movement can be found in Regan (1997).

Poulton (1966) reported on the deterioration in tracking performance due to an intermittent (low frame rate) display from an engineering perspective. The work again demonstrates that low frame rates caused an increase in tracking error.

2.3 Effects of Delayed Sensory Feedback

Having ascertained the perception of stroboscopic motion and the equivalent effects of low frame rates, studies dealing with delayed sensory feedback are presented.

Feedback delay can be defined as

> *'a transmission lag in any part of the closed-loop pathways that govern action in organic systems'* (Smith et al., 1965).

Of more particular interest to this study, however, are the external delays in visual feedback (instead of the internal delays associated with organic pathways noted by Le Berre et al. (1987, 1992, 1993, 1998) and others).

The earliest observation of delayed sensory feedback that could be found appears in the Foxboro study (Foxboro Co., 1945) which unfortunately could not be obtained. According to reports by Smith and Wargo among others, delayed feedback was only mentioned in passing in this report. Warrick (1949) considers these effects in more detail in the context of a tracking system. Results from this study showed an inverse linear relationship between the delay and the logarithm of time on target.

Early studies in the field of delayed sensory feedback were concerned with auditory feedback. Lee (1950a,b, 1951) carried out experiments whereby a participant's voice was played back to them after some delay. The experiments made use of a dual audiotape device that recorded a participant's speech and played it back to the participant, while introducing a delay. The participant wore headphones so that they could not hear the actual speech, but instead could only hear the delayed speech.

In the first set of experiments Lee (1950b) noted that there was little or no effect on speech at 1/15s (67 ms), a 'marked effect' at 1/8s (125 ms) and a different effect at 1/4s (250 ms) delay. In the second set of experiments (1950a) delays of 40, 140 and 280 ms were used. These experiments were concerned more with the effect of the delay on the speed of reading but did note that stuttering errors were introduced by the delays. In the third set of experiments (1951), delays of 40, 80, 140 and 280 ms were used. In addition to the points noted before, Lee also mentioned that some of the subjects not only slowed down their speech, but also increased their intensity (volume). Again, halts and repeated syllables were noted. In general, Lee found that in the majority of participants, delays of approximately 200 ms caused dramatic effects such as stammering, pausing at inappropriate points, making errors in speech and sometimes completely preventing the participant from speaking.

Tiffany and Hanley (1956) and Winchester et al. (1951) also studied the effects of delayed auditory feedback and found that adaptation to it is slight or even non-existent. Similar findings were reported by Yates (1963). Biel and Warrick (1949) were also working in a similar area, with a particular emphasis on studying the perception of visual delay. They investigated the length of time delay present before it could be perceived and found a limen (threshold) at between 50-75 ms.

Archer and Namikas (1958) experimented with pursuit rotor performance as a function of the delay of information feedback, but results showed no significant differences between delay settings.

Garvey et al. (1958) investigated the differential effects of 'display lags' and 'control lags' on the performance of manual tracking systems. In their experiments, which considered the human operator to be a non-linear (and noisy) control system element, they demonstrated no significant effect from increasing the time constant of the control lag, but a highly significant effect of display lag. However, this highly defined difference between 'control' and 'display' lags is not present in all systems, and, in the case of controlling a virtual artifact in a virtual world, there is no difference between 'control' and 'display' delays.

This work, especially those findings by Lee, was followed by the investigations of Smith (1962) into the effects of delayed sensory feedback on such tasks as tracking, steering, handwriting, posture, head movements and other behaviour. This work was extended into research on the relationship between body movements and feedback control circuits (for example Smith and Smith, 1962; Smith, 1963; Smith et al., 1963; Smith, 1970). The main research findings of these investigations were as follows:

1. All motor-sensory mechanisms are degraded to some extent in accuracy, timing and integration by the introduction of feedback delay.
2. Some motor-sensory mechanisms show peak disturbances at specific delays. For example, the speech of young adults exhibits peak disturbance with delays of 200 ms. By contrast, other mechanisms show a degradation of performance in proportion to the delay.
3. Complex movements are more affected by delays in feedback than less complex or precise tasks.
4. The effects of feedback delay are exacerbated when they occur in combination

with additional perturbations such as spatial displacements of feedback.

There also appears to have been work by US defence funded projects as is shown by the review by Muckler and Obermayer (1964). This review shows similar findings to Smith's investigations.

Rapin et al. (1963) in their studies of the effects of delayed auditory feedback on key-tapping of children show results that seem to indicate that the peak disturbance for children is not in the order of 160-200 ms as is the case with adults, but instead the 1000 ms delay being the most disruptive. However, they do note that this study was not concerned with the effects of delayed auditory feedback on speech (where a 200 ms peak disturbance would be expected) but instead is a general motor performance study and therefore findings from delayed visual feedback that show an increasing effect past 200 ms is reasonable.

Smith et al. (1960) noted that delayed auditory or visual feedback was found to seriously degrade performance, introduced characteristic redundant motions, increased performance time by marked amounts, and imposed very difficult and frustrating conditions upon the subject.

Others also contributed to the field in the 1960s. Kalmus et al. (1955) began with studies into the effects of delayed auditory feedback but then extended the work to visual feedback. Kalmus et al. (1960) reported severe loss of control in studies into the effects of delayed visual feedback on writing, drawing and tracing. Karlin (1965) reported on the effects of extra cues on pursuit-rotor performance, particularly delayed auditory feedback but found no significant effect with a change in delay. Smith et al. (1960) commented that the effects of delayed visual feedback on a number of simple visual-motor tasks were found to be both marked and deleterious. They also stated that performance became difficult and frustrating and that the following particular types of errors were noted (given in order of frequency):

1. letter duplication

2. error of insertion
3. error of omission

The use of delayed feedback in the study of hearing and speech disorders has continued but no new insight has been gained into the cognitive effects of delayed feedback. For example, Billings and Stokinger (1975) used the effects of delayed auditory feedback as an indicator of hearing loss (if subjects could not hear the delayed auditory feedback then their performance was unaffected by it).

Smith et al. (1960) also noted that delayed auditory or visual feedback seriously degrades performance, introduces characteristic redundant motions, increases performance time by marked amounts, and imposes upon the subject very difficult and frustrating conditions. A comparison between auditory and visual delays was carried out by Wargo (1965, 1967) who found that degradation in tracking performance was more apparent for visual delays than for auditory delays (as might be expected due to visual tracking being superior to auditory tracking), and little adaptation to the delays was seen. Results showed an increased degradation in tracking performance with increasing magnitudes of delay. Interestingly, Wargo makes the point that the amount of performance degradation seems to be dependent on the skill required to complete the task. For example, visual tracking was shown to be superior to auditory tracking across all delays and visual tracking was also demonstrated to be more severely affected by the delays. Wargo (1965) suggests that:

> 'the degrading effect of feedback delays on tracking performance is attributed to the detrimental effect of control-display lags on the operator's internal predictive model of the control system'.

Wargo also cites the findings of Smith (1966) in which expert musicians were more affected by delayed auditory feedback than novices, and more marked effects were seen with more complex musical scores than simple scores. This work demonstrated the remarkably similar effects between delayed auditory and visual feedbacks thus indicating that findings from delayed auditory feedback can justifiably be extended into the field of delayed visual feedback.

These general studies into the effects of visual delays were applied to the area of tracking and steering. Lincoln and Smith (1952) had already investigated the factors determining visual tracking accuracy but delays were not analysed in this work. However, Coleman et al. (1970) found that the main effect of feedback delays on eye tracking in steering was to restrict the normal capability of the eye to predict or anticipate the course of self-generated stimulus movements. A detailed study of human tracking behaviour was performed by Poulton (1966) that included reference to transmission and exponential lags. However, little new findings were reported in the area of delayed sensory feedback.

Smith and Sussman (1970) used delays of 200, 400, 600, 800 and 1500 ms to investigate their effects on steering. Of those settings, only 800 and 1500 ms were found to have marked effects on steering performance. Steering and stimulus tracking were affected more by the delays during the practice period rather than during the tracking period. The conclusion is drawn that *'both steering and stimulus tracking become less susceptible to the effects of delay with practice'*. In addition it was found that stimulus tracking was more severely affected by visual feedback delays than steering was; a finding that Smith and Sussman suggest is due to steering reactions involving coordinations between eye, hand and body which are not present in stimulus tracking. The steering task has these extra cues and it is therefore suggested that there is less reliance placed on the visual feedback than is the case with stimulus tracking, where a greater reliance on the visual feedback is necessary due to less cues. Similar findings were also reported in Smith and Putz (1970b).

More detailed analysis of learning and performance in steering and tracking was carried out by Smith and Kaplan (1970) and Smith and Putz (1970b) although this research was not directly concerned with delays. Smith and Kaplan (1970) investigated the role of delayed feedback on learning and the transfer of learning. As expected, delays severely impaired driving accuracy and learning. In particular, it was found that practice with larger delays produced a marked positive transfer of the learning to drive with smaller delays.

However, Smith and Putz (1970a,c) and Putz and Smith (1971) continued this investigation into tracking, especially the role that retinal feedback delay has on eye tracking. Once again delays of 0, 200, 400, 600, 800 and 1500 ms were used with three different modes of tracking control (head, eyes and head-eye motions). They found that a delay in retinal feedback greatly increased errors in eye tracking. In fact, the results showed that with increasing magnitudes of retinal feedback delay, tracking error increased in an almost linear fashion. Increased tracking error was particularly evident in the irregularity and magnitude of eye movements. Results suggest that visual impairment may be produced by delays in retinal feedback, and that there is little learned adaptation to reversed or delayed vision. Interestingly, in Smith and Putz (1970c), where visual delays were used only as a means of comparing steering and stimulus tracking, the results seem to show that the effects of delays on steering and stimulus tracking are the same, thus implying that the results of laboratory experiments that use stimulus tracking can be applied to the area of steering a vehicle (either directly or by teleoperation). This can be inferred if one considers steering to be a form of tracking a visual stimulus. Similar work by Vercher and Gauthier (1992) seems to show that participants are better able to compensate for delays when they are moving their limbs as well as their eyes. In particular it was shown that the eyes began moving in response to arm movements while the visual target was still motionless.

Smith and Bowen (1980) compared the effects of delayed visual feedback with that of spatially distorted feedback by use of prisms. Results showed that although both gave a similar behaviour (that of overshooting) the role of each in visuo-motor control is different.

An additional point made by Teal and Rudnicky (1992), and subsequently by O'Donnell and Draper (1995), is that delays can change user strategies and procedures. O'Donnell and Draper also noted that user strategies are often changed for reasons other than delays, with users often having a multiple number of alternative methods at their disposal. This point is important when considering experimental design, as results will be influenced by the strategies employed by the participant.

MacKenzie and Ware (1993) investigated delayed visual feedback (which they referred to as lag) as a determinant of human performance in interactive systems. In their paper they state that 10 Hz is considered minimal to achieve 'real time' animation. Delays of 8.3, 25, 75 and 225 ms were considered in their experiments with the 225 ms delay causing performance to be degraded substantially. An interesting point that they make is to tie in Fitts' index of difficulty (Fitts, 1954) by noting that the more difficult the task, the more effect that the lag has on the user.

Further studies have been carried out into the difficulties of tracking and steering in virtual environments (for example James and Caird, 1995) but little mention is made of the effect of delays in this area.

Smith et al. (1965) carried out experiments investigating delayed visual feedback of oral breath pressure control. Delays of 0 to 3.2 seconds were used. The results of these experiments were that severe disturbances were found in control under delayed feedback and that learning was severely hindered by delays in feedback. Henry et al. (1967) extended this work with similar findings. Although the area of oral breath control is not of direct relevance to this thesis, these studies again demonstrate the detrimental effects of delayed visual feedback on human control tasks, whether they are finger pointing, shape tracing, writing, breath control or any other task.

2.3.1 Reasons for detrimental effects of feedback delays

Brickman et al. (1994) put forward two hypotheses for the 'decorrelation' between control inputs and resulting sensory feedback.

1. **The information generation hypothesis**. This states that the decorrelation due to delay impairs the ability of active subjects to *generate* useful information thus degrading performance.

2. **The information pick-up hypothesis**. This states that the decorrelation due to delay impairs the ability of operators to efficiently *pick-up* information that is available to them thus degrading performance.

Brickman et al. (1994) briefly investigated whether the reafference theory, which suggests that action is crucial to performance, holds for feedback delay. Experiments used yoked pairs of active and passive observers but found no statistically significant difference between the two different modes thus implying that the operator's mode of interaction was not important for performance of the task. As a result no further use was made of the two hypotheses in this thesis.

A noteworthy study in the late 1950s is that of Conklin (1957) in which the effect of control lag on performance in a tracking task was studied. The interesting point is that two sorts of control lag were defined by Conklin; these being termed *transmission* and *exponential* lags. Transmission lag was defined as being a fixed time interval between control movements and feedback. Exponential lag on the other hand was defined as an exponential output of control displacement. With this exponential lag a control movement is immediately perceived in part but only attains completion as an exponential function of time. (Exponential lag is usually defined as the time between a control input and 63 percent of the maximum output.)

Results were shown to support the hypothesis that predictions enable subjects to overcome or compensate for delays thus behaving in the system as a continuous error correction device. However, the study only considered a combination of three sinusoidal waves; i.e. regular patterns only. Lags of 0, 0.25, 1, 4 and 16 seconds were considered. Similar findings were reported by Pew et al. (1967) in a study of sine-wave tracking, although these results seemed to suggest that the operator typically makes many discrete correctional movements rather than continuous movements. This finding is supported by Craik (1948) and Miall et al. (1989, 1993) among others.

From this work it can be seen that, if a delayed signal is regular, human compensation can be effective. Work by Hefter et al. (1996) seems to suggest that the peak disruption occurs when regular signals are presented exactly out of phase (i.e. at 50% of the time cycle of the signal).

2.4 Physiological Literature

Smith, Myziewski, Mergen, and Koehler (1963) investigated computer systems control of delayed auditory feedback. Studies were more concerned with the use of a digital computer system as a tool for use in delayed auditory feedback experiments rather than with the study of delayed feedback although results were collected that showed blocking of syllables and slowing of speech with delays of 0.1 and 0.2 s. This finding was also reported by Kalmus et al. (1960).

Held et al. (1966) investigated adaptation to displaced and delayed visual feedback of the hand and found that adaptation to displacement under no delay was completely eliminated in all delay settings, including the minimum setting of 0.3 s. This inability of users to adapt to spatial displacement when operating under delayed visual feedback implies that cognitive overload occurred with the users being unable to compensate for both temporal and spatial displacements simultaneously. This work was recently updated to consider the broader area of telepresence, time delay and adaptation by Held and Durlach (1993) and particular attention was again given to sensorimotor adaptation. Similar results were demonstrated by Welch (1978) and Wolpert et al. (1993a,b).

Similarly, Kalmus et al. (1955, 1960) studied the effects of delayed visual feedback of the hand position on writing, drawing and tracing. The main finding was that delays resulted in overshooting, repetition and wrong spacing. In addition, the duration of writing and error area in tracing also increased with the magnitude of delay. Kalmus compared these findings to existing work in the field of delayed auditory feedback (Lee, 1950a; Black, 1951; Fairbanks, 1955; Fairbanks and Clarkson, 1958) and also referred to similar work by Bergeijk and David Jr (1959). Similar work was also carried out by Tamada (1995) in studies into visuo-motor integration although this paper appears to add little to the already established findings.

This study of handwriting under delayed feedback was recently extended into a comparison of writing in English and in Kanji (Japanese characters) by Morikiyo and Matsushima (1990) and Matsushima and Morikiyo (1996). The first set of experiments consisted of 2 tasks; namely reciprocal tapping and handwriting of both Kanji letters and English words. The second set of experiments further investigated handwriting under delayed feedback. As was found in previous work handwriting performance decreased with an increase in the magnitude of delay, although in the early experiments errors were smaller for the largest delay of 1000 ms. It was suggested that this was due to the visual feedback being close to in-phase with the movements of the participants. In general, the mean number of fluctuations or hesitations was found to increase with the delay. Matsushima and Morikiyo noted that many participants adopted a *move and wait strategy* in order to compensate for the delay as was also seen in preliminary work by Day (1998, 1999) and Day et al. (1999).

Hanna et al. (1975) extended existing work on delayed auditory feedback and stuttering. Their paper was particularly concerned with the possible use of electromyographic (EMG) feedback in order to reduce stuttering rather than the particular effects of feedback delays.

Beuter et al. (1989) examined the effects of delayed visual feedback on a finger-tracking task (using a graphics tablet). Four out of the eight participants exhibited high amplitude tremor with the other four showing no effect. Experiments, which were carried out with normal and Parkinsonian subjects, consisted of the subject maintaining a constant finger position using time-delayed visual feedback in order to understand better goal directed movements. The subject had to align one line (controlled by the index finger) with a target line, both lines being displayed on an oscilloscope screen. A delay of 1500 ms was introduced by inserting an analogue delay line (a bucket brigade type device). Results discovered included an increase in finger fluctuations with delay. It was also found that the average inter-peak interval of regular oscillations increased continually with delay and was always between 2 and 4 times the delay. Beuter et al. comment that negative feedback systems with single control loops can be destabilised by increasing the delay to produce regular oscillations of between twice and four times the delay. Beuter et al. also commented that multiple feedback (such as visual and tactile) does not always stabilise a system. In fact, Glass et al. (1988) had previously found that multiple negative feedback could introduce instabilities in deterministic dynamics such as a human operator.

Beuter et al. (1990), Beuter and Bélair (1993) and Beuter et al. (1995) continued this work and again delayed visual feedback induced complex oscillations in healthy subjects and some Parkinsonian subjects. In addition, for finger movements, increasing the gain (i.e. in finger position) in visual feedback decreased root mean square (RMS) errors, while increasing delay increased errors. They noted that delayed visual feedback *'generally induced large amplitude low frequency oscillations in normal subjects'*.

It is interesting to note that in these experiments subjects produced index finger oscillations. This bears close similarity with the stutters and blocks that are exhibited in speech when delayed audio feedback is given and the oscillations in manual control that occur when controlling with delayed visual feedback.

Keran et al. (1994) also investigated behavioural control characteristics of performance under feedback delay, with a particular emphasis on tracking performance. They stated that

> *'the effects of delayed feedback have been found to occur for delays as small as 0.50 ms and tend to plateau at around 500 ms and have produced performance decrements ranging from 1.1 to 5 fold'.*

They also note that the extent of performance degradation determined not only by the duration of delay but also by the task itself.

This work was continued by Smith and Fucetola (1995) who investigated the effects of delayed visual feedback on handwriting in Parkinson's disease. The main purpose of this research was to assess the dependency of Parkinson's disease (PD) patients on visual information by having delayed (by 400 ms) and normal (no delay) feedback. The results found were that the effects of delayed feedback were longer stroke size and duration and more dysfluencies. Mild PD subjects showed the same effects as the control subjects.

This work was extended by Liu et al. (1999) in their studies into the effects of visual feedback on manual tracking and action tremor in Parkinson's disease. These experiments used visual delays as a method of investigating the effects that basal ganglia dysfunctions have on visual feedback control.

The suggestion was made by Vasilakos and Beuter (1993) that a possible explanation for the difficulty in finger tracking was that the tremor seen in patients with Parkinson's disease acts as coloured noise. Results show that augmented noise tended to reduce oscillations normally induced by time delays in a similar manner to what has been described in stochastic resonance (McNamara and Wiesenfeld, 1989).

Tass et al. (1995) noted that Langenberg et al. (1992, 1998) found that the highest values of the root mean square (RMS) error occurred for relative delays around 500 ms. RMS error decreased for larger delays.

More detailed studies on the exact effect of delayed visual feedback on joint movements have been performed (Cooke et al., 1995; Maitra et al., 1995) but these were found to be peripheral to this thesis. In a similar manner Jacobs and van Steenberghe (1993, 1995) investigated motor control using delayed visual feedback but again the findings were not directly relevant to this thesis.

In a similar manner, Sussman and Smith (1971) studied jaw movements under delayed auditory feedback. Delayed auditory feedback resulted in increased jaw-opening excursions, positional target overshoot, lengthened jaw articulation for vowels and increased jaw movement rates. These lengthened articulation and overshoots can be considered analogous to the overcompensation found in driving under delayed feedback, while the increased jaw movements appear similar to the stuttering noted in earlier experiments concerning speech and delayed auditory feedback (Lee, 1950b,a, 1951; Smith et al., 1960).

Tye-Murray (1986) extended the work performed to investigate the effects of delayed auditory feedback by combining the auditory feedback with instant visual feedback. The paper was particularly concerned with whether visual information affects oral production and described a preliminary study in addition to the main study consisting of 11 participants reading one practice and 8 test sentences. Five subjects began with delayed auditory feedback (200 ms) and then had additional instant visual feedback, with the remaining 6 subjects reciting the sentences with delayed auditory and instant visual feedback first. The control condition was instant auditory and visual feedback. The results of this study were that sentences of longer duration were produced with only delayed auditory feedback when compared with delayed auditory feedback with instant visual feedback, i.e. use of more than one method of feedback is preferable.

In the preliminary study by Tye-Murray, 13 participants spoke while looking at a delayed (by 2 seconds) video display of their head and neck. (The video signal was delayed using 2 coupled reel-to-reel video tape recorders). Subjects recited nursery rhymes from memory while listening to pink noise to mask acoustic outputs. It was found that visual information was a carrier of articulatory information that sometimes conflicted with the subject's speech.

Langenberg et al. (1992), Tass et al. (1996), Hefter and Langenberg (1998), and Langenberg et al. (1998) all studied sinusoidal forearm tracing with visual feedback. They noted firstly that tracking error had a cyclic behaviour with an increase up to delays of 50% (of the target signal time period) and a decrease for larger delays. They also discovered that with relative delays close to 0 and 100% subjects successfully tracked the target signal with a small phase lag. However, with delays in the 30-90% range, larger phase differences were observed. They noted that delays of about 50% of the movement cycle are harder to handle than smaller or larger delays.

Pratt and Abrams (1996) found that practice increased motor performance in rapid aimed limb movements (while under delayed visual feedback) thus replicating previous work (Smith and Sussman, 1970; Smith and Putz, 1970b). Similar findings were reported by Connolly and Goodale (1999) in studies into manual prehension. This has implications for experimental design in that learning will affect the results, therefore randomisation of task orders should be used to alleviate this effect.

In more specialised studies, Kitazawa et al. (1995) found that there was a threshold at 50 ms in the rate and amount of prism adaptation under delayed visual feedback. McCandless et al. (1998) showed that errors in localisations increased systematically with time delay and depicted distance. Detailed studies and modelling of optical systems have been carried out by Le Berre et al. (1987, 1992, 1993, 1998) and Wolpert et al. (1993a,c) with a particular emphasis on the delays inherent in the human vision system. More general models of the instabilities induced by delays in any non-linear feedback system (such as the human visuo-motor system) have also been produced by others such as Wischert et al. (1994) although these models were felt to be too complex to use as a basis for experimental work.

Weir et al. (1989) in their studies of visually guided tracking (of hand movements) described various cues that are used for planning tracking movements. They also considered methods of compensation for delays involved in the visual system, but these methods of compensation involved memorising the target waveform and are therefore only of use when the delayed signal is of a cyclic nature. For this reason this compensation was not of direct relevance to this thesis. Similar work on movement prediction has been carried out by Wexler and Klam (1999).

Carnahan et al. (1996) report that delayed visual feedback disrupted tracking of a target, but did not appear to disrupt learning (i.e. how to perform the task).

Cunningham and Tsou (1999) and Foulkes and Miall (2000) studied human adaptation to delayed visual feedback. Cunningham and Tsou present results that demonstrate that people do show sensorimotor adaptation to temporal discrepancies between perceived and actual occurrence of events. In a similar manner, Foulkes and Miall (2000) demonstrated that participants adapted to delays with a significant drop in the tracking error with delays of 200 and 300 ms. The authors suggested that this adaptation was consistent with the idea of subjects constructing an internal *predictor model* which includes not only a representation of the world but also a delay component that matches the observed delay. The suggestion is therefore that subjects modify this internal delay until the predictor model and the physical world match. However, no additional support was given for this hypothesis.

Mehta and Schaal (1999) investigated visuomotor control of a 'virtual pole' where participants balanced the pole on a computer screen by controlling the position of its base. These results were compared with results from a robot performing the same task. Visuomotor delays were 220 ms. Results suggest that humans might employ a predictive forward model of the task in order to compensate for delays although, in a similar manner to Foulkes and Miall (2000) little additional support was given for this hypothesis. As a result of this lack of support the hypotheses suggested in these two papers were not investigated further in this thesis.

2.5 Engineering Literature

An area of study which has produced a number of studies on the effects of delays is the aeronautics industry, with many investigations being performed concerning pilot performance under delayed feedback. (The impetus for this was the delays introduced by the use of computers in early flight simulators and fly-by-wire control systems.)

For instance, Gum and Albery (1977) investigated time delay problems encountered in integrating an advanced simulator for undergraduate pilot training. In this paper Gum and Albery state that delays in the order of 150 ms appeared to be tolerable in most cases.

Smith and Bailey (1982) investigated the effects of control system delays on fighter aircraft flying qualities. This was mostly concerned with the fact that early fly-by-wire systems introduced delays into the system. As expected, delays were shown to severely decrease performance with higher precision tasks being most sensitive to delays. Smith and Sarrafian (1986) also presented results from tests using fly-by-wire aircraft and discussed the deleterious effects of delays in the responsiveness of the aircraft.

Hess (1984) performed generic experiments investigating the effects of time delays on systems subject to manual control (the study was concerned with pilot dynamics and tracking performance). A definite link between system time delays and pilot workload was established in this study. A similar study of a helmet integrated sight system for the prototype Comanche attack helicopter by Wildzunas and Wiley (1996) produced similar findings. Interestingly, lower delays (67, 133 and 267 ms) did not seem to affect performance but were found to increase significantly pilot workload, with larger delays (400 and 533 ms) adversely affecting performance as well as workload.

Crane (1984) also carried out similar experiments along with reviewing other work. It was reported that delays were most troublesome when the pilot was attempting to control a highly responsive aircraft (for example a fighter). Similar findings were presented by Riccio et al. (1987).

An extension of these findings was put forward by Berry (1986) in which he stated that the effect of time delay was strongly dependent on the task. For example, his studies found that, in calm air and in the pitch axis, landings were most affected, whereas in the roll axis, formation flying was most affected. In a similar manner, a study by Whiteley and Lusk (1990) showed that simulator time delays adversely affected sidestep landing tasks. Work by Ricard and Parrish (1984) demonstrated that visual delay affected control of the roll axis in helicopter simulations, and also found an interaction between motion cuing and visual delays. Ricard (1994) also produced a bibliography of manual control with delays which proved useful for this thesis. The paper focused particularly on the aeronautics and simulation industries.

Bailey and Knotts (1987) investigated the effects of time delay on manual flight control and flying qualities during in-flight and ground-based simulation. Results showed that as time delay increased, control problems became evident with increasing tendencies to overshoots, oscillations and pilot induced oscillations. They also noted that delays of under 150 ms were found to be acceptable, and in simulating larger aircraft, even larger delays could be tolerated. Woltkamp et al. (1988) also described similar findings for helicopter simulators. Similar findings were reported by Levison and Papazian (1987) and a model that could be used to predict the performance of a flight simulator was presented. Jewell et al. (1987) took a slightly different approach to allow the overall dynamics of a visual simulator to be measured and analysed using frequency response identification.

Similarly, Frank et al. (1987) also studied visual display lags in simulators, with an additional comparison being made with motion system delays. Results showed that visual delays were more disruptive to participants' control performance and well-being than motion delay. They stated that a better performance was obtained when the visual system led the motion system, i.e. visual delays were smaller than motion delays. Cardullo and Brown (1990) also studied visual system lags in simulators and reported similar findings. A review of similar research is provided by Merriken et al. (1987).

Gawron et al. (1989) extended the ideas of Bailey and Knotts (1987) by producing a comparison of the effects of time delay during in-flight and ground simulation. It was found that tracking performance was degraded more in ground simulation than in-flight with time delays. It was suggested that this was due to the extra visual cues available in flight.

Bradley and Abelson (1995) studied the fidelity of desktop flight simulators and pilot performance. In their report they commented that the quality of performance in a flight simulator is limited by frame rate and delayed visual feedback. They put forward the idea that motion is apparent at frame rates of 15 fps and above, and refer to Wertheimer's findings (1912) as the basis for this figure, as has been previously discussed.

Bradley and Abelson used a Panasonic video camera equipped with a 'strobe' feature that sampled video every 167 ms. The star-tracing task as outlined in Smith's experiments (1962) was used with this camera, although only one subject participated in the experiments. The result discovered was that star tracing appeared to be affected by intermittent visual feedback at 6 fps.

Varying the frame rate of a video display also has a significant effect on operator performance. In particular, task times (i.e. time from start to completion of a task) tend to decrease with increased frame rates (Massimino and Sheridan, 1994). Particular applications where these effects have been noted include underwater robotics, (Boyle et al., 1995a,b; McMaster et al., 1994; Sayers et al., 1994) computer-assisted surgery (Austad and Pedersen, 1996; Karron et al., 1997) and space robotics (Hirzinger et al., 1993; Sheridan, 1993, 1997; Stoker and Hine, 1995).

An additional area of interest in engineering is that of teleoperation. Again, delays are known to have an adverse effect on operator performance (Sheridan and Ferrell, 1963). The fact that delays do often exist in teleoperations and other similar real-time systems is recognised, as is the fact that this impairs the performance of the operator (Lee and Lee, 1993; Liu et al., 1993; Sheridan, 1993; Tsumaki et al., 1996).

Elliott and Eagleson (1997) noted that:

> '... even latencies as small as a few hundred milliseconds will prevent the operator from controlling a device in a *natural* way. Instead, the control of the remote system becomes difficult; it requires that the operator anticipate the effects of inaccuracies and unexpected events, which will not be known immediately because of the communications delay. The task of controlling such a system will be cognitively difficult, requiring that the operator do planning, scheduling, reasoning with uncertainty, general problem solving, and diagnostic troubleshooting. [emphasis added]'

Boyle et al. (1995a,b) noted that delays in feedback caused operators to overcompensate by increasing the joystick movement. As a result, the robot was moved too quickly and overshot the target. In addition, it was noted that some participants found it hard to believe that the robot was doing what they observed from the (simulated) feedback, although this was probably only due in part to the effect of the delay in feedback. The simulated display in this case used wireframe modeling, and therefore needed interpreting by the operator, thus meaning that this lack of trust or belief is more likely to be linked with the simulation. In addition the interpretation of the wireframe display placed a heavy load on perception thus performance problems may have been partly due to the display used.

A detailed report by Smith et al. (1989) describes some of the consequences of time delayed sensory feedback on operators. This discussion is placed in the context of space-based teleoperation. Interestingly, Smith et al. not only mention the adverse effect on operator performance but also consider such factors as increased stress, impaired visual perception and impaired decision making citing work by Smith and Smith (1987b) among others in the area of the social and ergonomic aspects of delayed feedback. For more details of related work please see Salvendy (1987) and Smith and Smith (1987a, 1988)

Some teleoperator systems make use of force feedback and the problem of this feedback being delayed was investigated by Ferrell (1966). It was found that delayed force feedback introduced instability in a similar manner to delayed visual feedback. However, experimental results suggested that additional feedback can help to overcome this problem (i.e. force not applied back to hand providing positioning but to another part of the operator such as the leg).

Starr (1979) compared two methods of control for using a manipulator with a time delay in the system. Results showed that performance was greater when using a resolved-motion rate control (a multi-axis joystick constructed such that no force on the joystick means no change to the manipulator) than for conventional master-slave methods thus implying that if the operator is to adopt a move and wait strategy, then the rate control is to be preferred.

The area of teleoperation of land vehicles has been covered in a rather detailed set of studies by McGovern (1993) (with funding from the US military). The following points were made.

- It was found that a wider field of view on the camera made the operator feel more comfortable at manouvering. Similarly, steering-slaved viewing allowed tighter turning and obstacle avoidance although obstacle recognition was not improved.
- The camera resolution was not found to be a factor in the operator's ability to control the vehicle in the absence of any obstacles. It was shown to be important with large numbers of obstacles or when operating off-road where selecting the best route is important.
- Colour was found to be useful in giving additional visual cues to help with course planning (for example, the difference between dirt and asphalt). Colour was also rated as highly desirable by subjects. There was not, however, a quantitative difference in obstacle avoidance using colour compared to using a monochrome display.
- Vibration and bounce of the vehicle and camera did not significantly degrade operator performance.
- Operators consistently underestimated distances to obstacles. However, this may be due to the display being smaller than geometric similarity. It has been suggested that scene magnification may well help as shown by Roscoe (1979).
- So-called '*negative obstacles*' such as ditches and holes were found to be extremely difficult to see via video link.

- Tilt and roll control of the vehicle was a problem. This was due to vehicle attitude parameters not being displayed and therefore vehicles were often rolled over when attempting to climb inclines.

Interestingly, McGovern mentions the over-control of steering by novices giving rise to what he terms '*vehicle travel oscillating about the desired path*'. Similar results have also been reported by Spain (1987). It is not clear whether there was delay in the transmission system, but this behaviour has been clearly seen as a result of visual delay in experiments by Day (1998, 1999); Day et al. (1999, 2001b).

It is interesting to note that resolution only had an effect when large amounts of obstacles were present or when operating off-road. An additional effect not mentioned here but shown by Ziefle (1998) is that low-resolution displays increase fatigue in the operator. More information on the effects of various aspects of visual displays can be found in Bennett et al. (1997) although this was found to be outside the scope of this thesis.

Hill (1976) compared seven performance measures in a time delayed task (involving teleoperation using a master-slave manipulator) and discovered that two new derived measures, namely the fraction of time moving and the mean time per move, were more sensitive than conventional measures such as task time in determining performance changes. However, this paper assumed that a move-and-wait strategy would be used by all participants and in fact, this was considered to be an advantage in reducing control movements made by the operator.

Other problems that have been noted with delays in feedback are that of confusion and disorientation. In particular, Liu et al. (1993) noted that, in the context of head-mounted displays, delay affects the correspondence between head motions and the displayed scene in the display, thus resulting in disorientation of the operator.

Karron et al. (1997) note that the use of a simulator which exhibits such delays in visual feedback for extended periods of time gives rise to what they term *simulator* *sickness.* This sickness is caused by a time disparity between expected and perceived visual images. It can therefore be considered to be another case of disorientation on the part of the operator. Uliano and Kennedy (1987) and then Kennedy et al. (1996) have made an attempt to quantify the visual stimuli that lead to this *cybersickness* with some success. The presence of delay was found to be a major factor in the onset of such cybersickness. A more detailed review of the problems of simulator sickness was given by Pausch et al. (1992). In this review the significant effect of lag is described, as are the effects that refresh rate and other display parameters such as field-of-view and scene complexity. One interesting point that is made is that pilots noticed increases in lag and believed that it had a serious detrimental effect on performance even when the results showed that it actually only had a small effect on performance measures.

An additional area of study that has investigated the effects of feedback delays is that of computer mediated communcation as used in computer-supported cooperative work with the detrimental effects being reported by O'Malley et al. (1996) and Anderson et al. (1997, 2000) among others. O'Malley et al. (1996) observes that delay had a significant effect on the performance of a map task (following a route described by somebody else). In further experiments presented by Anderson et al. (1997), both audio and video signals were delayed in order to investigate the effects. It was found that *'having both signals delayed, even though synchronised, still disrupts the timing in normal conversation'.* This work was extended by Anderson et al. (2000) with the inclusion of the effects of frame rate, although these effects were measured ratings from participants rather than task performance. In this field of mediated interaction alternative strategies can be employed to compensate for delays, in particular, by refining the method of taking turns (often by signalling that the speaker may continue, for example, "mhm" or "uh-huh"). These strategies are analagous to the *move and wait* approach often adopted in controlling remotely operated vehicles.

2.6 Partial Solutions

Much work has been performed, particularly in the engineering disciplines, to attempt to compensate for the detrimental effects of delayed feedback. The major approaches taken are outlined in this section.

An early solution to the problem of delays in feedback is for the operator to adopt a *move and wait* strategy, as previously mentioned in reviewing the literature. Such a strategy involves a discrete control movement being made, after which the operator waits until confirmation of that action occurring by the remote robot before making another control movement (Sheridan and Ferrell, 1963; Ferrell, 1965; Sheridan, 1993) This approach is obviously inappropriate for such application areas as remotely operated aircraft that fly at high speeds.

Following on from these rather crude methods of controlling delays in feedback, much work has been done in eliminating this delay, often by using predictive methods such as predictive displays (Hirzinger et al., 1993; Sheridan, 1991, 1993). An early study of these approaches was performed by Poulton (1966) in his investigations into tracking behaviour. In these studies he mentions predictor displays in the context of changes to tracking behaviour. Sheridan (1991) has identified two types of predictive displays; one using extrapolation based on current position and time derivatives, and the other requiring operator input providing trajectory visualisation.

Noyes and Sheridan (1984) produced a predictive display consisting of wireframe graphics overlaying the conventional time-delayed video display. The graphics showed a wireframe of the manipulator plotted in real-time using control signals.

Park (1991) used computer-generated graphics to enable the operator to preview manipulator movements before committing to the move. The objective was to establish a minimum length, no collision trajectory.

Another method of eliminating this delay is to use simulated displays which can be thought of as an extension of early predictive displays (Boyle et al., 1995a,b; Cardullo and George, 1993; Hirzinger et al., 1993; Hogema, 1997; Lee and Lee, 1993; Sheridan, 1993). These studies have demonstrated that predictive or simulated displays can be of use in certain specific application areas but Sheridan (1993, 1997) notes that such supervisory control can only be fully used in sufficiently predictable tasks (such as free positioning). Sheridan also mentions that the use of wave transformation techniques can help to ameliorate the detrimental effects of delay.

Hirzinger et al. (1993) used both of these ideas in the design of ROTEX, a space robot technology experiment flown with the space shuttle COLUMBIA. Delay times in teleoperating such space-based robots from some distant site (such as the ground) were found to be in the order of 5-7 seconds. For this reason, predictive computer graphics were used in the visual feedback for the (ground-based) operator. These predictive computer graphics consisted of an immediately reacting simulation of the space-based robot with some storage for commands to be sent via the time-delayed transmission links (analogous to buffering signals in conventional electronics).

This idea of controlling a virtual or 'phantom' robot in real-time with the motion of the physical robot following that of the virtual with the communication delay has also been investigated by Bejczy et al. (1990); Bejczy and Kim (1991); Bejczy et al. (1994), Buzan and Sheridan (1989), Funda and Paul (1990, 1991b,a), Haule and Malowany (1995); Jägersand (1999) and Sheridan (1991) among others. As technology has improved, the quality of the virtual robot has also improved so, for example, Jägersand (1999) describes a system that produces predicted movies using a motor-visual model that is built from the delayed visual feedback and the operator's control signals. This system was produced using ideas from image and movie compression.

Many of these predictive measures use *Smith's principle* (Smith, 1958) which, to use Brown's (1990) paraphrase is as follows:

> *'The desired output from a control system with delay $\mathcal{T}$ is the same as that desired from a delay-free system, only delayed by $\mathcal{T}$.'*

A similar idea to this of predicting movement was investigated by So and Griffin (1991, 1996) in their studies of compensating for delays by image deflection and by predicting the position of the head. The focus of these studies was helmet-pointing systems. They were particularly concerned with the delays introduced by measuring head position and therefore reduced this delay by attempting to predict where the head is likely to be positioned. A refinement of this work used phase lead filters in conjunction with image deflection. Similar work was carried out by Ricard and Harris (1980) and Ricard (1995) in using lead/lag functions.

Compensating for delays in a graphical simulator (typically a flight simulator) has been approached using some other techniques. For example, Crane (1981) experimented with a compensation scheme based on control-system design principles. This compensation was shown to be effective for tracking (simulating keeping wings level in turbulence). Similarly, McFarland (1986) presented a compensation algorithm for improving helicopter simulator performance (compensating for the delay in the system) and Chen (1989) describe a compensation device for use in robotics. Sobiski and Cardullo (1987) outline a method of using a state transition matrix in order to compensate for delays in a simulator, and Smith (1992) described improvements to software in order to reduce delays in a flight simulator.

Some of these systems made use of compensatory devices that could not readily be used in real-time (i.e. a real world rather than a simulated one). It should also be noted that overcoming delays in a simulated world has often been achieved by the increase in speed and computational power such that modern simulators have few of the problems associated with simulators in the late 1970s. Similarly, work by

Namiki et al. (1999) and others in developing high speed visual sensors that process visual information in 1 ms means that some of the delays in teleoperations will also be reduced. For this reason, work that is solely concerned with reducing delays in a simulated environment is of limited use. However, work that considers delays due to physical constants such the speed of transmission are still highly relevant.

Lee and Lee (1993) mention a key concept that is widely used in simulated displays, that of time clutches. This idea is that real time can be disengaged (analogous to disengaging the engine from the transmission in a car by using the clutch) for discrete periods of time in order to stabilise the simulated and real worlds. A hypothesis that was put forward in the same paper is that short time delays of up to 3 seconds are better handled by a real-time control system than with simulated or predicted methods.

These ideas of simulated methods have been further extended by use of virtual reality, whereby the real world is modelled accurately (in a virtual world). Operations are then performed on this virtual world, which reacts in apparent real-time, using predictive techniques for analysing likely results of the operations. The operations are sent down the delayed transmission lines, and confirmation received along the same line. The real-world and virtual worlds are then compared to ensure that the 2 worlds are the same (apart from the time difference). (Hendrix, 1994; James and Caird, 1995; Karron et al., 1997; Tsumaki et al., 1996)

Massimino and Sheridan (1994) noted that operating at very low frame rates led to significant performance degradations. However, they also demonstrated that tactile (force) feedback could compensate to a large degree for these degradations. For example, it was discovered in their experiments that performance at 3 fps (frames per second) with force feedback was comparable to 30 fps without force feedback. It therefore seems reasonable to state that another method of reducing the effects of delays in visual feedback is to use additional forms of feedback. This assumption was also used by Karron et al. (1997) in their research into using aural feedback to compensate for problems in existing visual feedback (including time lags). However, if these other forms are subjected to the same delays as the visual feedback (as they often would be due to the limitations of the communication medium being used), then the advantages are less clear.

The use of haptic feedback in compensating for delayed visual feedback has also been studied by Anderson and Spong (1989), Bejczy and Kim (1991), Buzan and Sheridan (1989), Hale (1992), Kim et al. (1992) and Namiki and Ishikawa (1996) among others. Delayed haptic feedback was again shown to cause instability in a similar way to delayed visual feedback thus indicating that its use as a means of alleviating the deleterious effects of delayed visual feedback is limited to those applications whereby the haptic feedback is transmitted with little or no delay.

With all of these compensatory methods feedback is modified in some way and therefore additional training is required for effective use of this modified feedback (Bejczy et al., 1994). In this same study it was found that operators had to have a protocol and practice, and it was the protocol following habit that developed the skill of the operator.

A similar approach that could require less training of the operator was outlined by Conner and Holden (1997) who investigated methods to provide a low latency user experience in high latency applications. This was achieved by using visual effects to provide immediate feedback to the user even when delays (introduced by network delays) were present. Effects used were motion blur, transparency, and defocusing. Informal results suggested that this could increase usability. There does seem to be some potential to this idea in order to alleviate annoyance (analogous to the use of cues such as a rotating hourglass or timer to show that a task is being executed and the user should wait). However, applying these ideas to the control of remote vehicles requires more work.

Alternatives to the ideas of using some sort of predictive display or visual cues to show the operator how much delay is present have also been investigated. For example, Graves (1997) considered an enhancement of a bomb disposal robot using some automation on the robot. This led to the operator applying supervisory control rather than direct control thus reducing operator workload. Others have also taken this approach of automating the robot so that, in the example of the Mars Rover vehicle, it will stop moving if it detects an obstacle.

It is possible that the ideas of stochastic resonance (McNamara and Wiesenfeld, 1989) could be used in the development of compensatory measures; namely that of increasing the input noise resulting in an improvement in the output signal-to-noise ratio. The reasoning for this is that delayed visual feedback can be considered as introducing instability into the operator control loop. If one considers this instability as analogous to a high signal-to-noise ratio in the output, then the idea of introducing some carefully selected input 'noise' in order to improve the stability of the system (i.e. the performance of the operator) may hold. This idea has been explored by Vasilakos and Beuter (1993) among others, by means of mathematical models of the dynamics involved and does seem to have potential although further investigation is outside the scope of this thesis.

Another potential source of a solution lies in the area of control engineering. Smith (1957, 1959) outlines a method of introducing a minor feedback loop in order to prevent what Smith calls oscillations due to dead time (some lag due to transportation or flow). The analogy with human behaviour appearing to show some of these oscillatory characteristics (typically of motor control resulting in oscillations of the artifact being operated) is strong, and therefore a similar feedback mechanism might be possible. In a similar manner, Celka (1995) describes using a control scheme for controlling chaotic orbits (for time-delayed feedback systems) and applies this work to optics.

2.7 Human Memory

2.7.1 Introduction

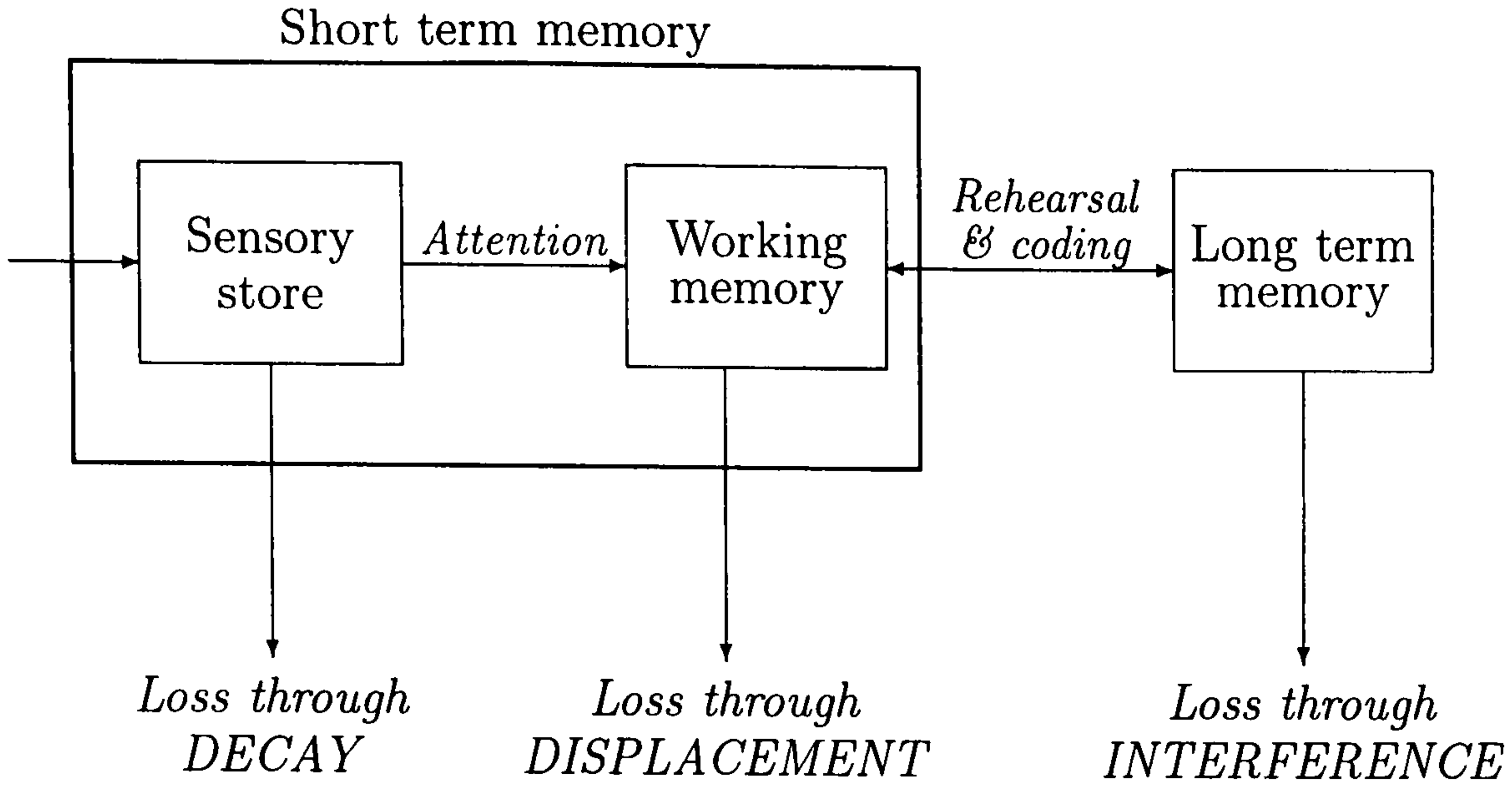
As has been demonstrated in the previous litereráture the effects of delayed visual feedback appear to be cognitive in nature. In particular the ideas suggested by some of the literature implies that the delayed feedback can be compensated for by using some prediction on the part of the operator, i.e. by using human memory to attempt to compensate for the delays. However, this compensation is not always adequate suggesting that there are limits to the amount of prediction that can be achieved; that is to say, there are limits on the capacity of human memory. It was therefore decided that a more detailed study of human memory literature be carried out in order to better understand this limit on memory and the relationship between memory and performance of physical tasks such as steering and tracking.

2.7.2 Background

There has been a great deal of work carried out in the last 50 years by cognitive psychologists in endeavouring to understand more of the workings of memory, often by designing models that encapsulate some of this understanding.

In the 1950s intensive study of the concept of short-term memory was carried out by Brown (1958), Broadbent (1958) and others. At the same time work was being carried out on long term memory, but little was done to link these two fields. In the 1960s, however, there was debate over the nature of memory and many models were designed, some of which included the concepts of both short and long term memory, for example that proposed by Atkinson and Shiffrin (1968) (see Figure 2.1).

Since the mid 1970s, the idea of a *Working Memory* (WM) has been explored. This concept has a variety of definitions and meanings. One view is that proposed by Honig (1978) and summarised by Becker and Morris (1999) in which a distinction is



Please note, this was derived from Atkinson and Shiffrin (1968).

Figure 2.1: Modal model of memory

made between working memory (information that is critical for one trial that is then forgotten), and reference memory (information that is true for all trials of a task). Miyake and Shah (1999) defined working memory as '*the system or mechanism underlying the maintenance of task-relevant information during the performance of a cognitive task*'. Anderson et al. (1996) outline two theories regarding working memory. The first of these theories is that working memory is the currently available information against which certain production rules match. The second, which was also discussed by Becker and Morris (1999) and Miyake and Shah (1999), is that WM consists of paradigms, which require the subject to maintain memory load while performing a task (Baddeley and Hitch, 1974; Daneman and Carpenter, 1980).

This last theory is the one that has been used as the basis for this thesis. (It should be noted that this model has gained widespread acceptance.) This model of working memory adopted has been defined in general terms by Baddeley et al. (1999) as follows:

> *'the temporary storage of information that is being processed in any of a range of cognitive tasks'.*

From experimental results by Baddeley (1975, 1980), Logie (1995, 1998) and others, the idea of visuo-spatial tasks being separated from articulatory tasks has been incorporated into a specific model of working memory given in Figure 2.2. This model was presented in greater depth in Baddeley (1986).

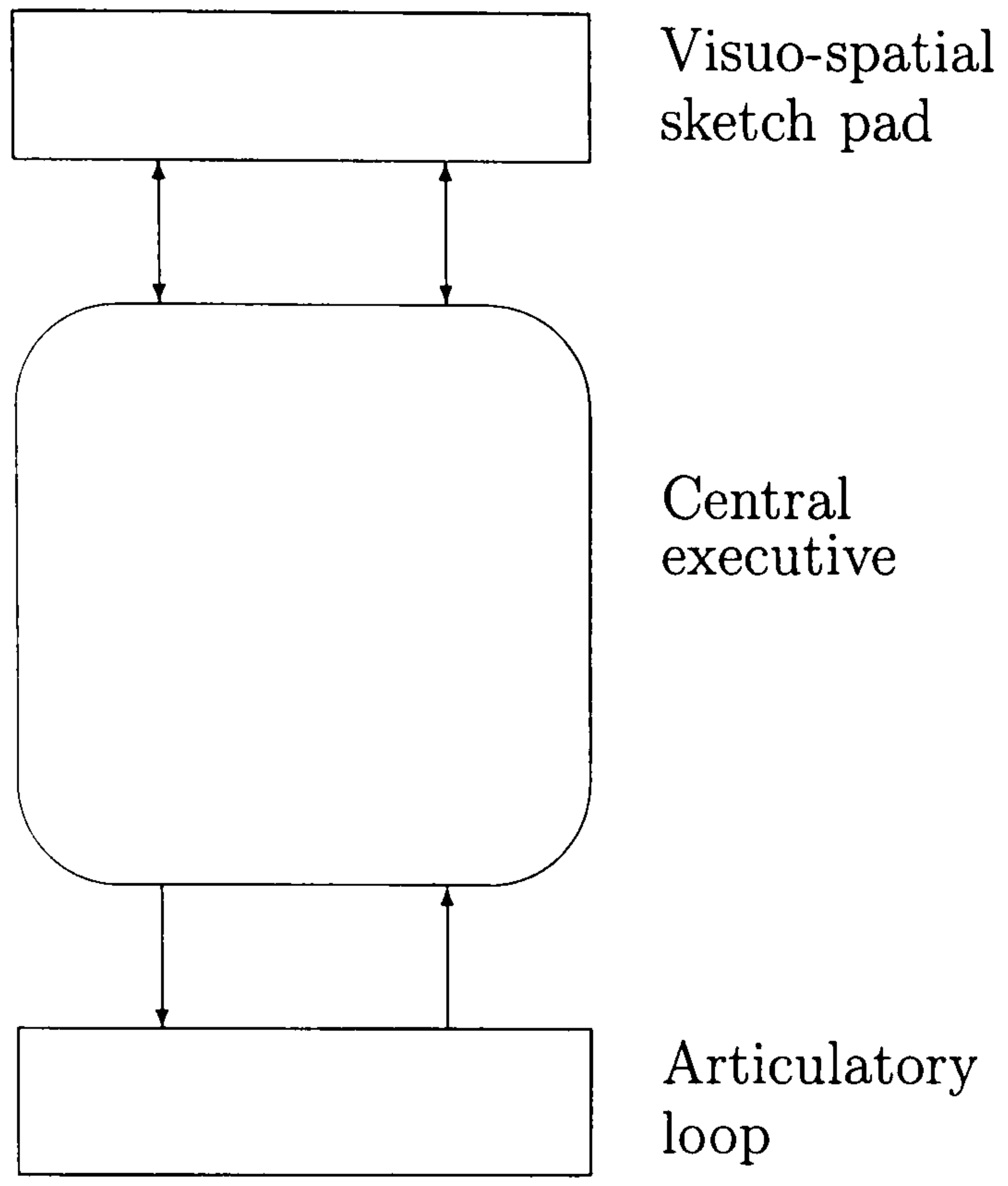


Figure 2.2: Simplified model of Working Memory

The justification for the separation into vocal and visual portions is that the two sets of tasks seem to be handled in a different manner to each other, and visuo-spatial tasks do not seem to interfere with articulatory tasks. This system, with single central executive and two slave systems (articulatory loop and visuo-spatial sketch pad) was developed from a structure suggested by Brooks (1967, 1968) and widely accepted since then (e.g. Bower, 1974). The fact that spatial tasks disrupt the visual system in some way is well accepted (Byrne, 1974; Shepard and Metzler, 1971).

This investigation of the processing of visuo-spatial material by using the model of a visuo-spatial sketchpad by Baddeley et al. (1986, 1991, 1992b, 1992a) has also been extended and adopted by Logie (1995) and Logie and Gilhooly (1998) among others.

Since the adoption of these ideas there have been investigations into the parameters (such as capacity) of working memory. For instance, Baars (1997) suggests that features often associated with attention (for example, limited capacity) can be viewed as properties of consciousness. He argues that WM may be a superstructure dependent on fundamental features of consciousness or awareness.

Chaiken et al. (2000) suggest that psychomotor ability has to do with general working-memory capacity and the ability to keep track of time. Similarly experimental results by Rosen and Engle (1998) suggest a relationship between working memory capacity and the ability to suppress intrusive thoughts and behaviours.

A more detailed theoretical investigation into the capacity of working memory was considered to be unnecessary for this thesis as the problem of remotely controlling vehicles under delayed visual feedback is a rather focused domain and thus task-specific results are perfectly justifiable (rather than the more general results that would be obtained by investigating working memory parameters).

There have also been studies into the possible internal structures concerned with working memory, for instance, Miall et al. (1989) investigated visuomotor tracking with delayed visual feedback. In these studies a rhesus monkey and 5 human subjects used a joystick to track a moving target. All subjects made discrete correctional movements, with the frequency of these movements reducing with the addition of visual delay. This work was then extended (Miall et al., 1993) with similar findings.

In a more detailed study, Miller et al. (1996) examined the neural mechanisms of visual working memory in the prefontal cortex of the macaque. Results suggested that the prefontal cortex has a dominant role in working memory tasks. Similarly Haxby et al. (2000) investigated neural systems for visual working memory using functional magnetic resonance imaging. Results showed 6 distinct frontal regions were used in tasks involving visual working memory.

These studies were found to be peripheral to this report and are therefore not discussed further.

2.7.3 Working Memory Disruption

The concept of forgetting has been explained by various theories and models. To summarise these, forgetting can be thought of as either

- a result of memory 'decay', or
- a result of interference between memories.

This concept of interference in recall can further be split into two categories: retroactive interference (forgetting old information due to new information interfering with the old) or proactive (forgetting new because of the old) (Baddeley et al., 1999).

As has been mentioned, one of the explanations for forgetting is that of interference between memories. Various tasks have been designed to induce this interference in order to understand more about the workings of memory. Relevant experiments which make use of such interference effects are outlined in Section 2.7.4 below.

2.7.4 Interference Tasks

Counting task

This task, reported in Baddeley (1986) involves the subject counting repeatedly from 1 to 6 out loud. This is for articulatory suppression (to interfere with the articulatory loop) and was therefore considered to not be of direct relevance for this thesis. An extension of this, however, is to hear and repeat back sequences of 6 random digits. This does appear to interfere more deeply with working memory but not visuo-spatial working memory and again is not of direct use.

Similar tasks were used by Anderson et al. (1996) in experiments consisting of holding a digit span, solving equations and then recalling the digit span. Results showed that as either task became more complex, performance decreased (both in terms of accuracy and latency) in both tasks. The majority of the errors noted were misretrievals which implies that working memory load has an impact on retrieval from memory.

Letter tracing task

In this task, designed by Brooks (1967, 1968), the subject is shown a block capital letter, with the bottom left hand corner marked with a star. The task is to look away from the letter and, holding it in their mind's eye, to go around the letter from the star responding *"yes"* if the corner in question was at the top or bottom and *"no"* otherwise. Hence for the letter F, the response would by *"yes, yes, yes, no, no, no, no, no, no, yes"*. This is a visuo-spatial task.

The letters used all had ten points and were: F, N, G, and Z. Each letter had an asterisk next to it indicating the start point and an arrow indicating that points were to be taken in a clockwise direction from the start. Brooks' findings were subsequently reported and confirmed by his contemporaries such as Neisser (1976), Segal and Fusella (1970), Byrne (1974), and Salthouse (1974, 1975). A verbal task was also used; classify each word in a sentence as a noun using the response 'yes', or a verb (response 'no'). This was concerned with articulatory working memory and is therefore not of direct relevance.

In Baddeley's experiments the letter tracing task was found to disrupt tracking of a pursuit rotor. The results of these visual pursuit rotor tracking experiments are presented in Table 2.1 (Baddeley et al., 1975; Baddeley and Lieberman, 1980).

These experiments, in which letter tracing was found to disrupt pursuit rotor tracking, were designed to investigate the kind of problems that one might experience

	Mean percent time on target	**Standard Deviation**
Control *(no memory task)*	90.8	5.7
Verbal memory task *(sentence classification)*	88.0	4.6
Visual memory task *(letter tracing)*	78.0	11.6

Table 2.1: Visual pursuit rotor tracking results

in driving along a winding road while listening to a football game on the radio with a conflict being experienced between steering and visualising the game. Baddeley argues that this is not due to simple distraction effects as Brown (1965) found that driving efficiency was not impaired by listening to music or discussions on the car radio. This type of task is highly relevant to research on visual delay as it provides an experimental mechanism by which to investigate the role of working memory in delay and control.

Colours/patterns interfering with mnemonic counting

An additional task designed by Logie (1995) used comparisons of colours or patterns to interfere with reciting numbers 1–10 using rhyming mnemonics (one-is-a-bun, two-is-a-shoe, etc). This was later refined to using pictures with participants listening and responding to aural information while ignoring visual information. This was more concerned with articulatory working memory and is therefore not of direct use for this thesis.

2.8 Peripheral Studies

These studies are of areas that have some connection with the problems of delayed visual feedback but extend into areas that are beyond the scope of this thesis. They are therefore included for the sake of completeness rather than for any direct relevance to the cognitive effects of delayed visual feedback.

2.8.1 Emotional impact of delays

An additional area of research involving delayed feedback is that of the emotional impact of delays on the users. Although this is not of primary importance to this investigation, it may have a subtle effect on the results and therefore a brief outline of the main studies in this area will be presented with their findings.

Treurniet et al. (1985) investigated viewers' responses to delays in simulated teletext reception. Results showed that the proportion of delays noticed and the proportion of negative viewer responses increased linearly with the square root of the system response time. This work was continued by Planas and Treurniet (1988) who described the idea that annoyance due to delays can be explained in terms of the experienced delay in system response where experienced delay refers to an awareness of its duration. This study found that annoyance grew at a smaller rate when continuous, regular feedback was presented. Continuous feedback was also shown to shorten viewers' estimates of the duration of delays.

Similarly, Lupker and Fleet (1987) studied perceptions of post-dialing delays, and again found that more delays gave rise to more impatience and abandoning of the task.

Karis (1991) investigated the transmission quality of mobile communication systems using conversation tests. It was found that delays *'changed the way that subjects interacted'* yet were not detected by the subjects. The suggestion was made that the effects seem to arise from disruptions in the normal patterns of turn taking in conversation.

Caldwell (1993) and Caldwell and Paradkar (1995) while investigating voice mail message transmission delays noted that message urgency, message content and sender-receiver distance was significantly related to tolerance as was user experience (i.e. frequency of use of the voice mail system).

Sears et al. (1997) noted in the context of Internet delay effects that participants preferred shorter delays in downloading documents.

From these findings the obvious conclusion that delays cause annoyance, impatience and sometimes abandonment of tasks can be drawn, but it should be noted that these subjective measures are specific to the tasks being performed. For this reason further study of this particular area is outside the scope of this thesis.

2.8.2 Human Error

It was the original intention to use general models of human error in order to understand the problems of delayed feedback. However, a model that explained or could be extended to explain the effects of delayed or perturbed feedback could not be found. The main work considered is briefly described in this section.

For more details regarding this field Reason (1990) provides a good starting-point.

Nature of error

Errors can be categorised into two major areas; namely variable and constant errors. Constant errors are predictable, for example cheques written in January are quite likely to have the previous year's date.

Error is tied in with intention and intentional behaviour or actions. Unintended actions fall into 2 classes; those that achieve the intended goal and those that do not. An obscure example of an unintended action that does however achieve the intended action is given by Searle (1980) and is as follows. A man intends to murder somebody by shooting, but misses. The missed shot stampedes a herd of wild pigs which tramples the intended victim to death. A related concept is that of absent-mindedness whereby one becomes aware that ones actions have strayed from the intended path.

Even if intended actions go as planned they can still be erroneous if they fail to achieve the desired outcome. The problem can be said to be in the adequacy of the plan rather than in the conformity of the plan to ones prior intention. Such errors are known as mistakes. Norman (1981, 1983) produced a useful definition:

> 'if the intention is not appropriate, this is a mistake. If the action is not what was intended this is a slip'.

These can also be categorised as *planning failures* (mistakes) and *execution failures* (slips and lapses). Planning failures are likely to arise from higher-level cognitive processes than slips/lapses.

There exist a number of different error taxonomies, usually for a specific purpose. However, all classifications are attempted at one of three levels; the behavioural, contextual or conceptual levels (what, where or how).

The behavioural level of classification is easily observable. It includes the formal characteristics of the error (omission, repetition, disordering) or the more immediate consequences (nature and extent of damage, injury). It is an easy system to note, however, no simple mapping of behavioural error types onto more theoretical categories of cognitive failure exists.

The contextual level includes limited assumptions about causality, for example, slips of the tongue due to anticipations. It illustrates interactions between triggering factors and underlying error tendencies and therefore places a high importance on the recording of as much data as possible regarding surrounding circumstances (internal and external). However, contextual factors cannot explain why the same circumstances do not always give the same errors.

Error taxonomies at the conceptual level are based on assumptions regarding the cognitive mechanisms involved. They are therefore more concerned with theoretical inferences than observable characteristics of error and context. Such taxonomies are used in order to attempt to identify underlying causal mechanisms. On a related note, errors can be split into types or forms. Error type relates to the assumed origin of the error within the stages of planning, storage and execution of some action sequence (or plan). Error forms are 'recurrent varieties of fallibility that appear in all kinds of cognitive activity, irrespective of error type' (Reason, 1990).

Mistakes can be further subdivided into failures of expertise where some predefined plan or solution has been applied inappropriately, and lack of expertise where a plan has to be drawn up from first principles. These areas correspond to Rasmussen's (1983) rule-based and knowledge-based levels of performance.

An important factor that was identified in analysis of major instances of human error such as the Three Mile Island accident (Bailey and Knotts, 1987) is that system design (particularly interface design) has a major impact on (human) operator performance. This has been confirmed and reported elsewhere, see, for example, Park (1997) and Carey (2000). In the work by Bailey (1982) errors were found to be due to a combination of events never experienced by the operators before and poor interface design. Bailey mentions that this sort of task would be much easier if instead of problem solving (finding a single solution) the system enabled the operators to make decisions (deciding from a limited set of alternatives). This idea that operator failure can be understood in terms of mental workload has also been explored by Tsang and Wilson (1997) among others.

Johnson (1998) made the point that accidents typically have complex causes that may take days, weeks or even years to develop. For this reason he and others have produced formal notations in order to analyse systems failure.

Methods of investigating human error

The major methods of investigating error can be split into naturalistic methods, questionnaires, laboratory studies and case studies.

Naturalistic methods *(corpus gathering)* involve the identification and description of naturally occurring phenomena such as slips and lapses. Such methods are reasonably comprehensive, provide ecological validity and give a broader perspective than focused lab studies. However, errors noted are often spontaneous and are therefore not under the control of the experimenter. Errors are noted using tools ranging from self observation (Freud, 1914) to extended diaries (Reason, 1979).

Questionnaire studies make use of self-reporting. The questionnaires often have different slips or lapses and ask the subjects to rate how often they have experienced each during some specified time period. Responses suggest that those who say that they are liable to one kind of cognitive failure are also highly susceptible to other types as well. This implies that error proneness is approximately uniform across all types of mental domain.

Laboratory studies are useful because the factors to be investigated are focused and the experimenter can control errors, but such studies can give rise to artificial conditions and sometimes trivial phenomena being noted.

Simulator studies extend the idea of laboratory studies but make use of computer based laboratory simulations for complex real world tasks, thus allowing the control of errors but giving more relevant results.

Case studies typically involve an intensive study of a single case.

Norman-Shallice model

This model (Norman and Shallice, 1980) represents a family of action theories and assumes that an adequate theory of human action can account for predictable varieties of human error. The model has horizontal threads comprising of specialised processing structures (schemas) and vertical threads which interact with the horizontals to provide the means by which attentional or motivational factors modulate schema activation. It is primarily concerned with minor action slips that occur in everyday life.

Rasmussen's skill-rule-knowledge framework

Rasmussen's framework (1983, 1986) is error oriented and primarily directed at serious errors by those in supervisory control. The three levels of performance correspond to decreasing levels of familiarity with the environment or task.

Skill-based level Performance at this level is governed by patterns of preprogrammed instructions. Errors are related to the intrinsic variability of force, space or time coordination.

Rule-based level At this level familiar problems are solved by solutions governed by stored rules of the type

`if [state] then [diagnosis or remedial action].`

Errors at this level are associated with misclassification of situations leading to the use of incorrect rules or procedures.

Knowledge-based level This level considers novel situations where errors arise from resource limitations and incomplete or incorrect knowledge.

Reason (1990), in summarising Rasmussen, notes that there is a non-linear relationship between the above levels thus meaning that shortcuts can be taken between stages. Reason also states that there are 8 stages of decision making: activation, observation, identification, interpretation, evaluation, goal selection, procedure selection and activation.

An extension of the skill-rule-knowledge framework is the Generic Error Modelling System (GEMS) (Reason, 1990).

There are three basic error types in this system:

- Skill-based slips (and lapses)
- Rule-based mistakes
- Knowledge-based mistakes

The GEMS system thus brings together the idea of slips and mistakes, instead of having a dichotomy. The dynamics of the system are shown in Figure 2.3.

General framework for human error

This framework, outlined in Reason (1990), describes a distinction between two control modes. These two modes are:

1. controlled or conscious processing
2. automatic or unconscious processing.

The modes can also be described as attentional and schematic modes. In a similar manner, the underlying cognitive structures can be considered as two structural elements; namely

- workspace or working memory (attentional) and
- knowledge base (schematic).

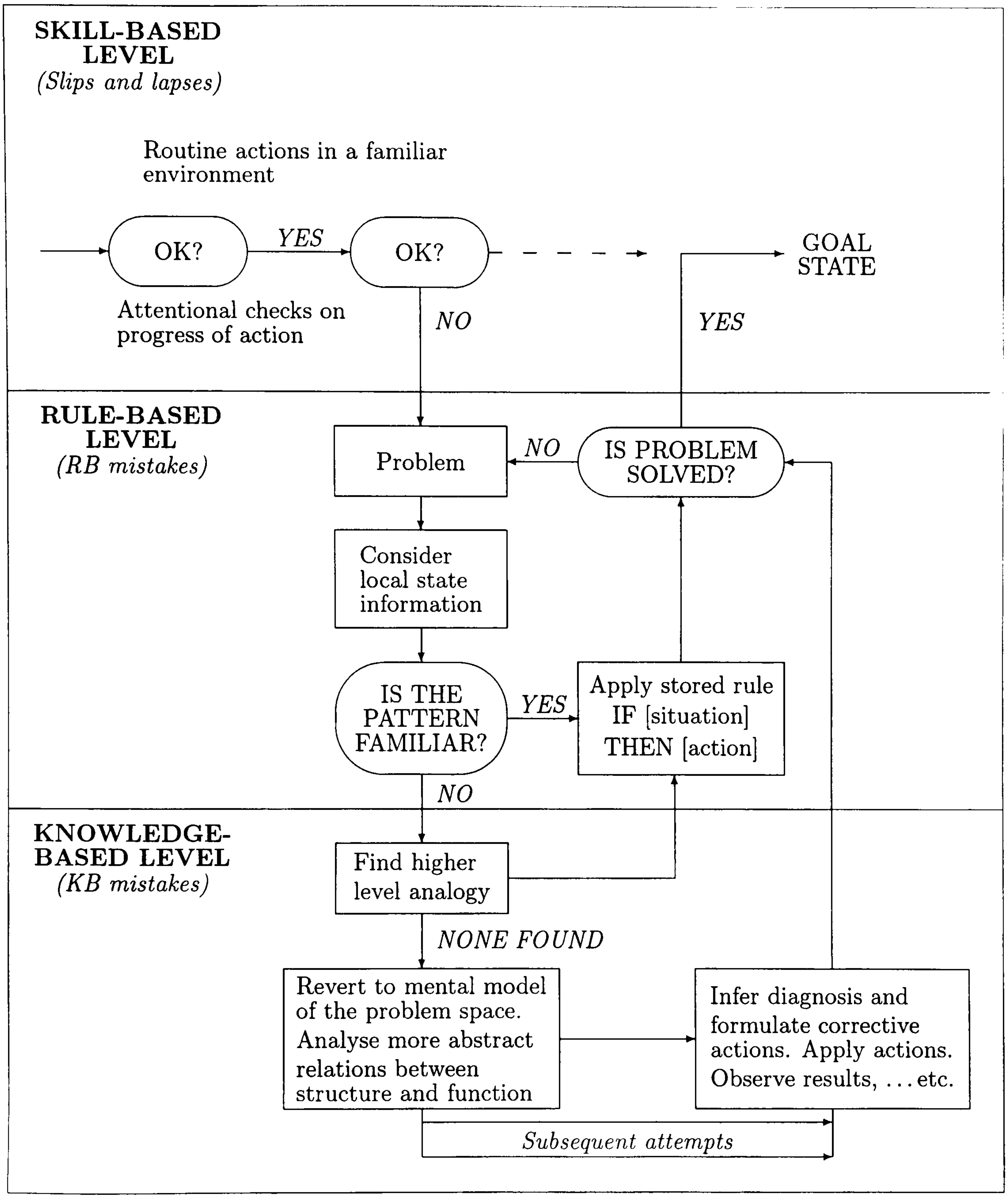


Figure 2.3: GEMS dynamics

The attentional control mode is closely identified with working memory and consciousness. It is limited, sequential, slow, effortful and difficult to sustain.

The schematic control mode involves modelling and internalising useful regularities of the past. It is operated in response to very specific triggering conditions. Schematic control mode can process familiar information rapidly, in parallel and without conscious effort. Activation is by means of two classes of activators; specific and general.

Specific activators bring a schema into play at particular time, for example, intentional activity. However, to change an established routine of action or thought requires positive intervention by the attentional control mode, otherwise the result is absent-minded slips of action.

General activators involve background activation of schemata irrespective of the current intentional state. The more frequently schema are used, the less intentional activation is required, i.e. frequently used schema are activated in the background.

This method of automatic processing (rather than the controlled processing of attentional control) has also been investigated in Norman's work on slips and mistakes (Norman, 1981). For instance, two of the three main categories of slips from Norman (1981) are faulty activation of schemas, and faulty triggering.

The ability of experienced operators of remote vehicles can therefore be understood in terms of schematic control with internal models being formed of the vehicle dynamics in order to compensate for feedback delays. If this suggestion is correct, then the effect of learning in experiments is to be carefully considered as participants will place less reliance on the visual feedback as they become more experienced (and therefore move from attentional control to schematic control). It is therefore suggested that the order of experimental conditions be randomised to prevent learning from affecting the results, and that all participants should, if possible, have a similar level of experience with operating remote vehicles (physical or simulated).

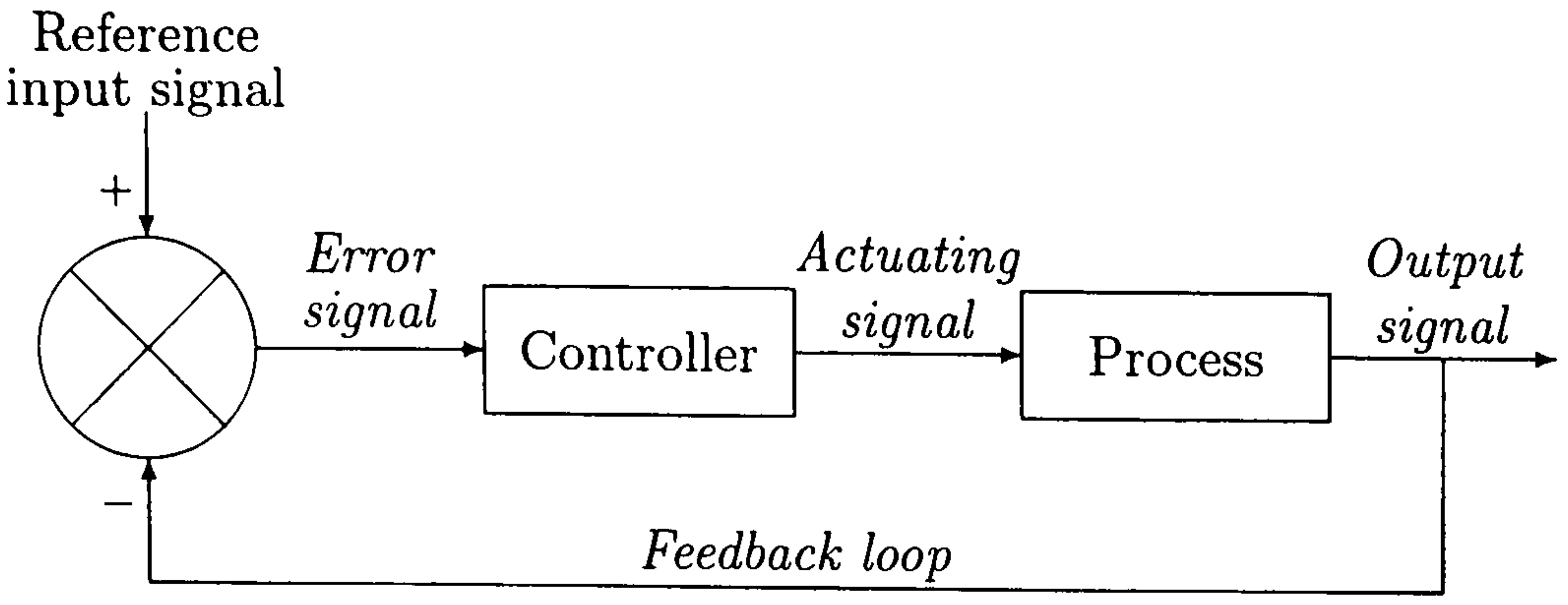


Figure 2.4: Error detection

Detection of errors

Reason (1990) reports three modes of error detection; self-monitoring, environmental cuing, and error detection by other people.

Self-monitoring is achieved by error driven feedback control. A general control system to achieve this is shown in Figure 2.4. Execution errors are detected very quickly in such a system with a person comparing what they felt or saw of the wrong response with a record of what was intended (Rabbitt, 1966, 1968; Rabbitt and Dornic, 1975).

Detection and correction of speech errors contains more detailed work of error detection. Most psycholinguists accept the existence of an internal monitor or editor that checks speech outputs both before and immediately after utterance. Findings suggest that humans edit spoken output at a number of levels and that errors obeying lexical rules are more likely to evade scrutiny of the editor. It is because of this specific ability of humans to understand and monitor speech that Baddeley's model of working memory separates articulatory tasks from the rest of working memory. This assumption was verified by Baddeley's experimental work in which articulatory tasks did not interfere with visuo-spatial tasks.

2.9 Summary

The fact that delays often impair performance (including accuracy, timing and integration) of motor-sensory mechanisms is well established. Effects of feedback delay include overcompensation, lack of trust in the feedback, confusion and disorientation of the system user.

Some motor-sensory mechanisms reach peak disruption at specific delays while others increase proportionally with the delay. Complex movements are more affected by delays in feedback than simple movements.

The effect of delayed feedback of all forms on the operation of a system is to reduce the bounds of stability of that system. For example, delayed auditory feedback is known to produce stuttering, delayed visual feedback is known to produce overcompensation in control movements in targeting exercises and finger oscillations in manual tracking exercises.

These findings that have been reported were replicated in pilot work considering the effects of pure delay and were extended into a comparison of pure delay with low frame rate as a form of visual delay. This pilot work is described in the following chapter. Later experiments made use of the findings described in the human memory section and are outlined in Chapter 4.

Chapter 3

Pilot work

3.1 Overview

The work originates in investigations into the cognitive effects of delayed visual feedback when controlling remote vehicles. Some of the pilot work reported in this chapter has been outlined elsewhere (Day, 1999; Day et al., 1999, 2000, 2001a,b) but is described in detail here. In particular, the first pilot experiment described in this chapter was undertaken as part of an MSc dissertation (Day, 1998).

These investigations began with the aim of gaining some understanding of visual delay effects by empirical methods. Initially this took the form of replicating previous work in finding that visual delays cause a marked decrement in operator performance as found by, among others, Smith (1962); Smith and Sussman (1970); Keran et al. (1994); Elliott and Eagleson (1997). Operator performance, in the context of this thesis, is measured in terms of time to complete a task and errors in performing the task. Errors measured in the pilot work outlined here included targeting error and time in error, a crude measure of how accurate the track-following was. More sophisticated measures were used in the main experimental work described in Chapters 4 and 9 including the integral of squared tracking error (ISE) which was also used in measuring the performance of the control system discussed in Chapter 11.

This work was then extended into a comparison of the effects of delayed video compared with that of video with a low frame rate which also produced a performance decrement and confusion on the part of the operator thus replicating findings by Poulton (1966); Massimino and Sheridan (1994). Additional experiments into the effects of control delay also gave similar performance decrements to that experienced with visual feedback delay thus demonstrating that the difference between control and display lags, found by Garvey et al. (1958), does not appear to hold in the context of remotely driving a vehicle. In fact, these additional experiments instead reinforced findings from studies of flight control systems that showed a marked performance decrement with control delays such as is found with visual feedback delays (Smith and Bailey, 1982; Crane, 1984; Bailey and Knotts, 1987).

In all preliminary experiments, which were hypothetico-inductive in nature, subjects performed remote controlled driving tasks using a wheeled vehicle driven along a track towards a target. The vehicles were fitted with video cameras that displayed real-time or delayed images to the operators. The tasks involved driving within boundary lanes and hitting a target at the end of the track. The first experiment used actual delay in image transmission (0, 2, 4 and 6 second delays) while the second and third experiments used video frame rate as a form of delay (4, 3, 2 and 1 fps as compared to a control setting of 25 fps).

The first experiment was designed to look at the effects of delays but due to the equipment used also introduced low frame rates into the visual feedback. For this reason it was felt that an additional investigation into the effects of low frame rate was needed. This was investigated in the second and third experiments.

3.2 Pilot Study 1

3.2.1 Aims

This experiment aimed to replicate previous work that observed that visual feedback delays produced a performance decrement. The following hypotheses were tested.

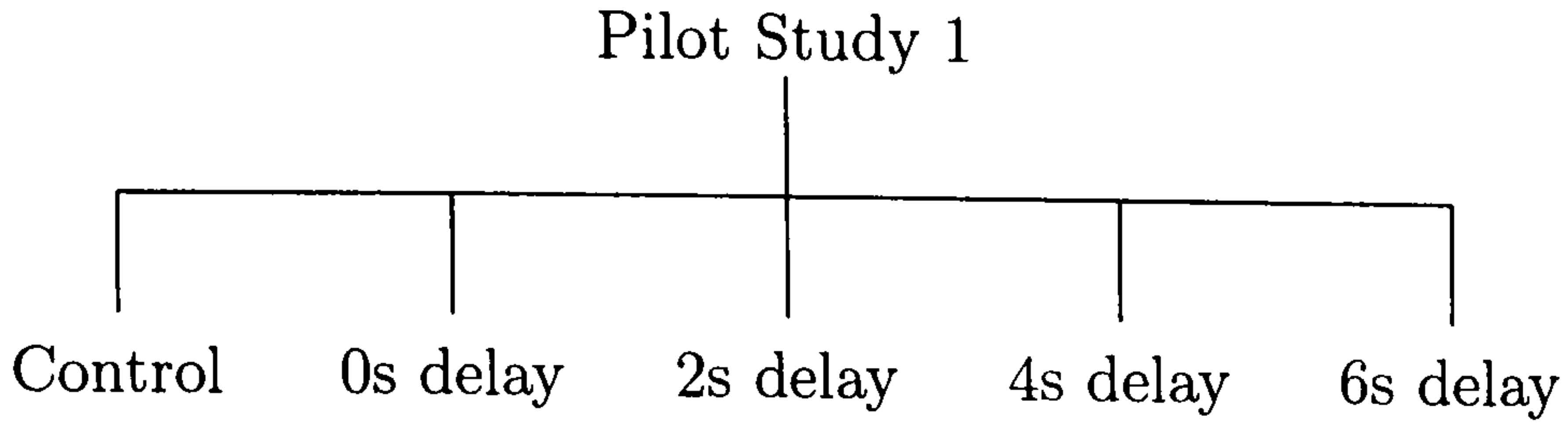


Figure 3.1: Pilot Study 1 Factorial Design

Null hypothesis

P1H00 The presence of delayed visual feedback will have no significant effect on completion times (time taken to complete each task).

P1H01 The presence of delayed visual feedback will have no significant effect on targeting errors.

Alternate hypotheses

P1H11 An increase in delay magnitude will cause completion times to increase.

P1H12 An increase in delay magnitude will cause errors to increase.

3.2.2 Design

A within subjects single factor design (with five levels) was used as illustrated in Figure 3.1.

The independent variable (or single factor) was delay magnitude consisting of delays of 0, 2, 4, 6s and an additional control setting. This setting consisted of bypassing the video delay software entirely in order to compensate for the unpredictable delays introduced by the software. (These unpredictable delays occurred when the software discarded frames from the feedback.)

The dependent variables were:

1. User Performance

2. Protocols

These variables were captured using the following dependent measures:

1. Completion times (time in seconds to complete the task)
2. Targeting errors (distance in mm from centre of target)
3. Protocols (such as questionnaires before and after the experiment and using a talk-aloud protocol during the experiments with user comments being recorded on paper).

3.2.3 Participants

30 subjects participated in this experiment. 24 participants were male, 25 were right-hand dominant. 16 of the participants normally wore spectacles or contact lenses and 15 of them were wearing them for the experiment. Ages of the participants varied, with 2 being below 21, 24 in the 21–30 age group, 3 in the 31–40 group and 1 in the 41–50 age group. All participants were students or research staff at Heriot-Watt University. No participant reported any other problems that might have affected their ability to control the vehicle.

3.2.4 Materials and Apparatus

A Vision VL5402 CCIR single chip monochrome camera, a Nikko Strike radio-controlled single-speed car with external gearbox fitted to reduce its speed, and a Sony KX20PS1 video monitor running at a resolution of 512*512 pixels on CCIR signals were used for this experiment. The maximum speed of the radio-controlled car was constant for all trials and participants. The car and controller are shown in Figure 3.2. The mean speed of the car (measured repeatedly along a 2m straight section) was 2.52 m/s with a standard deviation of 0.49.

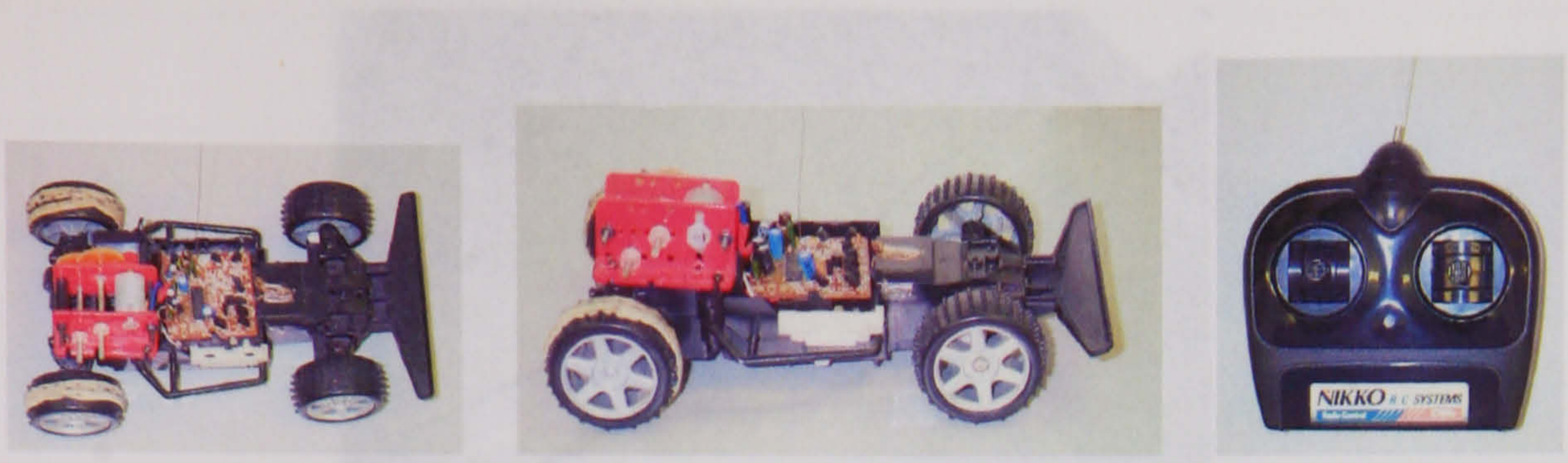


Figure 3.2: Radio controlled car and controller

In addition to these items, an Elonex MTX-6266 Pentium II personal computer with 128M of RAM, a Matrox Mystique 4M video card and a miroVIDEO DC20 video capture card were used to produce the delays. This computer was running EMULive Imaging Corporation's EMULive Video Producer v3.99d, EMULive Active Theater and EMULive Server v3.4 on Microsoft Windows NT v4.0. The computer display was set to 1280*1024 pixels at 16-bit colour and shown on an Iiyama T917E 17" CRT monitor.

Materials used included pre and post-experiment questionnaires in addition to data recording sheets for recording timings, errors and user comments. The questionnaires were designed to capture any potentially confounding factors such as physical disabilities that would affect driving performance. Examples of all materials can be seen in Appendix A.1.

3.2.5 Procedure

Subjects performed remotely controlled driving tasks using a wheeled vehicle driven along a track towards a target. The vehicle was fitted with a video camera that displayed real-time or delayed images to the operators. The tasks involved driving within boundary lanes and hitting a target at the end of the track. Latencies and errors were collected. The track used is shown in Figure 3.3.

All subjects drove along the same track to alleviate the effect of track complexity

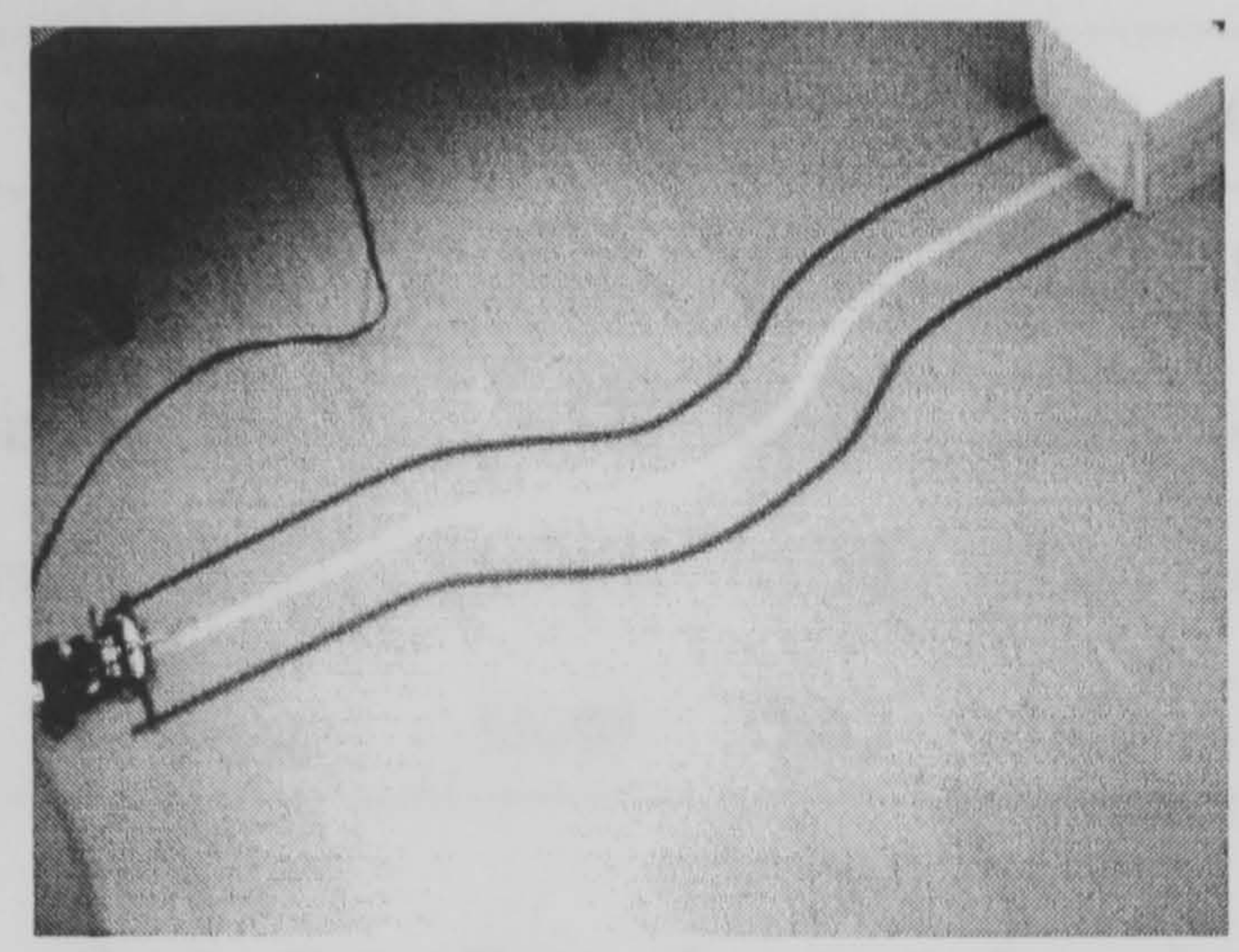


Figure 3.3: Pilot Study 1 Track

from the results. As this experiment was a within subjects design, all participants were tested with all delays. Subjects completed a questionnaire before the experiment began outlining their experience and background. This data was then used in analysis to ensure that data from individual subjects with more relevant experience did not skew the results.

The preparation of subjects was formalised and an instruction script read for all subjects in order to ensure consistent treatment.

Task orders (i.e. delay settings) were randomised in order to remove a possible source of confounding variables. This was achieved by using a randomly seeded random number generation program written in C. This program was extended for later experiments and this extended version can be found in Appendix H.

Reaction times and targeting errors were recorded using a prepared data recording sheet in addition to user comments. Timings were made with a stopwatch, and targeting errors measured with a measuring tape (calibrated in mm).

3.2.6 Results

The results of this experiment, in which four delay settings were used, showed a marked decrement in performance not only when measured in terms of time, but

	Control	A(0s)	B(2s)	C(4s)	D(6s)
Mean time taken (s)	9.56	65.66	78.06	89.17	89.53
SD time taken	4.87	29.59	52.41	47.63	53.53
Mean error (mm)	18.53	33.23	43.29	47.49	43.20
SD error	15.40	27.52	31.71	46.40	31.83

Table 3.1: Pilot Study 1 Results

also in terms of the magnitude of error that was measured (see Table 3.1 and Figure 3.4).

Due to limitations with the experimental setup, additional arbitrary delays were introduced into the system (by the video delay software discarding frames). For this reason, an additional control setting was used (which bypassed the video delay software completely) and gave participants full-motion, real-time visual feedback.

Analysis of variance between each delay setting and the control (using single factor ANOVAs) was found to be highly significant for completion times ($F = 18.88, df = 4, 29, P < 0.001$) and targeting errors ($F = 3.94, df = 4, 29, P < 0.005$).

Difference between delays was significant (compared using a 2 tail, paired orthogonal t-test between each delay setting and the control) for completion times ($df = 29, P < 0.001$ for all delays with respect to control), and errors ($df = 29, P < 0.01$). Results of the t-tests (each with respect to the control) are summarised in Tables 3.2 and 3.3.

Completion times (time taken to complete the task) and targeting errors appear to follow a similar trend according to Figure 3.4.

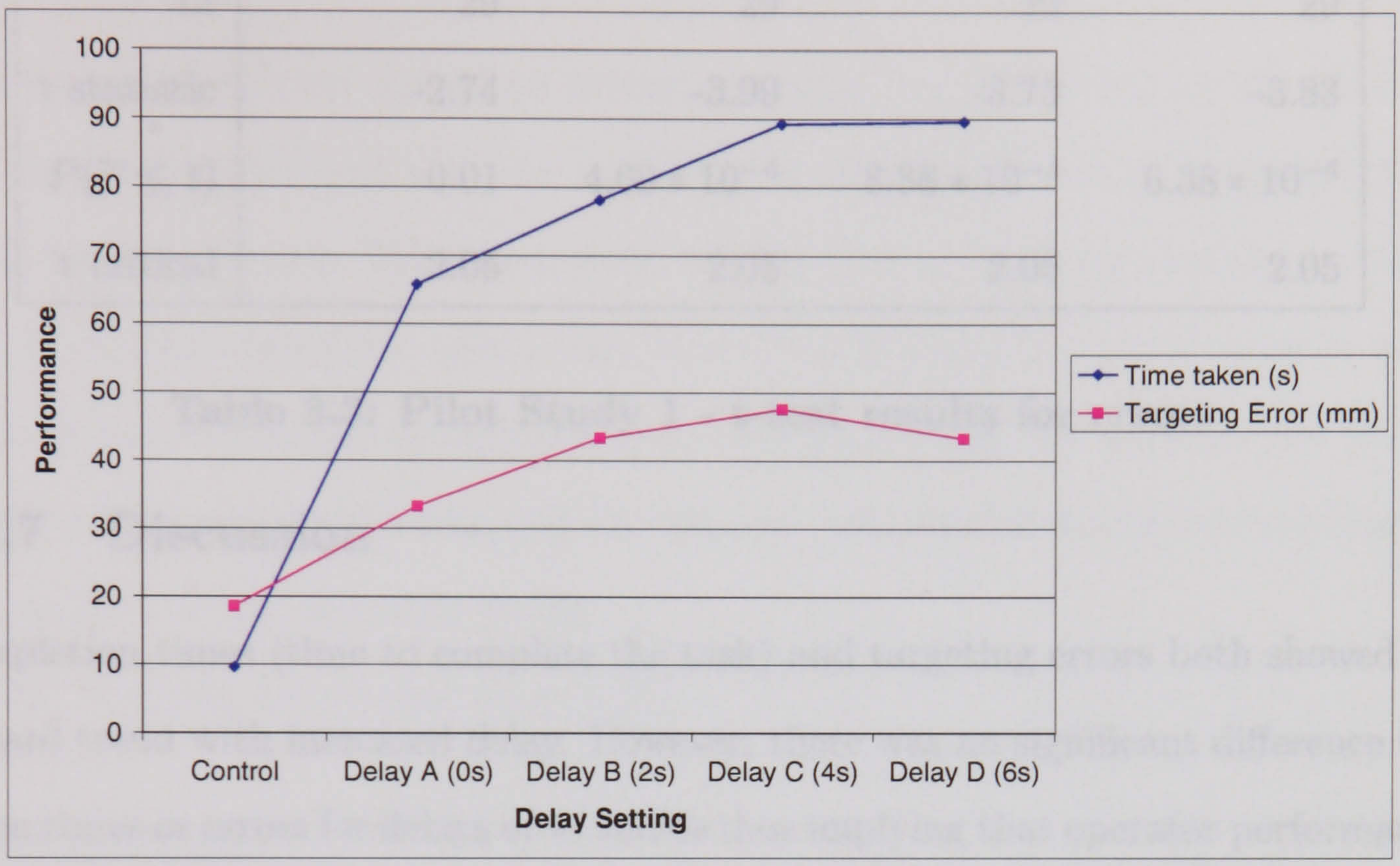


Figure 3.4: Pilot Study 1 Results

	A(0s) (wrt control)	B(2s) (wrt control)	C(4s) (wrt control)	D(6s) (wrt control)
df	29	29	29	29
t statistic	-10.36	-7.32	-9.38	-8.20
$P(T \leq t)$	$2.94 * 10^{-11}$	$4.68 * 10^{-8}$	$2.79 * 10^{-10}$	$4.86 * 10^{-9}$
t critical	2.05	2.05	2.05	2.05

Table 3.2: Pilot Study 1 - t-test results for completion times

	A(0s) (wrt control)	B(2s) (wrt control)	C(4s) (wrt control)	D(6s) (wrt control)
df	29	29	29	29
t statistic	-2.74	-3.99	-3.73	-3.83
$P(T \leq t)$	0.01	$4.09 * 10^{-4}$	$8.38 * 10^{-4}$	$6.38 * 10^{-4}$
t critical	2.05	2.05	2.05	2.05

Table 3.3: Pilot Study 1 - t-test results for errors

3.2.7 Discussion

Completion times (time to complete the task) and targeting errors both showed an upward trend with increased delay. However, there was no significant difference between times or errors for delays of 4s and 6s thus implying that operator performance reduces to some plateau at which point performance cannot get any worse.

It should also be noted that the delay equipment that was used introduced arbitrary amounts of delay at various points during the experiment in addition to only giving a low frame rate display (an approximate average frame rate of 5 fps). Further work is therefore required to investigate the effects of low frame rate. This work was performed in pilot studies 2 and 3 which are presented later in this chapter.

These results do however give a preliminary description of performance with a significant performance deficit being seen with visual delays and a plateau in performance with larger delays as suggested by Keran et al. (1994). Further discussion of these results is placed in the context of all preliminary work and can be found at the end of this chapter.

3.3 Pilot Study 2

3.3.1 Aims

The second experiment aimed to extend previous work by investigating whether low frame rates produced a similar reduction in driver performance compared with visual feedback delays. This experiment was designed in part because the previous experiment introduced not only a pure time delay but also low frame rates as well. It was therefore decided to separate these two factors and just consider low frame rate as a form of delay, building on the ideas of stroboscopic movement outlined in Section 2.2.3 of the literature review.

The following hypotheses were tested.

Null hypothesis

P2H00 Reducing the frame rate of the visual feedback will have no significant effect on completion times.

P2H01 Reducing the frame rate of the visual feedback will have no significant effect on errors.

Alternate hypotheses

P2H11 A decrease in frame rate will cause completion times to increase.

P2H12 A decrease in frame rate will cause errors to increase.

P2H13 Delayed visual feedback and low frame rate visual feedback will both have an adverse effect on operator performance.

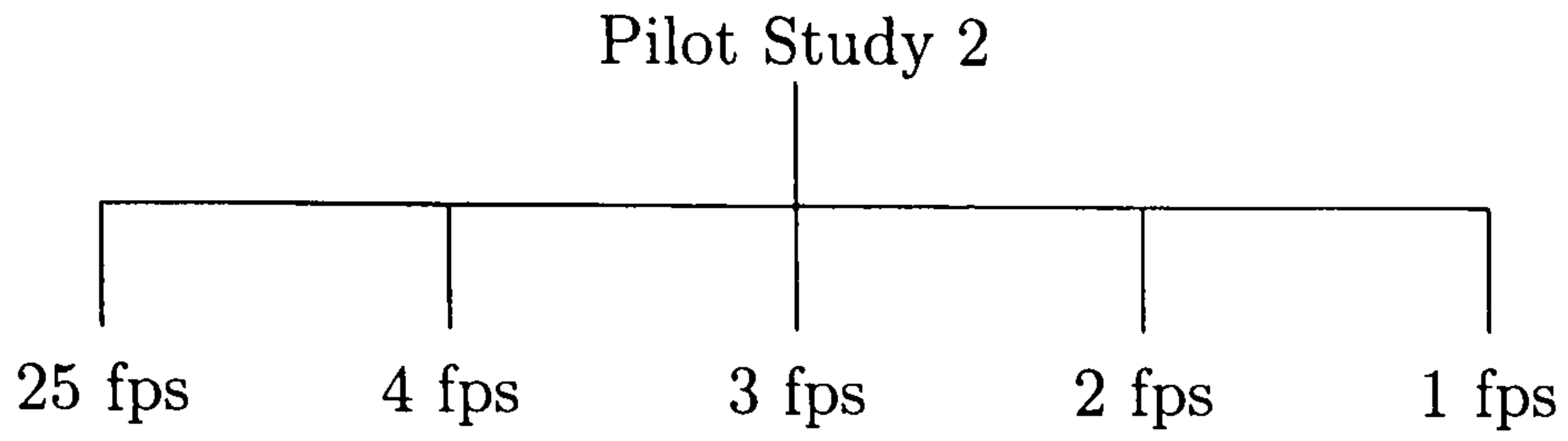


Figure 3.5: Pilot Study 2 Factorial Design

(fps = frames per second)

3.3.2 Design

A within subjects single factor (with five levels) design was used as illustrated in Figure 3.5.

The independent variable was video frame rate (as a form of delay) with settings of 4, 3, 2 and 1 fps as compared to a control setting of 25 fps being used. The dependent variables were the same as used in the previous experiment; being user performance and protocols. These were calculated using the following dependent measures:

1. Completion times (time in seconds to complete the task).
2. Targeting errors (distance in millimetres from centre of target).
3. Time in error (length of time in seconds that the vehicle was outside the boundaries of the track).
4. Protocols (captured as in experiment i).

The additional error measure of 'time in error' was used to give an indication of the severity of tracking error (deviation from the ideal track) in addition to the targeting error (distance from the centre of the target). However, this measure of deviation was abandoned as all results were recorded on the same acetate sheet so individual results could not be distinguished.

3.3.3 Participants

30 subjects participated in this experiment (with no participant having previously been involved in the previous study). 27 participants were male, 22 were aged 18-25, 4 aged 26-35 and 4 aged 36-45. 9 of the participants wore correctional lenses and all who needed to were wearing them for the experiment. No participant reported any other problems that might have affected their ability to control the vehicle. All participants were students at Heriot-Watt University.

3.3.4 Materials and Apparatus

The same camera, car and video monitor were used as in the first experiment. In addition a Mitac 486SX 33MHz PC with 8M RAM and running MS-DOS v6.22 was used to lower the frame rates. This was fitted with a Data Translation DT2851 High Resolution Frame Grabber and Data Translation DT 2858 Auxiliary Frame Processor. Software was written using Borland C for MS-DOS (see Appendix A.2 and A.3).

3.3.5 Procedure

Subjects performed the same driving task as that in the first preliminary experiment (consisting of driving within boundary lanes and hitting a target at the end of the track). The track used is shown in Figure 3.6.

3.3.6 Results

This experiment, in which 5 frame rates were used, also produced results that demonstrated a performance decrement when delay was increased (delay in this case referring to the time between frames being increased thus decreasing the frame rate). Summarised results are given in Table 3.4 and Figure 3.7.

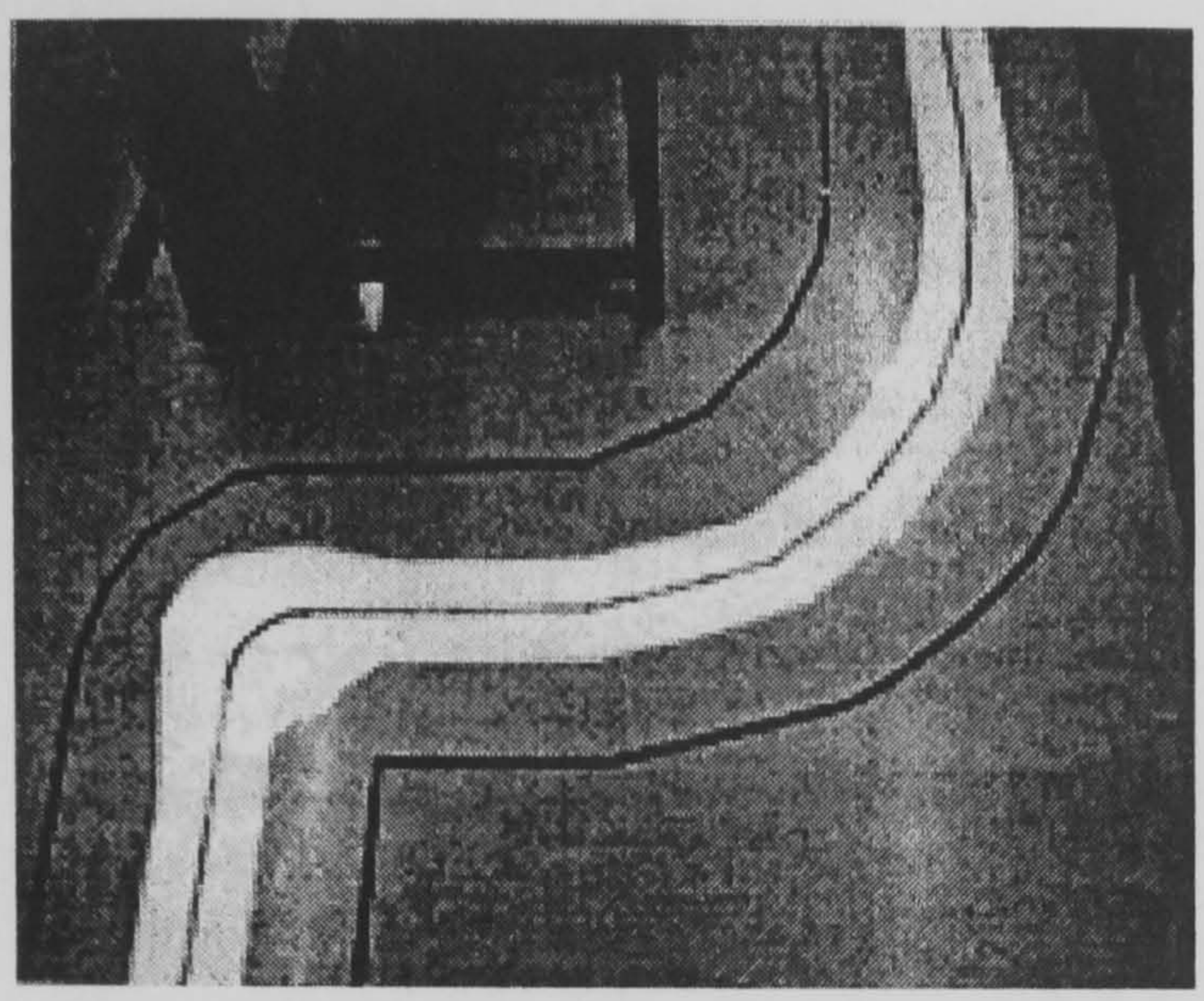


Figure 3.6: Pilot Study 2 Track

	Control	A(4 fps)	B(3 fps)	C(2 fps)	D(1 fps)
Mean time taken (s)	17.92	25.05	24.94	25.99	32.90
SD time taken	11.43	13.38	13.09	11.59	14.50
Mean error (mm)	20.27	17.71	24.37	33.96	34.37
SD error	16.23	13.69	19.91	21.38	34.16
Mean time in error (s)	5.41	8.99	9.14	8.61	13.06
SD time in error	1.75	3.32	3.96	2.70	5.95

Table 3.4: Pilot Study 2 Results

3.3.6 Results

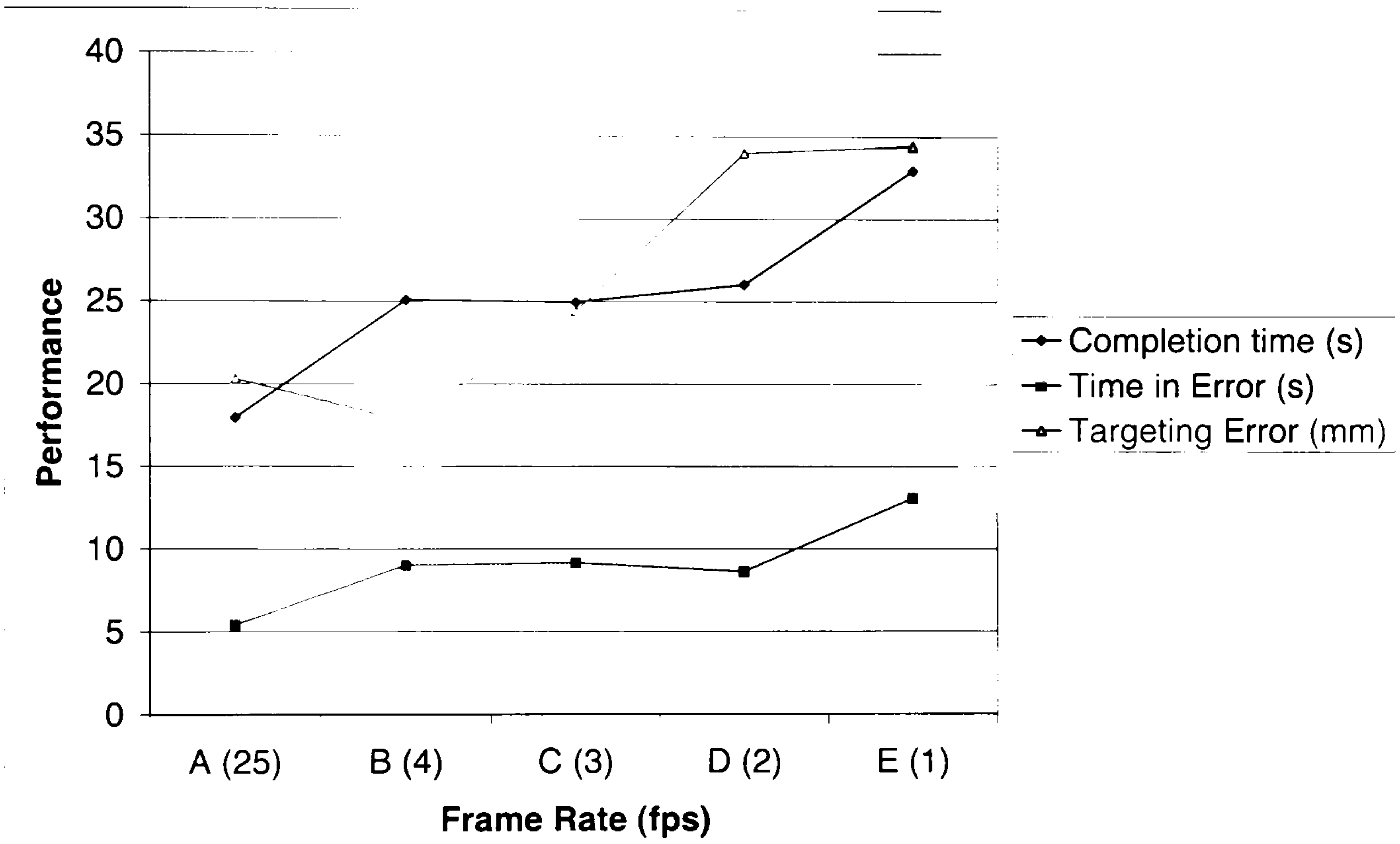


Figure 3.7: Pilot Study 2 Results

	4 fps (wrt 25 fps)	3 fps (wrt 25 fps)	2 fps (wrt 25 fps)	1 fps (wrt 25 fps)
df	29	29	29	29
t statistic	-6.44	-6.41	-6.82	-8.84
$P(T \leq t)$	$4.86 * 10^{-7}$	$5.21 * 10^{-7}$	$1.72 * 10^{-7}$	$9.96 * 10^{-10}$
t critical	2.05	2.05	2.05	2.05

Table 3.5: Pilot Study 2 - Completion time t-test results

	4 fps (wrt 25 fps)	3 fps (wrt 25 fps)	2 fps (wrt 25 fps)	1 fps (wrt 25 fps)
df	29	29	29	29
t statistic	-6.65	-5.87	-6.44	-7.50
$P(T \leq t)$	$2.70 * 10^{-7}$	$2.29 * 10^{-6}$	$4.83 * 10^{-7}$	$2.90 * 10^{-8}$
t critical	2.05	2.05	2.05	2.05

Table 3.6: Pilot Study 2 - Time in error t-test results

Analysis of variance (single factor ANOVAs) was significant for completion times ($F = 5.13, df = 4, 29, P < 0.001$), time in error ($F = 15.27, df = 4, 29, P < 0.001$) and targeting errors ($F = 3.60, df = 4, 29, P < 0.01$).

Difference between delays (2 tail paired orthogonal t-test) was significant for completion times ($df = 29, P < 0.001$ for all 4 frame rates with respect to A), time in error ($df = 29, P < 0.001$ for all 4 frame rates with respect to control), targeting error ($P < 0.001$ for D only). Results of the t-tests (each with respect to the control are summarised in Tables 3.5, 3.6 and 3.7.

Completion times and times in error are also similar while targeting error appears to follow a somewhat dissimilar trend (Figure 3.7).

	4 fps (wrt 25 fps)	3 fps (wrt 25 fps)	2 fps (wrt 25 fps)	1 fps (wrt 25 fps)
df	29	29	29	29
t statistic	0.98	-1.21	-4.27	-2.45
$P(T \leq t)$	0.33	0.24	$1.93 * 10^{-4}$	$2.07 * 10^{-2}$
t critical	2.05	2.05	2.05	2.05

Table 3.7: Pilot Study 2 - Targeting error t-test results

3.3.7 Discussion

Performance is degraded with a decrease in frame rate as is consistent with the idea that low frame rates can be thought of as a form of delay. Significant changes were seen in completion times and errors between all 4 frame rates compared with the control setting.

There do appear to be thresholds at certain frame rates below which performance deteriorates sharply. For instance, between 3 and 2 fps little change was seen in performance whereas the difference between 2 and 1 fps is marked. Further investigation is necessary.

3.4 Pilot Study 3

3.4.1 Aims

This experiment replicated the findings of pilot study 2. The following hypotheses were tested.

Null hypothesis

P3H00 Reducing the frame rate of the visual feedback will have no significant effect

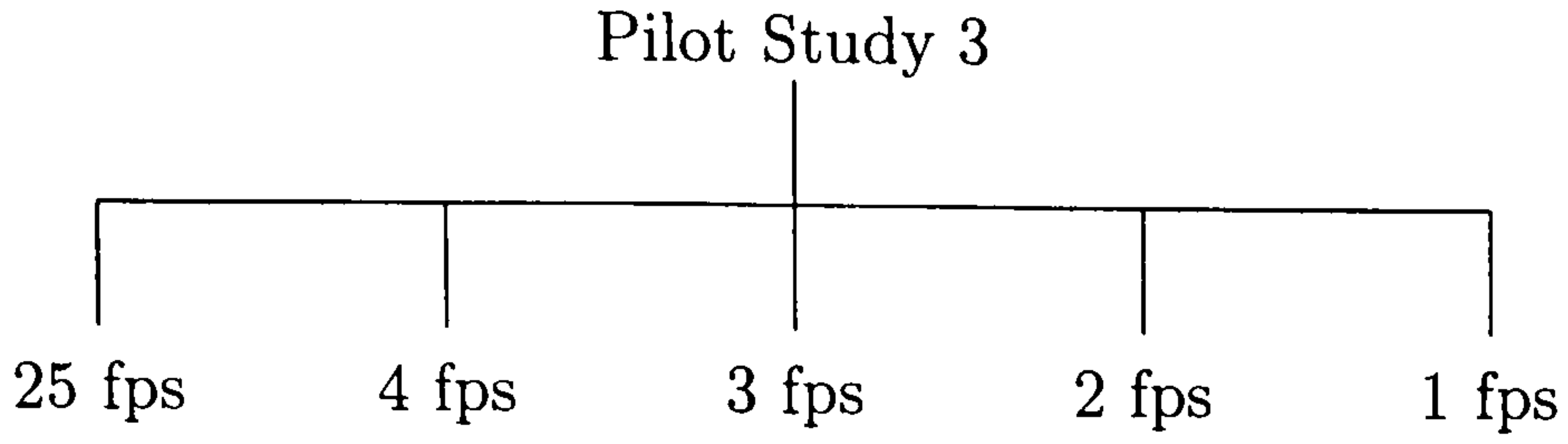


Figure 3.8: Pilot Study 3 Factorial Design

on timings.

P3H01 Reducing the frame rate of the visual feedback will have no significant effect on errors.

Alternate hypotheses

P3H11 A decrease in frame rate will cause completion times to increase.

P3H12 A decrease in frame rate will cause errors to increase.

P3H13 Delayed visual feedback and low frame rate visual feedback will both have an adverse effect on operator performance.

3.4.2 Design

As in the previous experiment a within subjects single factor (with five levels) design was used (see Figure 3.8).

Measures taken were as in the first pilot study, these being the time taken to complete the task and errors in position. In addition to this the exact route taken in each trial was recorded by means of a pen attached to the vehicle in order to give an indication of the severity of tracking error in addition to the targeting error.

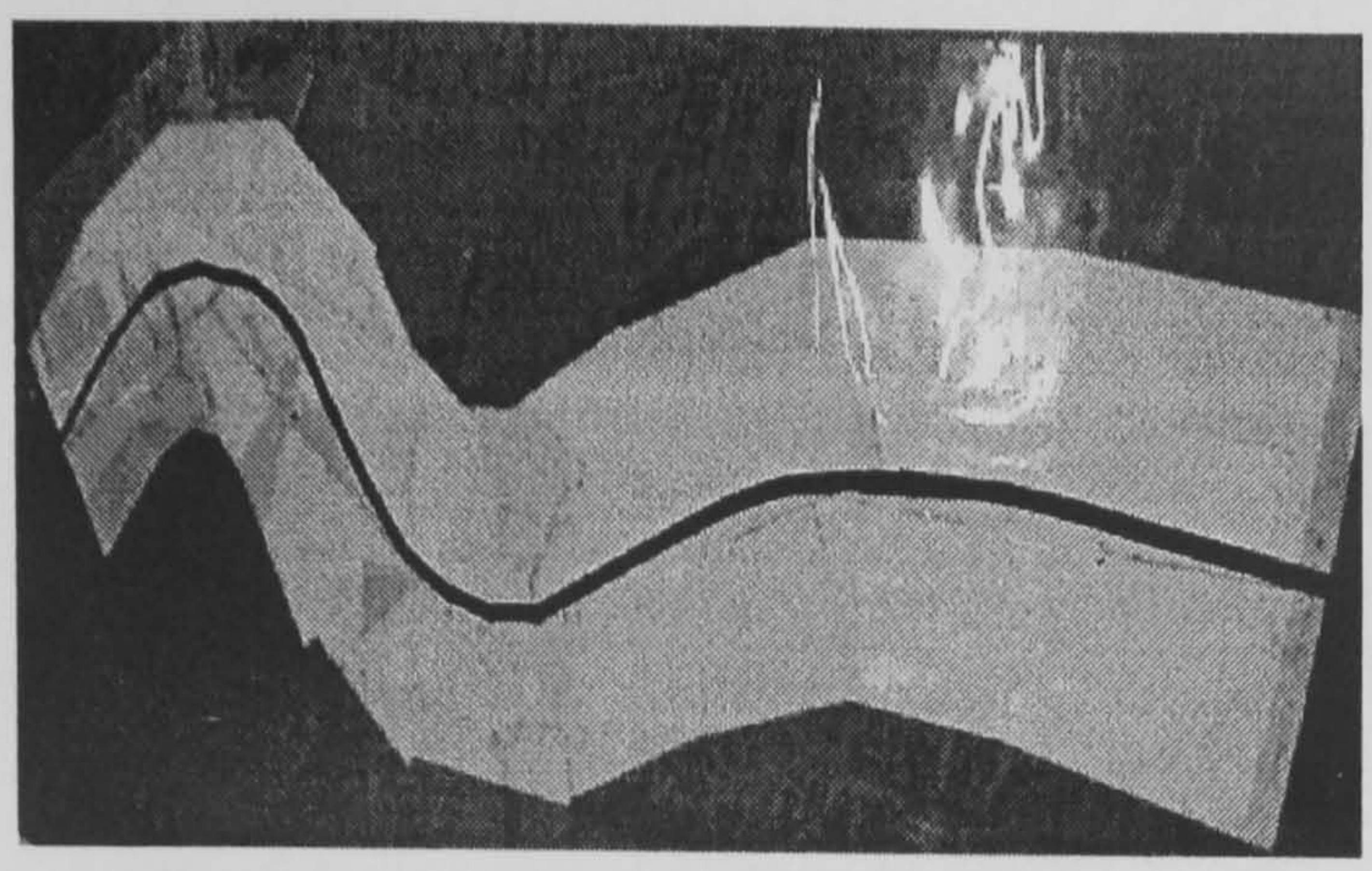


Figure 3.9: Pilot Study 3 Track

3.4.3 Participants

Of the 30 participants, 23 were male, 2 were below the age of 18, 24 were aged 18-25, 3 were aged 26-35 and 1 above the age of 35. 10 participants wore correctional lenses and all who needed to were wearing them for the experiment. No participant reported any other problems that might have affected their ability to control the vehicle. All participants were staff or students at Heriot-Watt University (in the Computing and Electrical Engineering Department).

3.4.4 Materials and Apparatus

All equipment was the same as in the previous experiment, with the exception of a modified track design.

3.4.5 Procedure

Subjects performed driving tasks as before, although there was no target at the end of the track. Subjects therefore drove between boundary markings. Video frame rate was used as a form of delay with settings of 4, 3, 2 and 1 fps as compared to a control setting of 25 fps being used. Participants were allowed 2 minutes to practice controlling the vehicle, and then did 15 tasks in a random order (with each of the 5 delay settings being used 3 times). The track used is shown in Figure 3.9.

Frame rate	A	B	C	D	E
Mean time taken (s)	17.22	32.36	32.63	41.98	44.38
SD time taken	8.50	22.61	12.48	24.11	15.48
Var. time taken	72.30	511.01	155.79	581.27	239.51

Table 3.8: Pilot Study 3 Results

	4 fps (wrt 25 fps)	3 fps (wrt 25 fps)	2 fps (wrt 25 fps)	1 fps (wrt 25 fps)
df	29	29	29	29
t statistic	-4.85	-11.11	-7.19	-13.37
$P(T \leq t)$	$3.90 * 10^{-5}$	$5.77 * 10^{-12}$	$6.42 * 10^{-8}$	$6.31 * 10^{-14}$
t critical	2.05	2.05	2.05	2.05

Table 3.9: Pilot Study 3 - t-test results

3.4.6 Results

This experiment, in which 5 frame rates were used, also produced results that demonstrated a performance decrement when delay was increased (i.e. when the frame rate was decreased). Summarised results are given in Table 3.8 and Figure 3.10.

Analysis of variance (single factor ANOVAs) of the completion times was significant ($F = 10.99, df = 4, 29, P < 0.001$).

Difference between frame rates for completion times (2 tail paired t- test) was also significant ($df = 29, P < 0.001$ for all frame rates with respect to control). Results of the t-tests (each with respect to the control are summarised in Table 3.9.

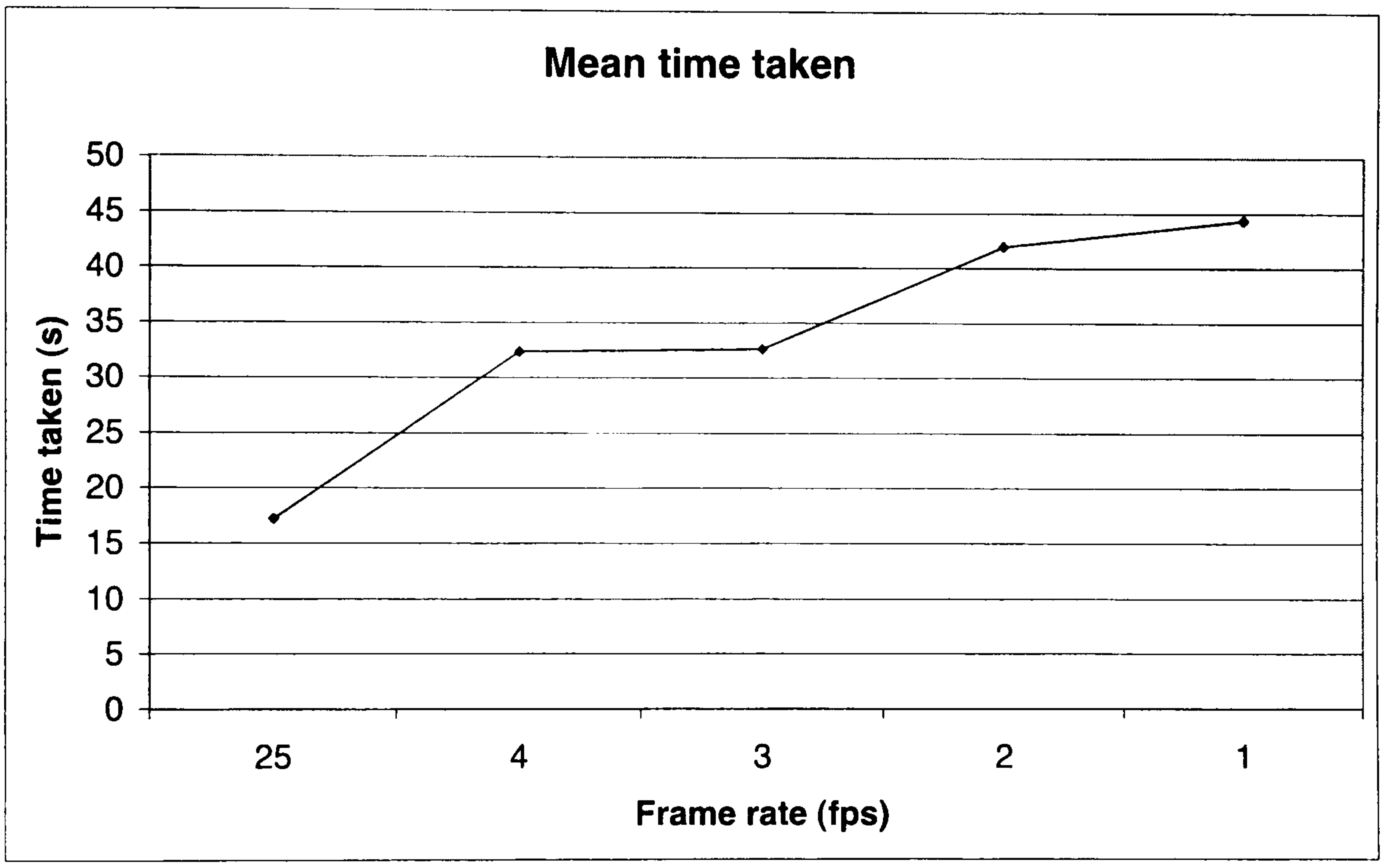


Figure 3.10: Pilot Study 3 Results

3.4.7 Discussion

This experiment showed similar results to pilot study 2 in that performance was adversely affected by low frame rates. However, the differences between delay settings were slightly different with the transition between 2–1 fps no longer showing such a marked effect. It may well be that the more complex track that was used in this experiment had an effect on the results, thus differences between frame rates interacted with the track complexity. It is therefore suggested that further experiments take account of the track complexity in analysis of results.

3.5 Overall discussion

Results in general show a graded and consistently shaped decrement in performance as regards time and error with an increase in the delay magnitude. In addition, low frame rates also give similar results with timings and errors increasing with a decrease in the frame rate.

Results from pilot study 1 showed a marked performance decrement with both errors and timings being significantly affected. For this reason the null hypotheses, P1H00 and P1H01, were rejected and the alternate hypotheses, P1H11 and P1H12 were accepted, thus demonstrating that delayed visual feedback was found to have a significant effect on driving performance. This study therefore replicated what was found by Smith (1962); Smith and Sussman (1970); Keran et al. (1994); Elliott and Eagleson (1997) among others.

Results from pilot studies 2 and 3 showed a marked performance decrement with both errors and timings being significantly affected. The null hypotheses for both experiments were rejected due to these results and the alternate hypotheses were accepted, thus demonstrating that low frame rate visual feedback had a similarly detrimental effect on performance as visual delays do, i.e. the findings of Poulton

(1966); Massimino and Sheridan (1994) were replicated. In particular, low frame rate has been clearly demonstrated to be a form of delay rather than just having similar effects as was shown by Poulton (1966) and Massimino and Sheridan (1994).

This investigation between pure delay and low frame rates gave rise to the idea that, if low frame rates are also considered as a form of visual interference, then delay may have a similar effect to visual interference with the same cognitive mechanisms being involved. As a result of this idea detailed research into visual interference effects (and then specifically human memory) was carried out as described in Chapter 2, Section 2.7 (starting on page 44).

From the findings of this research hypotheses were formed and investigated in the main experiment described in Chapter 4 overleaf.

Chapter 4

Experimental Design: Visuo-spatial WM Disruption

4.1 Outline

The major experimental work of this thesis extended the findings from earlier preliminary experiments (discussed in Chapter 3) and therefore made use of the behavioural data gained from the pilot work. However, the emphasis of this experiment was to examine the cognitive mechanisms which may be at the heart of the problem rather than simply investigate the effect on operator performance as was the case in the pilot studies. From the work outlined in Section 2.7 of the literature review, it was thought that a useful starting point was to investigate whether the problem could be explained in terms of working memory disruption. As a result of this assumption the experiment used the same driving task as in the pilot work; that of navigating between track boundaries towards a target. However, in order to test this assumption that working memory disruption was a factor, the driving tasks also included additional visual interference tasks that were carried out while driving.

It should be noted that visual interference has many different meanings. In the context of this thesis it refers to two distinct cases:

1. Interrupting the visual feedback (for example, covering the operators eyes, or degrading the frame rate of the visual feedback which can be thought of as inserting 'blank' frames).

2. Interfering with the cognitive mechanisms associated with vision (for example, visuo-spatial tasks such as letter tracing).

The working hypothesis that motivated the design of this experiment was as follows.

- Delayed visual feedback has a detrimental effect on human performance.
- Visual interference (affecting human working memory) also has a detrimental effect on performance.

This detrimental effect introduces confusion in the operator which affects the time taken to complete a driving task and increases errors in driving. For this reason it was decided to investigate whether delays in visual feedback cause a decrement in performance due to a disruption in *Working Memory* as has been suggested is the case for visual interference by Baddeley (1974, 1980, 1986).

4.2 Background

As was mentioned in Chapter 1, these experiments began with an attempt to understand the nature of the confusion induced by delayed visual feedback. For this reason a general model of the system as a whole (including the human operator and the physical artifacts to be used) was derived as shown in Figure 4.1. More discussion is given in Section 1.4 (page 3) of this thesis. This model was later refined and expressed as a control system model and is presented and discussed in detail in Chapter 11.

The model shown in Figure 4.1 was derived from results of the pilot work described in the previous chapter. The task objective was therefore to keep the vehicle within the boundary lines and to hit the target as close to the middle as possible. The perceived error was the difference between the position shown by the delayed

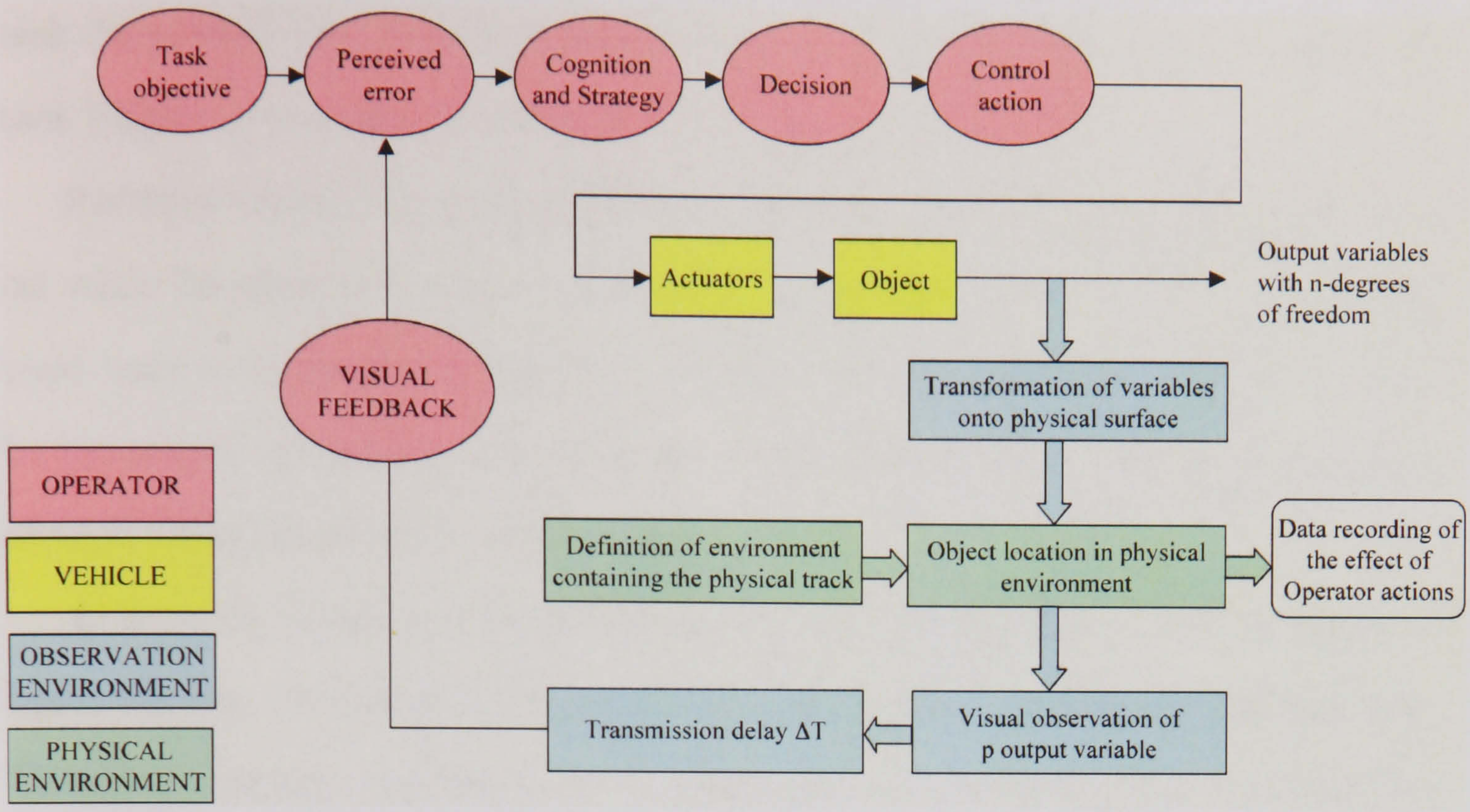


Figure 4.1: General Model of Experimental System

visual feedback and the expected position. The cognition and strategy was assumed to be the operator attempting to select an appropriate strategy for compensating for the delay as seemed to be the case in preliminary work and as suggested by Teal and Rudnicky (1992); O'Donnell and Draper (1995). The resultant decision therefore gave rise to a control action to either change the heading of the vehicle or its speed.

From this overall view of the system and exploratory attempts to model the confusion demonstrated it was decided that a model of the cognitive processes involved in remotely operating a vehicle under delayed visual feedback should be designed and that experiments should test this cognitive model.

Similar attempts had been made to model the cognitive processes involved in compensating for visual interference by Brooks (1967, 1968) and extended by Baddeley et al. (1975) and Baddeley and Lieberman (1980). In the work by Baddeley, an attempt was made to explain these effects in terms of a disruption to working memory. The experimental tasks chosen in these experiments were a letter tracing task (to provide the visual interference element of the exercise) and a pursuit rotor task (chosen to simulate the complex nature of driving).

Baddeley (1986) was inspired by the difficulty that he experienced in driving a car while listening to a game of American football (pp. 110–111). For this reason, tasks were designed that replicated this effect with the driving element being tested by the pursuit rotor task, and the mental visualising element of listening to a game of sport being modelled by letter tracing tasks.

As a result, it was decided to extend this work of Baddeley's by using the same letter tracing, but substituting a driving task for the pursuit rotor tracking task. This design decision was discussed with Baddeley and he agreed that such an extension was valid (Baddeley, 2001). Hypotheses were formed as a basis for this round of experiments.

4.3 Hypotheses

Null hypotheses

H00 An increase in visual delay magnitude will have no effect on driving performance.

H01 The presence of visual interference tasks will have no significant effect on driving performance.

H02 The presence of visual interference tasks will not affect driving performance in a similar manner to visual delays.

H03 An increase in track complexity will have no significant effect on driving performance.

Alternate hypotheses

H11 Results of the experiments will show a similar performance decrement due to delays as has been found in preliminary experiments, namely that an increase in delay magnitude will cause a performance decrement.

H12 There will be threshold value of delay below which the effects of the delays will be negligible.

H13 There will be a threshold value of delay above which the performance does not decrease any more (complete failure).

H14 The spatial letter-processing task will disrupt tracking (driving) performance, i.e. Baddeley's findings will be replicated.

H15 Delays in visual feedback cause confusion due to disruptions in visuo-spatial working memory, therefore visual interference which also disrupts visuo-spatial working memory will give a similar performance decrement to visual delays.

H16 An increase in track complexity will cause a performance decrement.

4.4 Overview of Design Stages

The design of the main experiment underwent various changes before evolving into its final state. This section will briefly outline the significant stages before describing the final design in more detail.

Early ideas for the experiment were to provide video delay by using a computer as a large video buffer. This delayed video would then form the basis of the experiments, with participants performing remote driving tasks with a vehicle along a track. The vehicle would have a camera mounted on it, and the images from this camera would be sent to the computer, delayed and subsequently displayed.

4.4.1 Initial Design

Many of the design decisions involved choosing equipment that could provide the required delay of video or control movements. The first set of equipment to be considered was a dedicated robotics kit including a digital video camera, computer and necessary software libraries for readily building a video delay application (in addition to a 2 dimensional Cartesian robotics rig). This was rejected on financial grounds.

The next setup to be considered was a 486 PC with dedicated frame grabber card and libraries. This equipment was eventually used for low frame rate experiments (as outlined in Sections 3.3 and 3.4) due to the computer having insufficient speed to display full-motion video.

The client-server approach, as used in Day (1998) was briefly considered for building video delay software. However, all software for video streaming is time-critical with frames being thrown away in order to maintain the timeline. For this reason, this approach is inappropriate for experiments that require fixed frame rates due to the software not only producing lower frame rates, but the frame rate varying and therefore affecting the delays involved as well.

Following on from these considerations of delay equipment to use in experiments, the following design decisions were made.

Video delay was to be implemented by storing video frames in a queue (a first-in first-out structure). Implementation choices for this queue were either a 3-dimensional (3D) array (with two dimensions for the video frame, and the other being the length of the queue i.e. length of delay required), or a linked list of frames.

The decision was made to use an indefinite linked list, with a write pointer and read pointer moving along the list (in a manner analogous to a magnetic tape with the write and read heads being displaced such as were used in early delayed auditory experiments). This design is represented graphically in Figure 4.2.

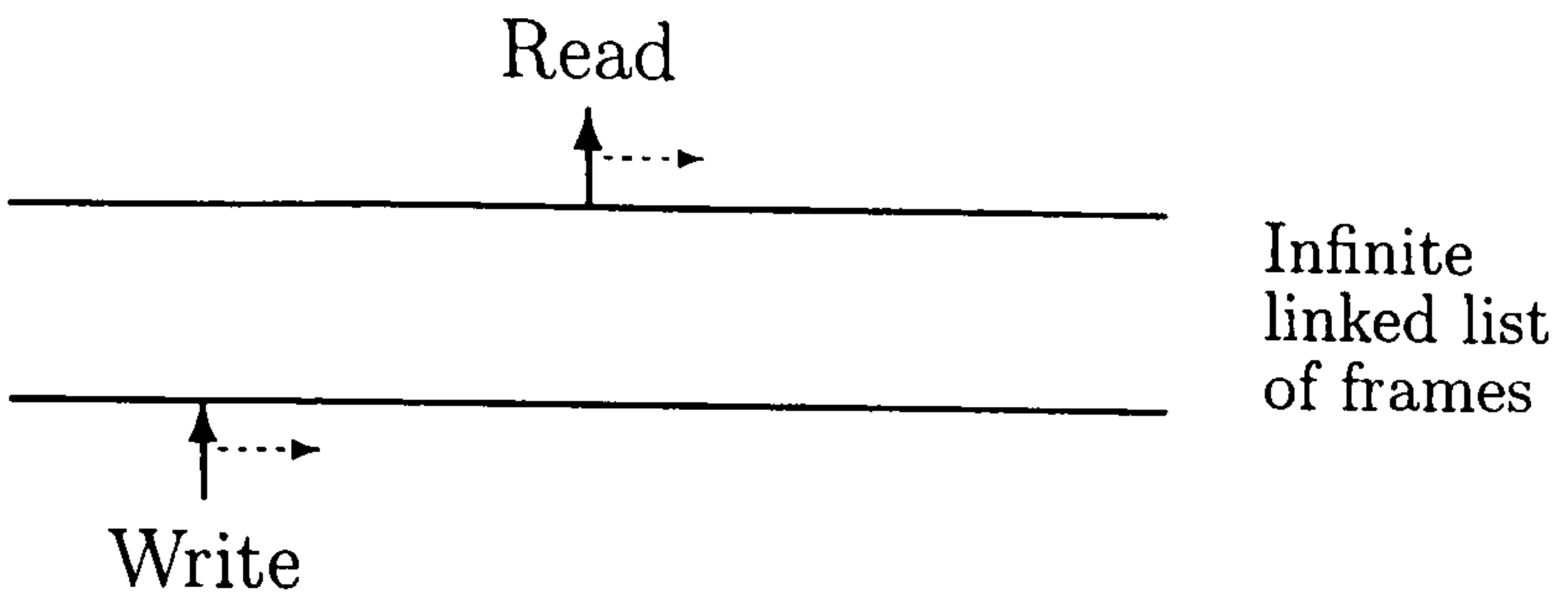


Figure 4.2: Conceptual list of video frames

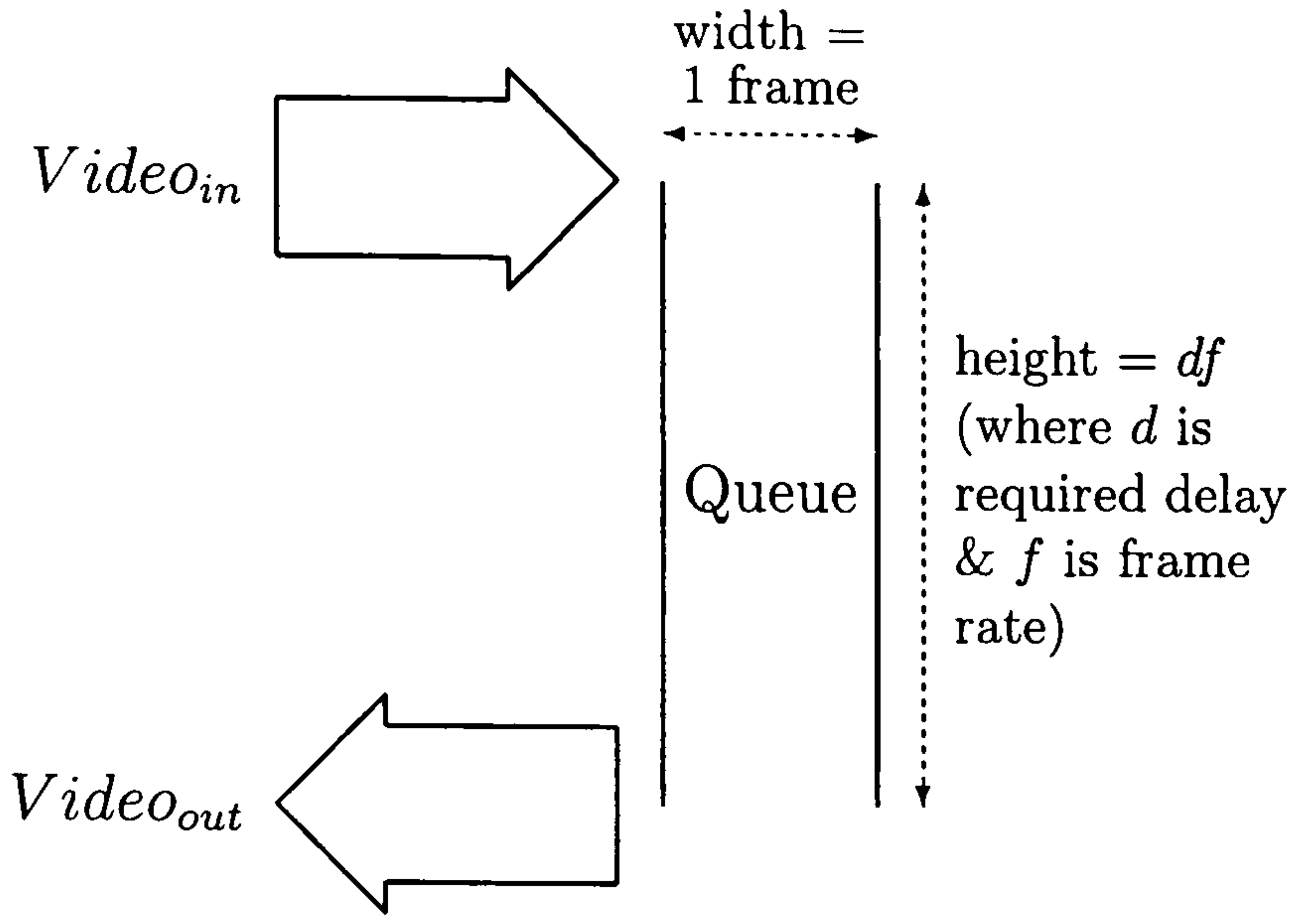


Figure 4.3: Conceptual video queue

In order to speed things up, it was decided to have each frame stored in contiguous blocks of memory. The design is shown in Figure 4.3.

The dimensions of a single frame in the NTSC format are 640*486 pixels at 30 fps. A single frame stored in the PAL format consists of 768*512 pixels at 25 fps. The decision was made to use PAL as the frame rate is easier for timings. Therefore, assuming the use of PAL dimensions, 1 full-size frame = 9830400 bits = 1.17 MB

It was thought that playback of video must be direct (write to screen buffer or video card) for reasons of speed. In addition, a potential design issue was highlighted. This issue was that playback for each frame must take the same time no matter how much information is stored in the frame. For this reason, it was decided that the design would probably need to slow down small (less data) frames.

This need to control the display of individual frames such that each frame is displayed at strict time periods (for example, every 1/25 s) implies a possible need for a 'timing' routine - on every time click, a new frame is added to the queue and an old frame displayed from the queue (removing it in the process).

After considering the specifications of equipment to allow such real-time video capture and the associated costs it was decided that this approach was likely to be too costly both in terms of purchasing the required equipment and the time required for writing software for such a device to allow video buffering. As a result of this decision major changes were made to the design as described in the following section.

4.4.2 Modifications to the initial design

The major modification that was made to the initial design of experiments was to move away from using physical vehicles and conventional data capture methods (using stopwatches, tape measures and manually recording results) to using a virtual reality (VR) system and allow participants to control a virtual vehicle in a virtual world.

The reasons for this decision are documented in Section 4.5.

4.5 The use of VR: a discussion

As has been outlined in Chapter 3 preliminary experiments made use of a remotely operated car, camera and personal computer as a delay device. However, various problems were encountered during these experiments which meant that an alternative approach or solution was needed.

The first major difficulty was that of providing some reliable method for delaying video from the on-board camera. Although the video signal could be successfully sampled to a low frame rate, providing full-motion (25+ fps) video after a certain time delay proved rather difficult. After some investigations into possible hardware and software solutions it was decided that, although software could be written for this purpose, it was likely to take too long to be feasible for this project.

Other difficulties that were experienced during the preliminary work were concerned with errors in using conventional measurements. For example, all timings were made by an observer using a stopwatch thus introducing the additional factor of human reaction time to the times recorded. In a similar manner, vehicle speed was not always constant with factors such as battery life and electro-magnetic interference sometimes affecting it. Finally the vehicle sometimes skidded slightly on turning corners. As such it was decided that some method of automating measurements and reducing errors introduced into the experiments would be advantageous.

The above reasons meant that a move from physical vehicles and manual data capture seemed sensible. For this reason virtual reality equipment was used to overcome the difficulties mentioned. Another advantage was that visual interference could readily be introduced in a VR system where otherwise it would more difficult.

In addition to the fact that the VR equipment gave the experimenter more control over the environment (with such physical constraints as wheel skid being removed) and enabled automated data capture, other advantages were also found as discussed by Day et al. (2000).

These advantages consist mainly of improved data yield and ecological validity of data as discussed in Sections 4.5.1 and 4.5.2.

4.5.1 Comparison of data yield and error by physical and virtual experimental worlds

In the experiments reported in Chapter 3, data collection used techniques familiar to experimental psychology and human factors engineering. Measures taken in the earlier 'physical' experiments were latencies (the time taken to complete the task) and errors in position (targeting distance i.e. distance to left or right from centre of target). An additional measure of 'time in error' was taken for the second experiment, this being the length of time that the vehicle was outside the boundaries of the track. This was to give an indication of the severity of tracking error in addition to the targeting error. All timings were taken using a conventional stopwatch. In these experiments measurements were taken by an experimenter using a timing device, counting based on observation and physical measurements with tape measures when quantifying errors.

The experiments performed using VR took similar measures, with a position and orientation in three dimensions being recorded along with an exact time-stamp every 10 ms. Other measures recorded were start time, stop time, and time when visual interference tasks began and ended. Analysis of the positional data gives traces of the actual route taken by participants along a track, along with error measures of deviation from the centre line. Due to the large amount of data, more in depth analysis should be possible at a later date (for example, strategies employed by participants when a visual interference task is introduced).

A summary of the number of data measures yielded in a single experimental task using the two experimental approaches can be seen in Table 4.1. As might be expected, the automated nature of measurements that can be taken when using VR generates a much larger amount of data than the more conventional, manual methods employed with physical experiments. Although it is true that such automated data capture methods can be used in a 'physical' setting, additional equipment is required. With VR, however, no additional equipment is required to automate the measurement and recording of experimental data. VR therefore gives enhanced data collection in addition to a larger amount of data than the physical experiments.

In addition to the quantity of data yielded by the two approaches, another significant consideration is the quality of the data, in particular, the amount of variation there is in the data due to factors outside the experimenter's control (confounding

4.5.1 Comparison of data yield and error by physical and virtual experimental worlds

Physical world experiments	Virtual world experiments
Start time	Start time
Stop time	Stop time
Count of times strayed off track	1584 measurements of position
Distance from centre of target	1584 measurements of orientation
	1584 time-stamps relating to position and orientation measurements
	Start time of interpolated tasks
	Stop time of interpolated tasks
	Further analysis gives actual route taken, RMS error (deviation from centre line)

Table 4.1: Quantity of data measured in a single experimental task

factors). The physical experiments had a number of confounding factors including skidding of tyres, variable speed of vehicle due to battery voltage, intermittent vehicular response to control signals due to RF interference, audible feedback of vehicle movements allowing compensation, and inaccuracy in measurement of data by experimenter. For example, timings were captured manually and therefore included reaction time of the experimenter.

In the experiments performed in a virtual world, due to no physical artifacts being controlled and automatic data capture all of the above confounding factors are eliminated. This results in much cleaner data, i.e. data that is affected by experimental variables rather than external confounding variables, thus meaning that the experimenter gains an increased control over the variables.

4.5.2 Ecological validity of VR

In addition to the advantages of automatically capturing large amounts of clean data, VR can also give more ecological validity (using the meaning as defined by Neisser (1976)) to the data (by creating a virtual world that is a more accurate representation of the physical world that is being modelled). (It should however be noted that the highest ecological validity would be achieved by using a real remotely operated vehicle and visual feedback system.) It also provides a means of testing hypotheses that cannot be safely examined in full-scale physical experiments. For example, it would not be sensible to place participants in a real vehicle and delay or interfere with their vision due to the obvious safety concerns. A realistic driving scenario however ensures that hypotheses concerning delayed or interfered vision can be safely tested and that the data is more reliable than from more abstracted experimental tasks. This is also true of using custom-built simulators, but VR has the additional advantage of being a cheap and flexible alternative to these simulators. A side effect of using VR as an experimental tool is that participants are willing, and often eager, to volunteer to take part in experiments. It can often be difficult to persuade people to participate in human factors or psychology experiments without some level of remuneration, but the lure of immersive VR has been found to be a sufficient incentive!

4.5.3 Preliminary design using VR

Even after the decision had been made to perform experiments using VR, further modifications to the experimental design had to be made. The original design was a $3 * 4 * 7$ factorial design (with 3 interference settings, 4 delay settings and 7 tracks) meaning that each participant would take between 90-120 minutes to complete the experiment. However, in the interests of keeping the experimental tasks within a reasonable timescale this design was reduced.

In addition to reducing the number of tracks the decision was made to reduce the number of visual interference settings from 3 to 2; comprising of no tasks, and 2 interference tasks. The number of delay settings was also reduced from 4 to 3 (0, 400 and 800 ms) after 2 pilot studies showed that the tasks took at least 90 minutes of intense concentration which was felt to be an unreasonable time period as all participants were volunteers. Fatigue was also a factor in reducing the task time as both participants in the pilot studies complained of how tiring the experiment was (with one participant even showing physical signs of fatigue and stress including increased perspiration and pallour).

4.6 Final Design

4.6.1 Overview

Experiments were designed to consider the effects of visual delays on driving behaviour. An extension of this was to compare the effects of visual delay with visual interference and for this reason participants not only had to drive a vehicle down a track towards a target, but also had to perform interpolated visual interference tasks.

4.6.2 Design

A within subjects 2*3*3 factorial design was used with all subjects doing all tasks as shown in Figure 4.4.

Independent Variables

1. Delay setting: 0, 400, 800 ms

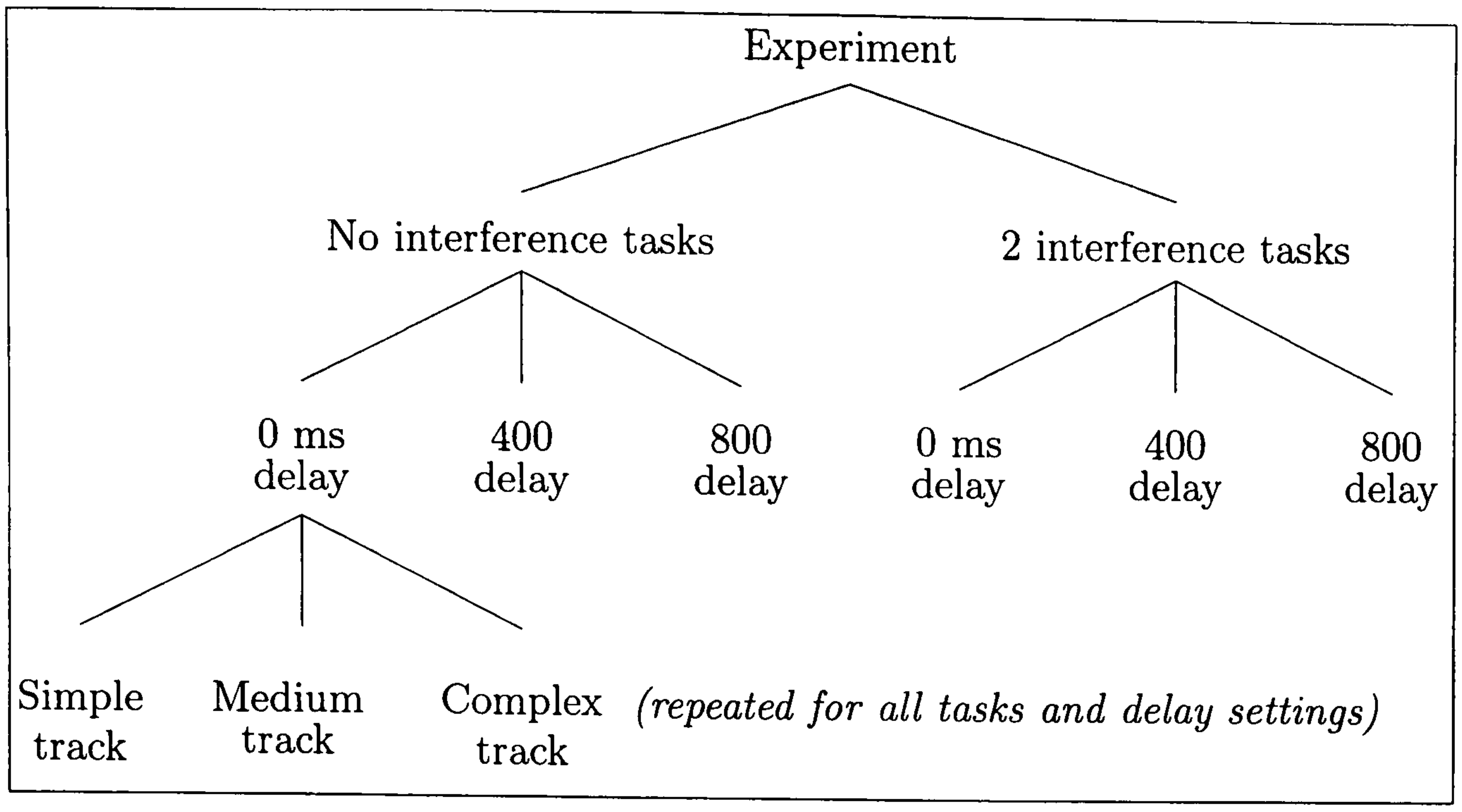


Figure 4.4: Main Experiment Factorial Design

2. Visual interference: none, 2 per task
3. Track complexity: simple, medium and complex

Dependent Variables

1. Operator Performance
2. Operator satisfaction

The above dependent variables were measured using the following dependent measures. Operator performance was measured in terms of completion times (times to complete each track), targeting error (distance from middle of target) and tracking error (distance from centre line of track). Tracking error measurements were squared and then totalled to give the Integral of Squared Tracking Error (ISE). Letter tracing performance was also measured with a count being taken of successfully traced corners (thus giving a total out of 20 with 20 being all corners traced correctly).

Operator satisfaction was measured by means of multi-point rating scales on questionnaires (see Appendix B for more details).

4.6.2 Design

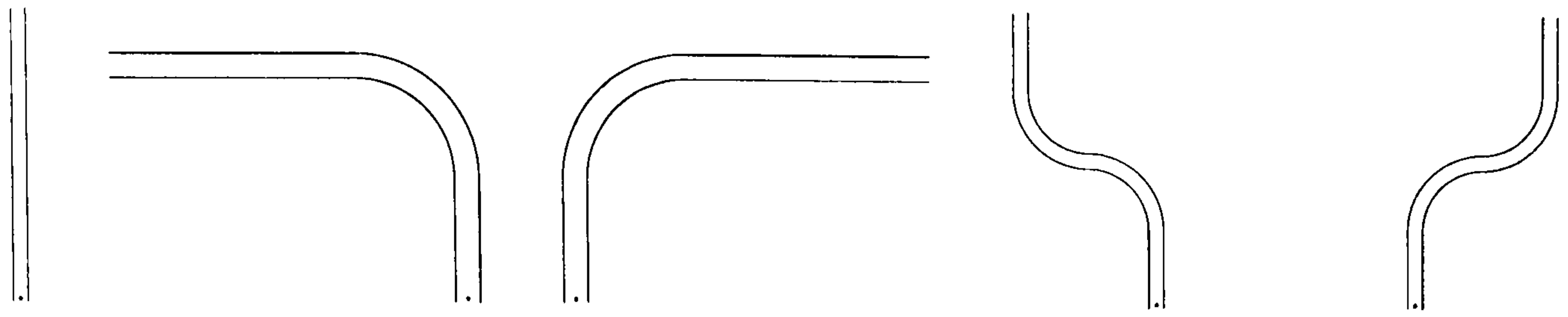
The choice of letter for the interference tasks could be considered as an additional variable but as the task involved was not specific to any particular letter this was not included as an independent variable. Letter selection was randomised to reduce the effect of learning.

It should be noted that an effect shown by Ziefle (1998) is that low-resolution displays increase fatigue in the operator. More information on the effects of various aspects of visual displays can be found in Bennett et al. (1997) although this discussion was found to be outside the scope of this thesis. In the context of the experiments outlined in this thesis, however, display resolution is unlikely to have affected the results as the display was very simple, a low number of turns (analogous to obstacle avoidance) were required and all participants used the same resolution display.

The tracks were designed to give low, medium and high levels of complexity (indicated by the number of turns to be made). The decision was made to balance the left and right turns thus giving a total of 5 tracks (2 at each level of complexity except for the low complexity track which was a straight road) as shown in Figure 4.5. All measurements were averaged for each level of complexity with a mean value of track 2 and 3 giving measurements for medium complexity tracks and another mean of tracks 4 and 5 for complex tracks. Each of the tracks was made up of 4 portions selected from the following 3 components:

1. Straight track (100 long, 20 wide).
2. Left bend (90 degree bend, 20 wide track, bend 100 radius).
3. Right bend (90 degree bend, 20 wide track, bend 100 radius).

Please note, the units of measurement for the VR system were in metres (according to the documentation from Division), i.e. 1 unit = 1 metre.



(a) Track 1

(b) Track 2

(c) Track 3

(d) Track 4

(e) Track 5

Figure 4.5: Track Designs

4.6.3 Participants

It was decided to use a sample size of at least 30 people in order to ensure that parametric statistical tests could be used in analysis (due to the results following a normal distribution).

Questionnaires were used to ascertain relevant experience that participants had in order to compensate for a potentially biased sample, being drawn as it was largely from the Computing and Electrical Engineering department. Past experience with remote operation of vehicles, computer games and VR (all of which could have an impact on driving performance) along with driving experience attitude about driving were all considered. These questionnaires, along with all other experimental material can be seen in Appendix B. Results from these questionnaires are presented in Sections 9.2.1 and 9.2.2.

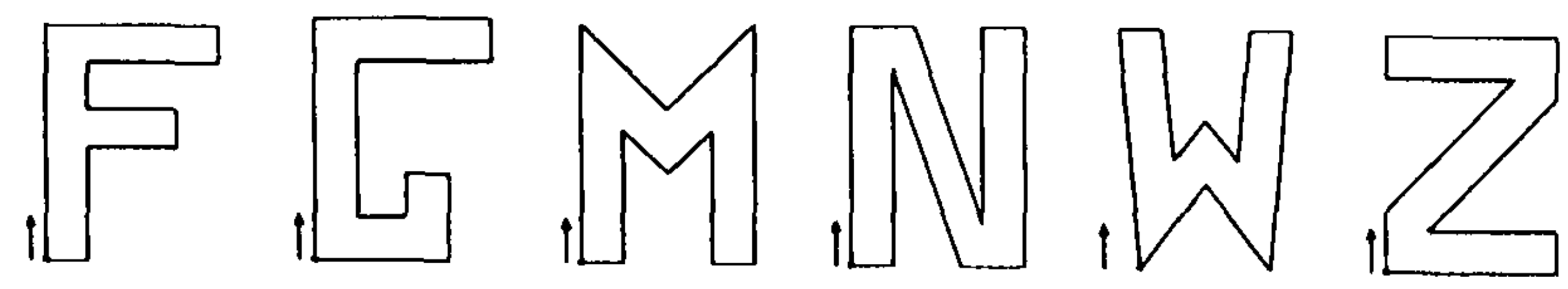


Figure 4.6: Visual Interference Letters

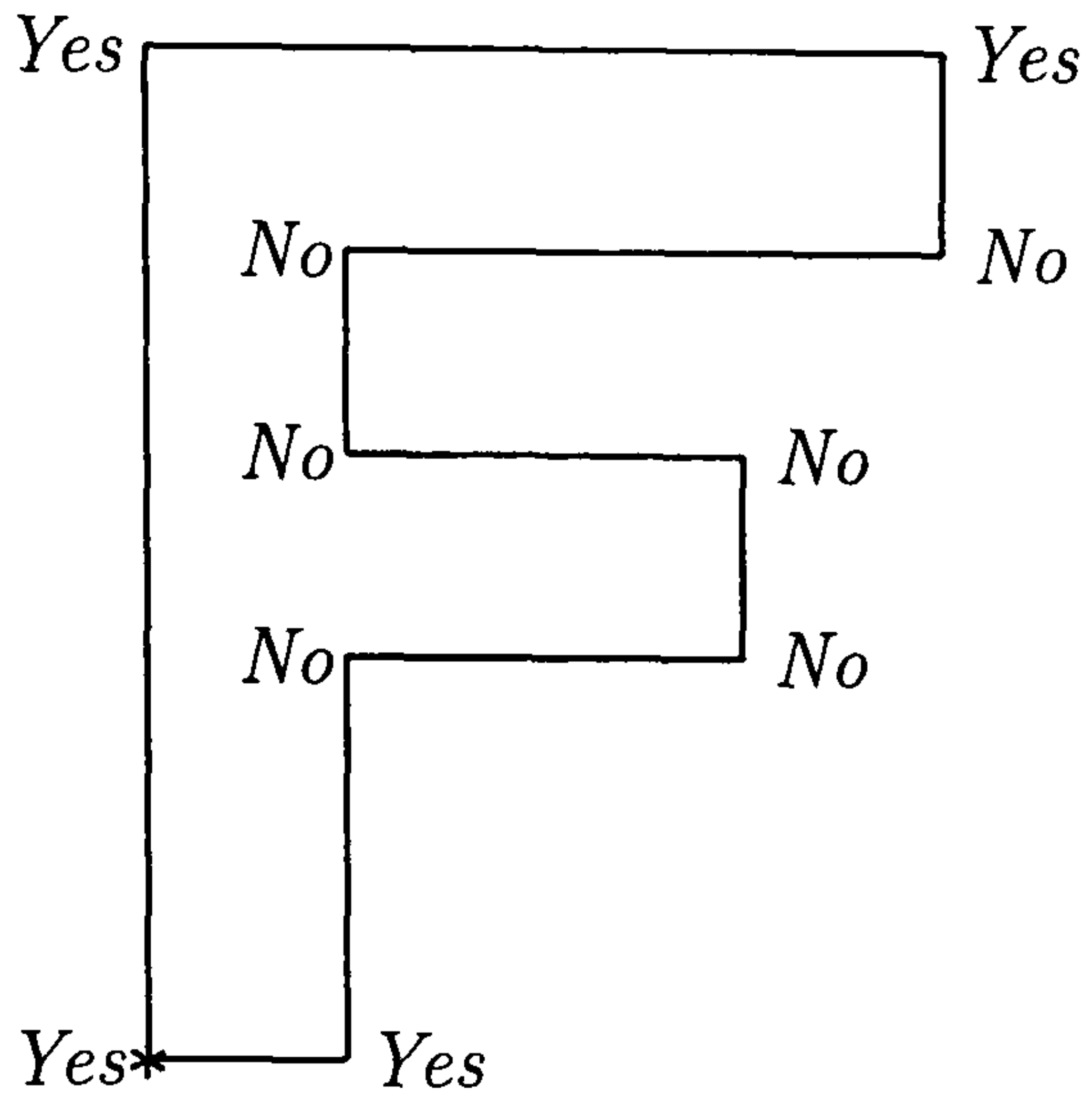


Figure 4.7: Letter tracing example letter

4.6.4 Materials and Apparatus

Visual interference tasks

These tasks were taken from work by Brooks (1967, 1968) and subsequently extended by Baddeley et al. (1975) and Baddeley and Lieberman (1980) as has been previously discussed.

In these tasks, the subject is shown a block capital letter, with the bottom left hand corner marked with a star. The task is to look away from the letter and, holding it in their mind's eye, to go around the letter in a clockwise direction from the star responding *"yes"* if the corner in question was at the top or bottom and *"no"* otherwise. Hence for the letter F, the response would by *"yes, yes, yes, no, no, no, no, no, no, yes"* as shown in Figure 4.7. This is a visuo-spatial task.

The letters used were: F, G, M, N, W and Z. All have 10 data points (corners) and are displayed as shown in Figure 4.6. Each letter had an asterisk next to it indicating the start point and an arrow indicating that points were to be taken in a clockwise direction from the start.

Tracing is begun at the bottom left corner (marked with an asterisk) and continues in a clockwise direction as indicated by the arrow.

In Baddeley's experiments the letter tracing task was found to disrupt tracking of a pursuit rotor. (This tracking exercise was actually chosen to simulate driving, thus meaning that the use of letter tracing for interfering with a driving task has arguably been established.)

The size of letters used was selected by trial and error in order to ensure that the letter was clearly visible for all participants.

In order to ensure that the choice of letter did not affect the results, letters were randomly selected for each user from random sampling numbers in the New Cambridge Statistical Tables (2nd ed). (Each digit in the random sampling number table was an independent sample from a population in which digits 0–9 were equally likely. In order to select from the 6 letters, each digit in the table was divided by 10, then multiplied by 6 and rounded to the nearest integer to give samples from a population of 0–5. These were then converted to the 6 letters.)

4.6.5 Procedure

All participants were given the same information read from a script (given in Appendix B.1). They then completed a pre-experiment questionnaire (given in Appendix B.2) and performed practice tasks to familiarise themselves with the equipment and tasks involved. Once they could successfully complete all tasks and were familiar with the equipment, they then performed the 30 driving tasks of the experiment, before finally completing a post-experiment questionnaire (Appendix B.3). Participant responses to the letter tracing tasks (i.e. "*yes*" or "*no*" for each corner of the letter) and additional comments were recorded on paper during the experiments

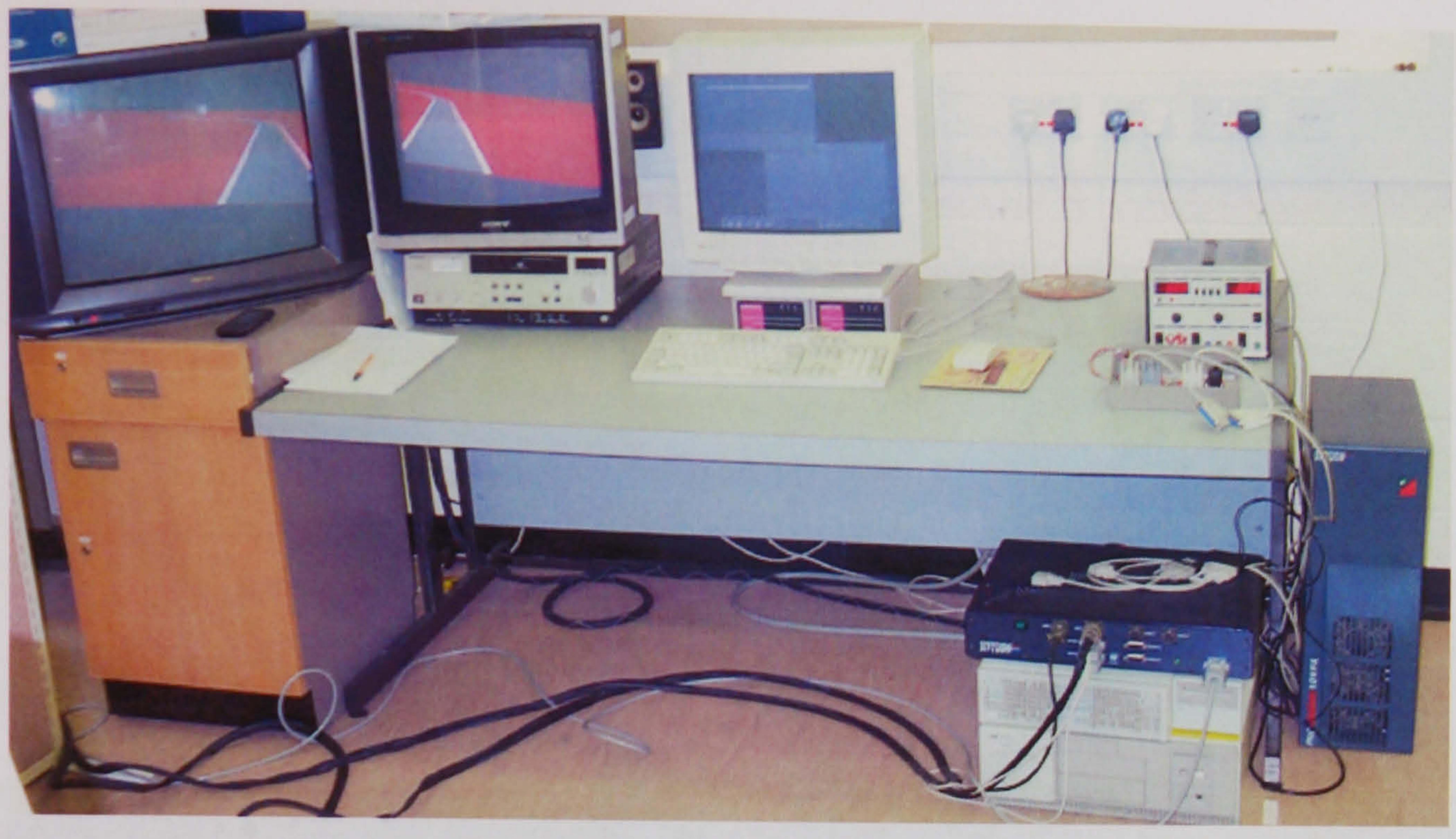


Figure 4.8: Virtual reality equipment for experiments

using the form given in (Appendix B.4).

Participants were placed behind screens in order to minimise the possibility of inadvertent visual cues or miscues being given. The layout used for the experiments is illustrated in Figures 4.8 and 4.9.

Because the experiments were performed using virtual reality software which was specially developed, the design and implementation of this software is described in Chapters 6 and 7. The delay system used is described in Chapter 8 before the results of the expererriments outlined in the present chapter are presented, analysed and discussed in Chapter 9.

The work described in this chapter was later extended to include a consideration of general working memory interference (i.e. disruption to the central executive) rather than focusing solely on the visuospatial sketch pad as was the case in this chapter. This investigation into the role of central executive is described in Chapter 5.

Figure 4.9: Virtual reality headset for experiments

Chapter 5

Experimental Design: Central Executive Disruption

5.1 Background

The experiments described in this chapter extended the work presented in Chapter 5. These original experiments (also described in Chapter 10) investigated whether visual delays could be explained in terms of disruption to visuo-spatial working memory (i.e. the visuo-spatial sketchpad). However, it was suggested that the results of these experiments could be further validated by checking whether visual delays could be understood as an increase in the load to general working memory resources (i.e. the central executive) or as a specific disruption to the visuo-spatial sketchpad.

The task of random number generation was used as a mechanism for disrupting the central executive portion of working memory. This task was selected as it is thought to not place a particular load on either the visuo-spatial sketchpad or the articulatory loop, but rather load the central executive. The task, which is presented in more detail by Baddeley et al. (1996) and Baddeley et al. (1998), involves a participant saying a random number between 1 and 10 every time they hear a beep (typically every few seconds). The key point about the task is that the participant must endeavour to give a random choice each time, rather than reciting a sequence of numbers.

This task of random number generation was used in experiments by Logie and Salway (1990); Salway (1991) which investigated how much general load (i.e. on the central executive) was involved in Brook's task of letter tracing. In fact, Salway and Logie (1995) suggests that the cognitive processes involved in the letter tracing task may be more complex than has been assumed, with the task loading the central executive as well as the visuo-spatial sketchpad. This suggestion is further supported by Miyake et al. (2001) who provide an interesting discussion considering the relationship between visuospatial working memory, executive functioning and spatial abilities. From the results of their study Miyake et al. suggest that the visuospatial sketchpad is closely tied to the central executive. They do however offer the useful extension that the 3 spatial ability factors (of spatial visualisation, spatial relations and perceptual speed) differ in the degree of executive loading, with visualisation highest, and perceptual speed lowest.

It should be noted that the random number generation task has been widely used as a method of loading the central executive (see Baddeley et al., 1999; Logie, 1995; Miyake et al., 2001; Wareing et al., 2000, for example) It was therefore decided that the random number generation task be compared to the letter tracing task to see how much effect they have on driving performance. If the letter tracing task was indeed purely a visuo-spatial exercise then it should have a much greater effect on driving performance than a task that places a burden on general cognitive processes (i.e. the central executive).

5.2 Hypotheses

Null hypotheses

H01 The presence of random number generation tasks will have no significant effect on driving performance.

H02 The presence of random number generation tasks will have a negligible effect on driving performance when compared with the letter tracing tasks.

Alternate hypotheses

H11 The presence of random number generation tasks will have a significant effect on driving performance.

H12 The presence of random number generation tasks will affect driving performance in a similar manner to the letter tracing (visuo-spatial interference) tasks at least to the same order of magnitude.

5.3 Design

5.3.1 Overview

A within subjects

Independent Variables

1. Random number generation: none, 1 every 3s.
2. Track complexity: simple, medium and complex

Dependent Variables

1. Operator Performance
2. Operator satisfaction

The above dependent variables were measured using the same dependent measures as in the previous experiment; namely completion times, targeting error and tracking error. Tracking error measurements were again squared and then totalled to give the Integral of Squared Tracking Error (ISE). Random number generation performance was recorded and analysed after the experiments with the frequency of each digit being measured for each participant in addition to missed prompts.

Operator satisfaction was again measured by means of multi-point rating scales on questionnaires as before. The same tracks as described in Chapter 4 were used in this experiment, with low, medium and high levels of complexity (indicated by the number of turns to be made).

5.3.2 Participants

It was decided to use a sample size of at least 30 people in order to ensure that parametric statistical tests could be used in analysis (due to the results following a normal distribution).

Questionnaires were used to ascertain relevant experience that participants had in order to compensate for a potentially biased sample, being drawn as it was from the School of Mathematical and Computer Sciences. The same questionnaires were used as in the previous experiment.

5.3.3 Materials and Apparatus

All the materials used for this experiment are presented in Appendix N.

Central Executive loading tasks

In these tasks, the participant said a random number between 1 and 10 inclusive every time they heard a beep. These beeps, which were heard through the virtual reality headset worn by the participant, occurred every 3 seconds.

5.3.4 Procedure

All participants were given the same information read from a script (given in Appendix N.1). They then completed a pre-experiment questionnaire (given in Appendix N.2) and performed practice tasks to familiarise themselves with the equipment and tasks involved. Once they could successfully complete all tasks and were familiar with the equipment, they then performed the 15 driving tasks of the experiment, before finally completing a post-experiment questionnaire (Appendix N.3). Participant responses to the random number generation tasks were recorded on minidisc and later entered into a spreadsheet.

Participants were again placed behind screens as was the case with the previous experiments. The results of the expereriments outlined in the present chapter are presented, analysed and discussed in Chapter 10.

Chapter 6

VR Software Design

6.1 Background

Virtual Reality (VR) can be defined as '*the science of integrating man with information. It consists of three-dimensional, interactive, computer generated environments.*' (Roberts and Warwick, 1993) This definition includes both complex, fully immersive systems and smaller desktop VR applications.

Virtual Reality technology has been used in a variety of application areas including simulation, design and prototyping in manufacture, training, complex 3D modelling, architecture and psychotherapy.

The use of VR in simulation is well-documented. Jackson (1993) gives an analysis of the use of VR in simulation with a particular emphasis on training simulators. Du Pont (1993) in a similar manner describes VR systems being used for astronaut training (in particular space walks) and Stinger missile training for infantry personnel.

A particular area where virtual environments can be of obvious value is that of safety critical simulations, such as medical training, flight simulators and process control room design and training (see, for example, Banerjee et al., 1999; Boud and Steiner, 1999; Sourin et al., 2000).

Mayfield (1999) also outlined the use of VR in simulation and training and made the point that simulation based prototypes can be used for enhancement of training. In particular Mayfield states that VR can be used to increase the realism of a simulation at a cost benefit by reusing existing simulation data. In a similar manner Sourin et al. (2000) studied the use of VR as a medical training tool (in virtual orthopaedic surgery training).

Due to the ability to immerse the user in a virtual environment, VR is of use in the design and prototyping stages of manufacture. Products can be viewed and even interacted with in VR without any physical production of prototypes being required. VR allows the developer to not only model the visual characteristics of the product but also some of the physical properties as well, thus meaning that, for instance, a car dashboard can be produced and the user can turn the steering wheel to check for visibility of dials or explore a new design feature.

For example, Boud and Steiner (1999) mention VR in concept design, virtual prototyping, design for manufacture and design for assembly. Similarly Du Pont (1993) describes using VR for industrial conceptual design for automotive engineering and Banerjee et al. (1999) discusses VR in assembly planning.

The Department of Mechanical and Chemical Engineering of Heriot-Watt University have also used immersive VR in recent projects concerned with cable harness design and planning (Ng et al., 1999).

Du Pont (1993) mentions the use of VR in computational chemistry (in particular, molecular modelling), along with uses in architecture applications such as complex lighting visualisation for lighting design, kitchen showroom sales, living environment simulation for building designers, and office design and planning. Useful information is also included on the technical requirements of a VR system and details of developing software using Division dVS and dVISE.

VR has also been used for its highly immersive and engaging qualities, rather than the ability to recreate interactive environments. Various medical therapies have exploited this highly immersive quality.

For instance, Roberts and Warwick (1993) describe the use of VR in the rehabilitation of handicapped patients. Glantz et al. (1996, 1997) in their studies into treating phobic conditions have used VR as a form of therapy in order to provide exposure and desensitization for conditions such as acrophobia, agoraphobia and a fear of flying. Riva et al. (1999) then extended the work into treating anorexia nervosa, again using VR. In a more general study by Marks et al. (1998) the use of computers in self-treatment is discussed, in particular the computer-aided treatments of mental health problems using computerised self-treatment. In a recent news item Ahmadi (2001) described studies that indicate that VR may help children undergoing chemotherapy. The children in the study were immersed in an entertaining virtual environment in order to distract them from the sometimes traumatic or painful treatments thus reducing anxiety in the patient.

A general review of VR applications in manufacturing has been produced by Boud and Steiner (1999). In addition to the uses already mentioned Boud describes the use of VR in factory layout analysis and robot programming (programming a remote robot by using a local virtual robot as described in Section 2.6 of this thesis).

One final study worthy of note is Bullinger et al. (1997) in which a detailed overview of virtual environments is given including a brief discussion of the human factors issues involved in using VR.

6.2 VR Hardware

Once the decision to use VR as the basis for driving experiments, as documented in Chapter 4, the VR platform, programming language and development libraries had to be selected. The VR platform used was an HP 725/75 UNIX workstation with a single pipe PV10 (ProVision 10 virtual reality accelerator) from Division, an Integrated Peripheral Unit (IPU) also from Division, dVISOR head-mounted display, Division 3D mouse and Polhemus magnetic tracking. (The magnetic tracking from Polhemus used a single transmitter to set a point of origin in the 3 planes X, Y and

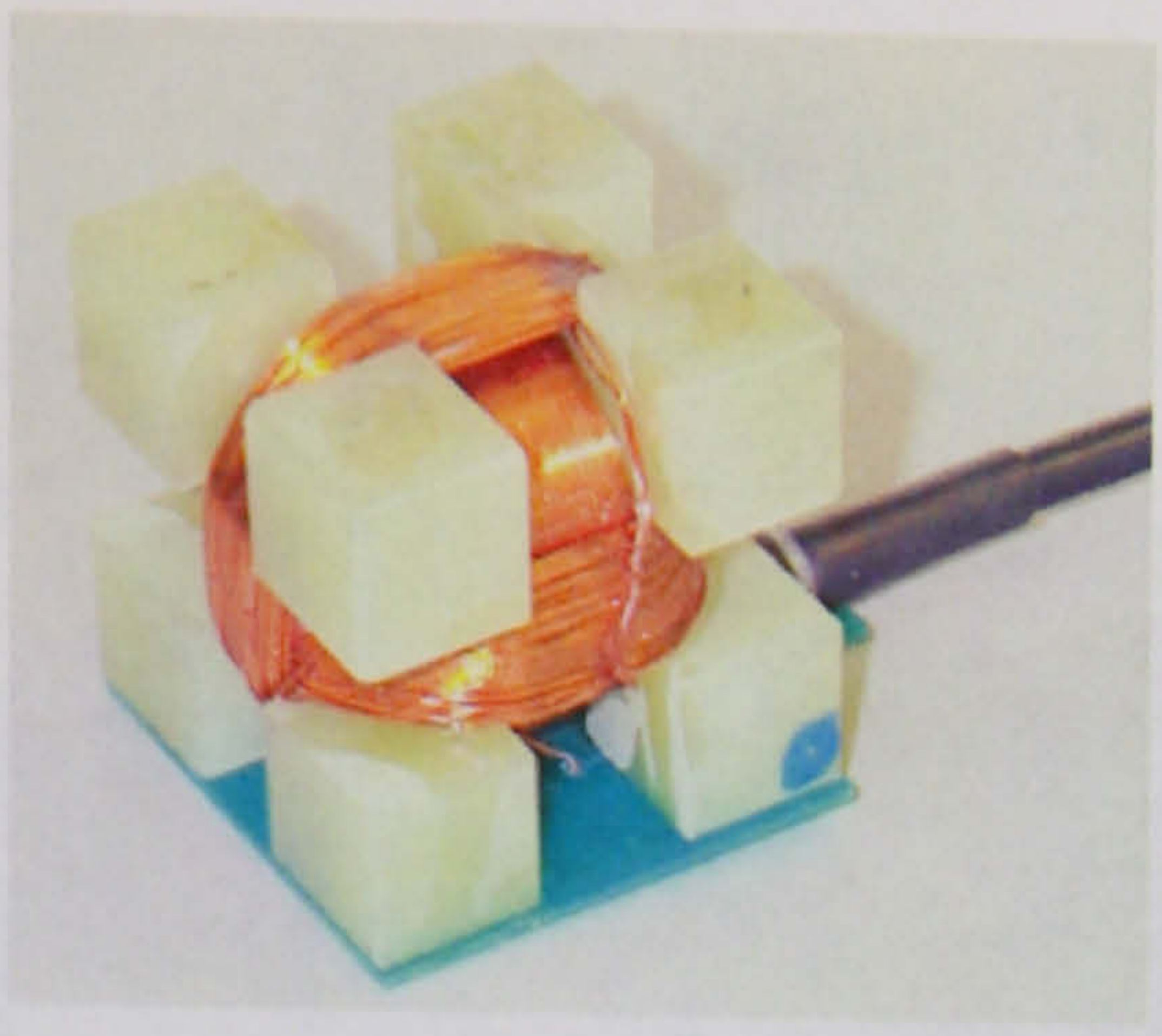


Figure 6.1: Magnetic transmitter (without cover)

Z. The transmitter can be seen with external casing removed in Figure 6.1.) This equipment is shown in Figure 6.2. An overview of the hardware is given in Figure 6.3.

It should be noted that prior to designing any VR software the VR system had to be reconfigured and an in-depth understanding gained. This was due in part to the fact that the VR system had been used in a department with a different network structure than the Computing and Electrical (CEE) Department, in addition to the fact that the underlying operating system had to be upgraded twice due to potential security loopholes that the CEE departmental computer officers were concerned about (the system was finally used with HP-UX 10.20). Because of these changes the VR system did not operate at all when it was first received by the author and in fact a period of approximately 6 months of configuring, diagnosis and reconfiguring was undertaken before the system was fully operational and design and implementation could take place. The design and implementation stage of the experiments and associated software took approximately another six months.

After investigation it was discovered that delays could readily be introduced into the system on the RS232 serial lines between the integrated peripherals unit (IPU) and the HP workstation as shown in Figure 6.4. These delays were introduced by using custom built hardware designed and manufactured by the Department

Figure 6.2: Interconnections of VR equipment

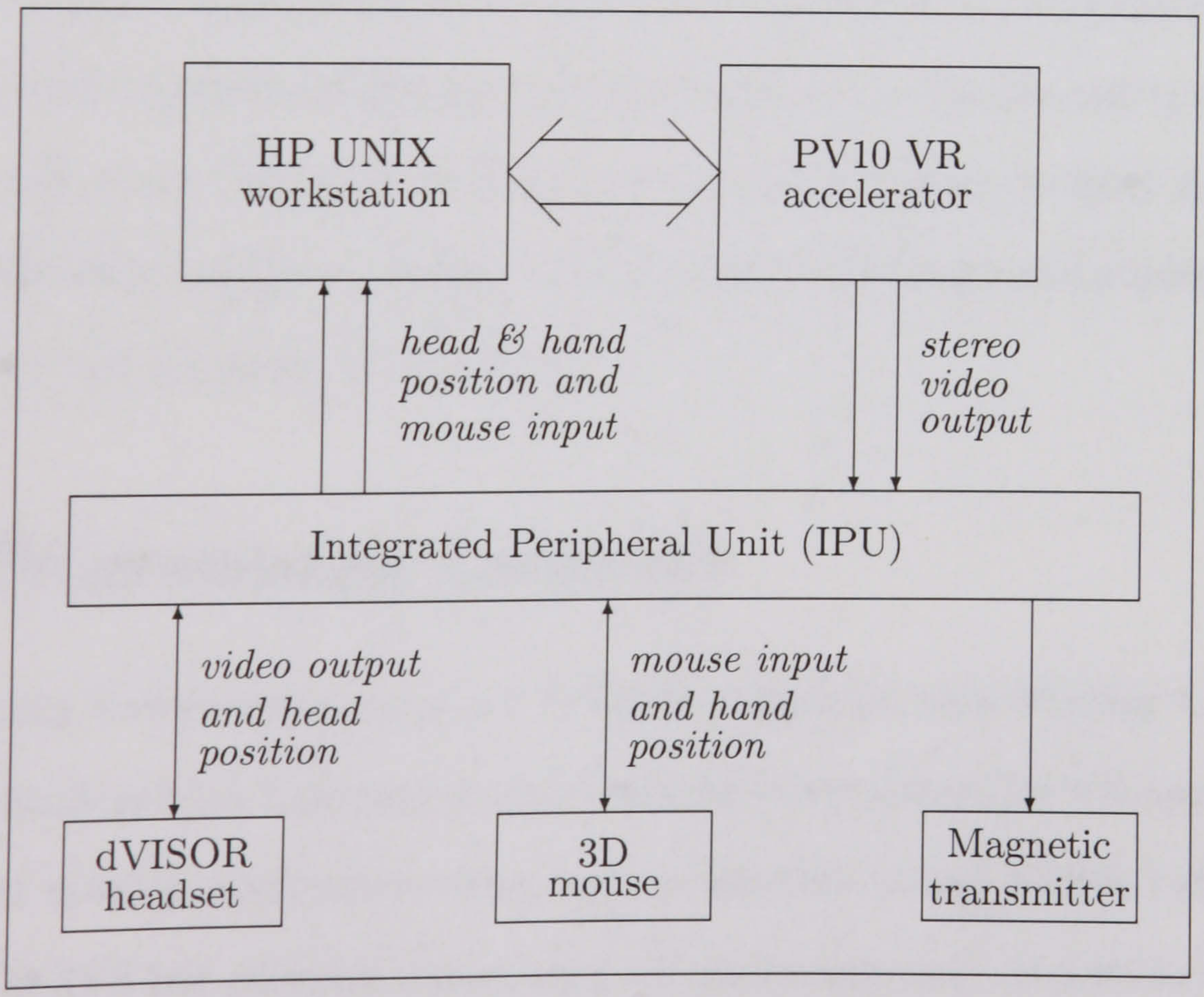


Figure 6.3: VR System Hardware

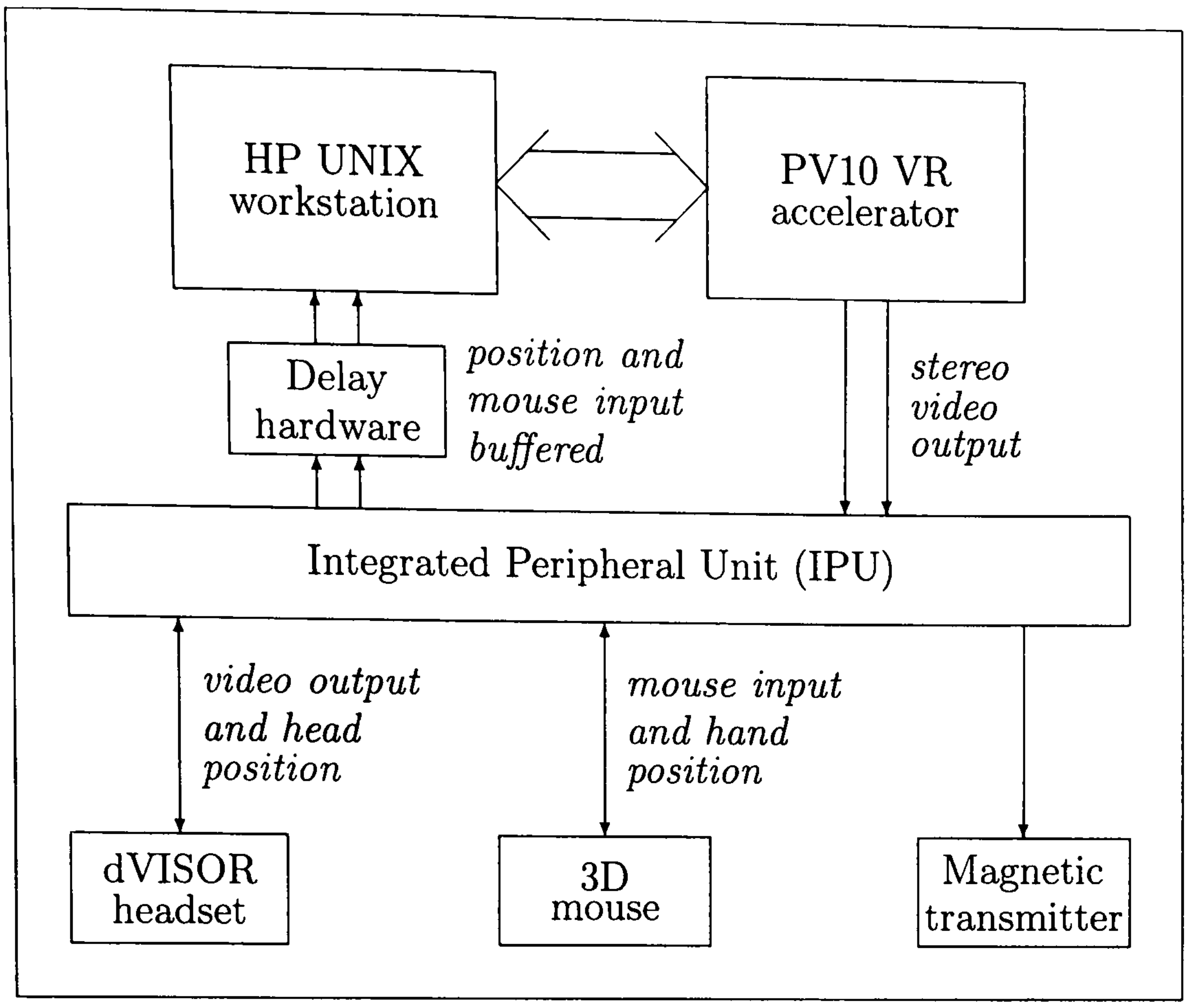


Figure 6.4: Modified VR System Hardware

of Computing and Electrical Engineering of Heriot-Watt University. This delay circuitry consisted of connections to and from the serial lines, programmable chips and a program that buffered signals transmitted on the serial line and output them after a certain time. Due to there being 2 serial lines the delay circuitry had 2 chips each with the delay program resident. More details of the design and implementation of this delay box are given in Chapter 8.

6.3 Programming Language

The two main choices when using the Division equipment were whether to use dVS libraries (which provide a general purpose runtime environment for VR applications) with C and develop applications that way, or whether to use dVISE (which itself makes use of dVS but provides a high-level VR authoring tool). It was decided that, as dVISE could be used to code all required functionality in less time than using

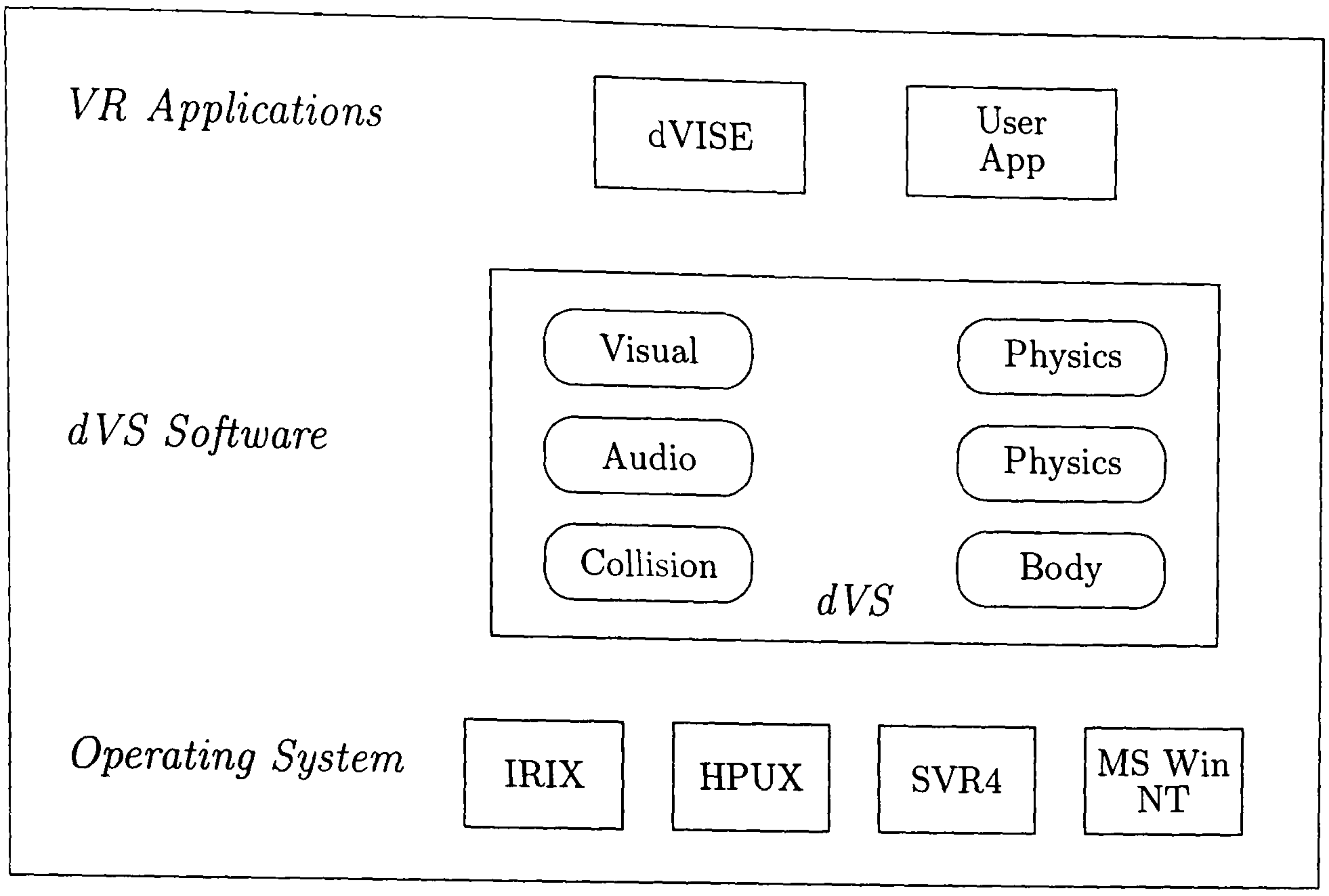


Figure 6.5: dVS Architecture

dVS and C, the software would be written using dVISE (version 3.1). Perl scripts would be written to provide a usable interface to the software.

6.4 dVS and dVISE overview

Division's dVS platform has a 3 layer structure as outlined in Figures 6.5 and 6.6. This means that the VR application developer (using either dVISE or C and the dVS libraries) is abstracted away from platform-specific implementation issues such as the exact method to be used for visual rendering. Please refer to the dVISE User Guide v3.1 (Division, 1996) for more details.

The dVISE tools include converters to take design data produced using a computer aided design (CAD) package and to optimise them for use in the virtual environment. However, due to the department not having the required CAD packages, the virtual environment and objects within it had to be defined and coded manually.

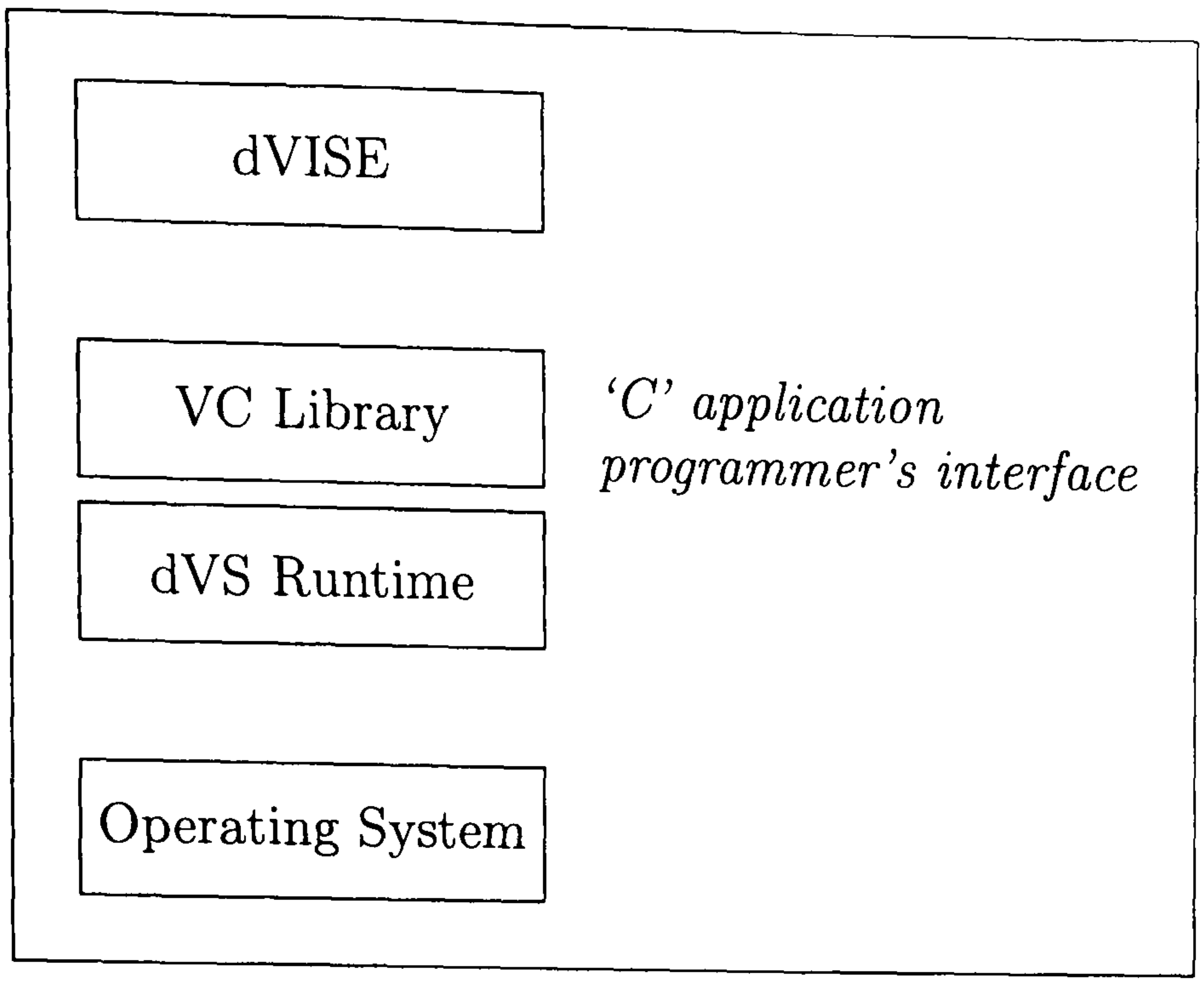


Figure 6.6: dVS Software Layers

6.4.1 dVISE File Structures

In order to define a virtual environment using dVISE there are 3 possible options:

1. using the ToolBox in order to use ready-made objects and change their properties (from within the VR environment),
2. using the Control Panel in order to create and modify virtual environments (from within X Windows running on the workstation used to render the virtual environment), or
3. using a text editor to create a VDI script which defines the environment to be rendered.

The approach that was used was the third option, that of explicitly coding the script to define the virtual environment. This was the only option that enabled some required functionality to be used (such as writing information to files for the data capture) and also meant that objects in the virtual world could be defined in as simple a manner as possible (to aid rendering speeds) rather than using built-in objects which may be unnecessarily complex.

The following types of files are used by dVISE to create a virtual environment:

- audio (digital audio data used to add sound effects to the environment) *[Not used.]*
- boundary (defines the spatial extent of a zone to prevent a user from moving outside the zone)
- geometry files (defines the geometric information for each virtual object)
- material (a definition of the surface characteristics of an objects, such as colour, shininess, texture and transparency)
- texture (a bitmap image applied to the surfaces of an object) *[Not used.]*
- vdifiles (a script that describes the objects in the virtual environment)

The boundary, geometry, material and texture files were defined in text files which were then compiled into binary form for use by dVISE. An example definition of a geometry file can be found in Appendix D as can a material file (Appendix E) and a VDI file (Appendix F).

6.5 Design of Virtual World

The following key design decisions were taken:

1. Keep the environment simple with no unnecessary textures or visual complexities such as photo-realistic overlays on objects.
2. Keep the track design simple with an equal number of left and right hand turns.
3. Maintain a controlled timeline (no uncontrolled delays added by system lag).

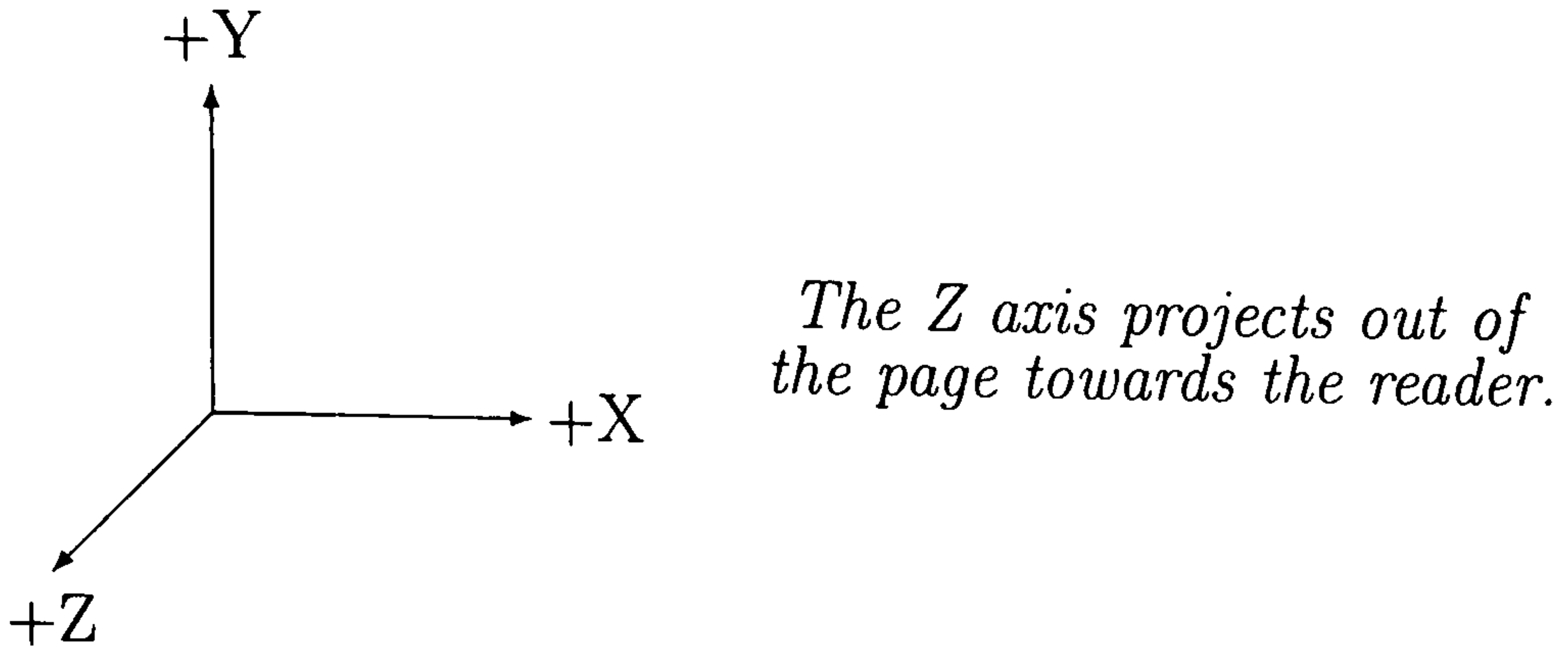


Figure 6.7: Axes of virtual world

4. Automate data capture of timings and errors.
5. Collect detailed performance data for additional analysis if required at a later stage.

It was decided to design the visual appearance of the world in as simple a manner as possible. This decision was taken in order to reduce rendering in the simulation, thus reducing simulator load and the possibility of uncontrolled delays in the system. As a result of this decision all objects in the virtual world have no additional texture or patterns applied to them and instead would be rendered as a solid block of colour.

The world was designed as a black void (following well-established precedents as in Genesis 1:2). Objects were then placed in this world relative to a point of origin at (0,0,0) according to the axes shown in Figure 6.7. In these experiments there was a red plain representing the ground, and then the road was placed on top of this plane. Examples of this can be seen in Chapter 7 with screenshots illustrating the implemented system.

The 'ground' was represented by a dark red plain extending from (-1000,0,0) to (1000,0,-1000). A dark grey track was then placed on this red ground, with white edge lines being placed on top of the track. The track started at (0,0,0) and extended in a negative z direction. A light grey target with a green vertical centre line was placed at the end of the track. As has been mentioned in Section 4.6, 5

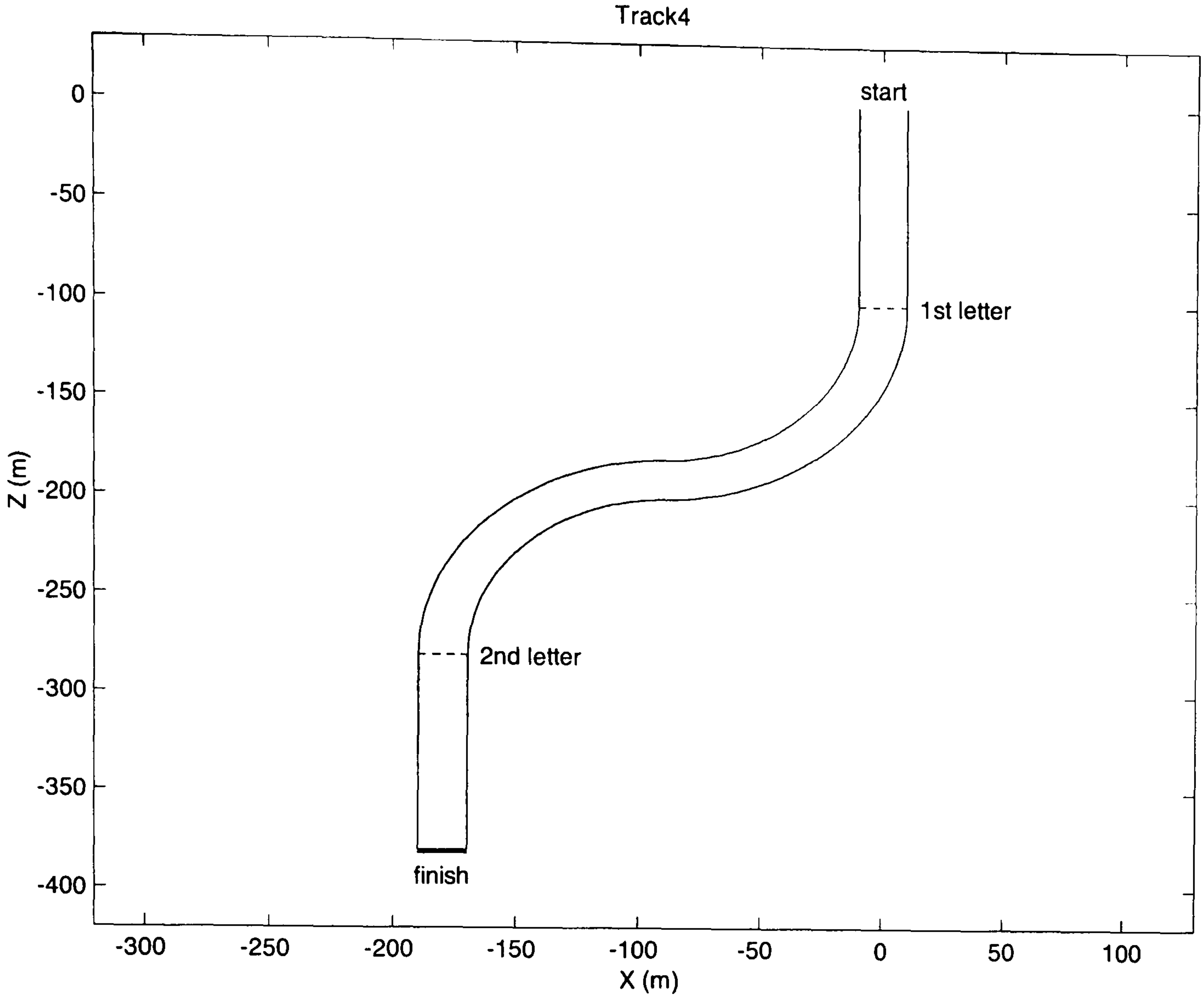


Figure 6.8: Example track layout

tracks were implemented with 0, 1 or 2 turns respectively. An example of the track layout is shown in Figure 6.8. More details are given in Chapter 7 describing how these objects were implemented.

In half the cases visual interference tasks were added to the tracks as described in Section 4.6.4. These visual interference tasks consisted of a white outline of a letter on a dark grey background which obscured the rest of the world (placed in front of the head such that the rest of the world is obscured). These letters appeared when the participant had reached two key points on the track, labelled 1st and 2nd letter on the example track layout (Figure 6.8). All letters were positioned relative to the participants head at (0,0.09,-0.7) with respect to the head.

Although this letter positioning could have been a potential confounding variable (with a potential for an increase in errors in navigation immediately after each letter appearing) the decision was taken to not treat this as a separate experimental variable and randomise for all participants. Instead, the same tracks were used with and without visual interference (letters appearing) therefore the potentially confounding effect was removed.

The implementation of this design is described in the following chapter.

Chapter 7

VR Software Implementation

7.1 Introduction

As has been previously mentioned the software was written using Division's VR authoring tool, dVISE version 3.1. The dVISE software was all developed on the target platform. Perl scripts were developed on the following platforms:

- HP 725/75 UNIX workstation running HP-UX 10.20,
- Silicon Graphics O2 workstation running IRIX 6.5,
- Viglen Pentium II-300 MMX PC running MS Windows NT 4.0,
- Dell Pentium II-333 MMX PC laptop running MS Windows 98.

The target platform for all software was an HP 725/75 UNIX workstation running HP-UX 10.20, HP CDE (Common Desktop Environment), dVS v3.1 and dVISE v3.1.

7.2 Objects

A number of objects were defined for the experiments. These were as follows; crosshair1, ground1, letterF, letterG, letterM, letterN, letterW, letterZ, startline, track1, track2, track3, track4, track5 and visual_task1. Each of these objects will be described individually.

Please note, in order to decrease rendering time all objects were defined in terms of strips of triangles (TRISTRIPs) as this was the most basic shape used by dVS.

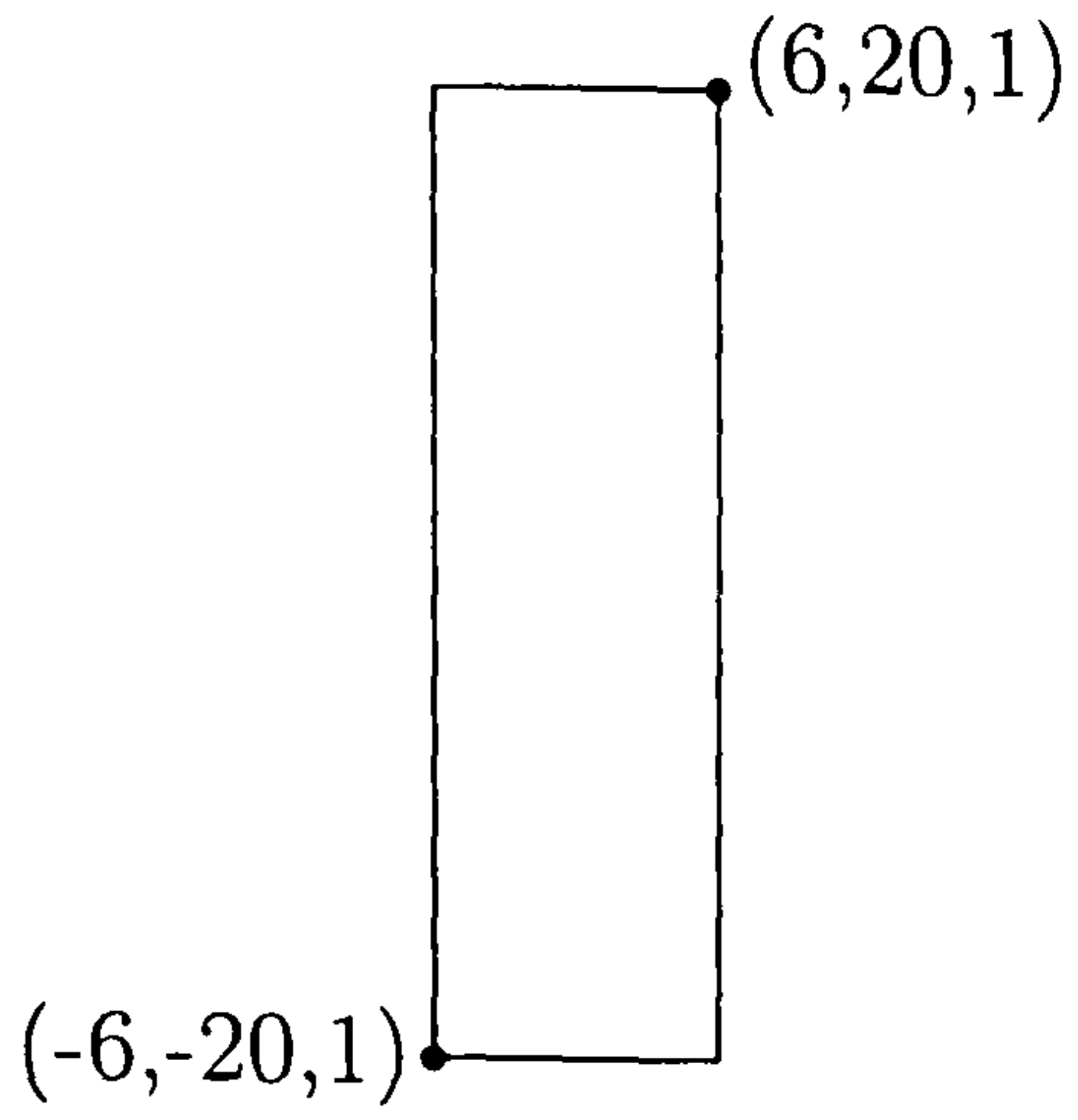


Figure 7.1: Crosshair1

These individual triangles are not shown in the figures. In addition the figures are individually scaled to fit and are therefore not all drawn to the same scale.

7.2.1 Crosshair1

This object was not visible in the environment but was used in order to detect collisions with the target along with the start line. These collisions were detected and recorded in the output file.

The object crosshair1 was defined to be a rectangle with bottom left corner at (-6,-20,1) and top right corner at (6,20,1) as shown in Figure 7.1.

7.2.2 Ground1

This object was visible in the environment as a dark red rectangle with bottom left corner at (-1000,0,0) and top right corner at (1000,0,-1000) as shown in Figure 7.2. The actual appearance of the object can be seen in the screen capture of track 1 in Figure 7.3.

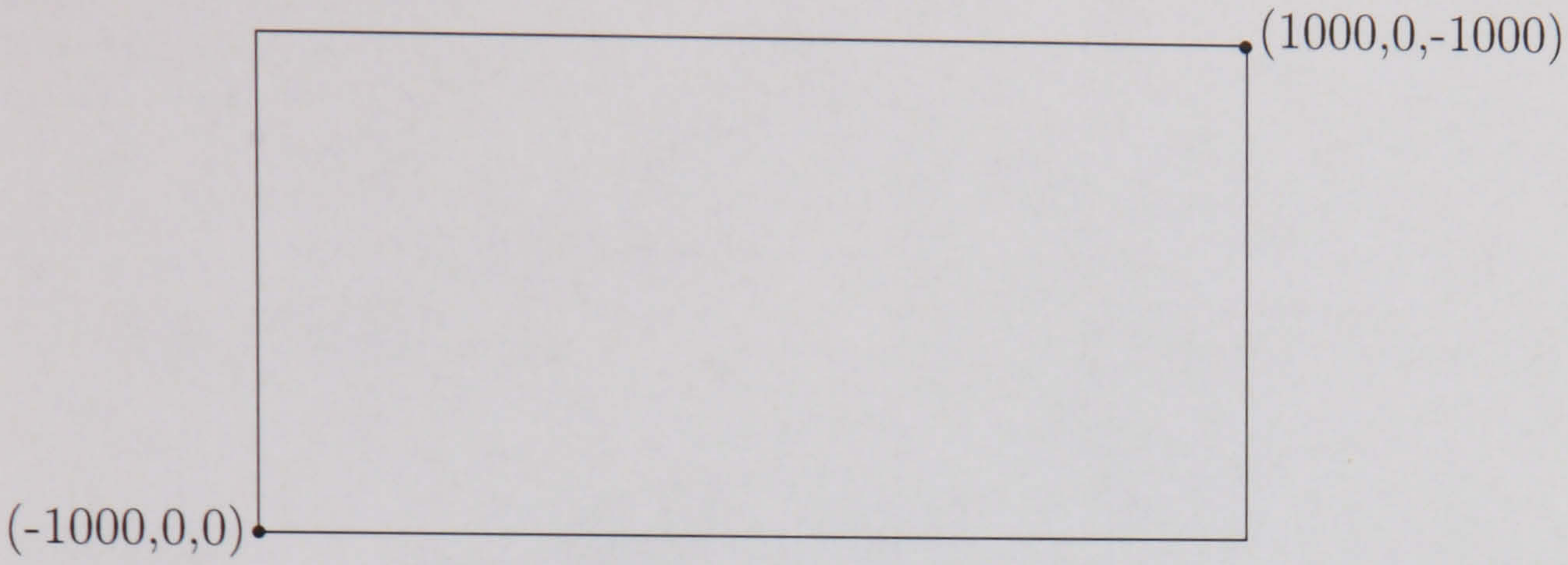


Figure 7.2: Ground1

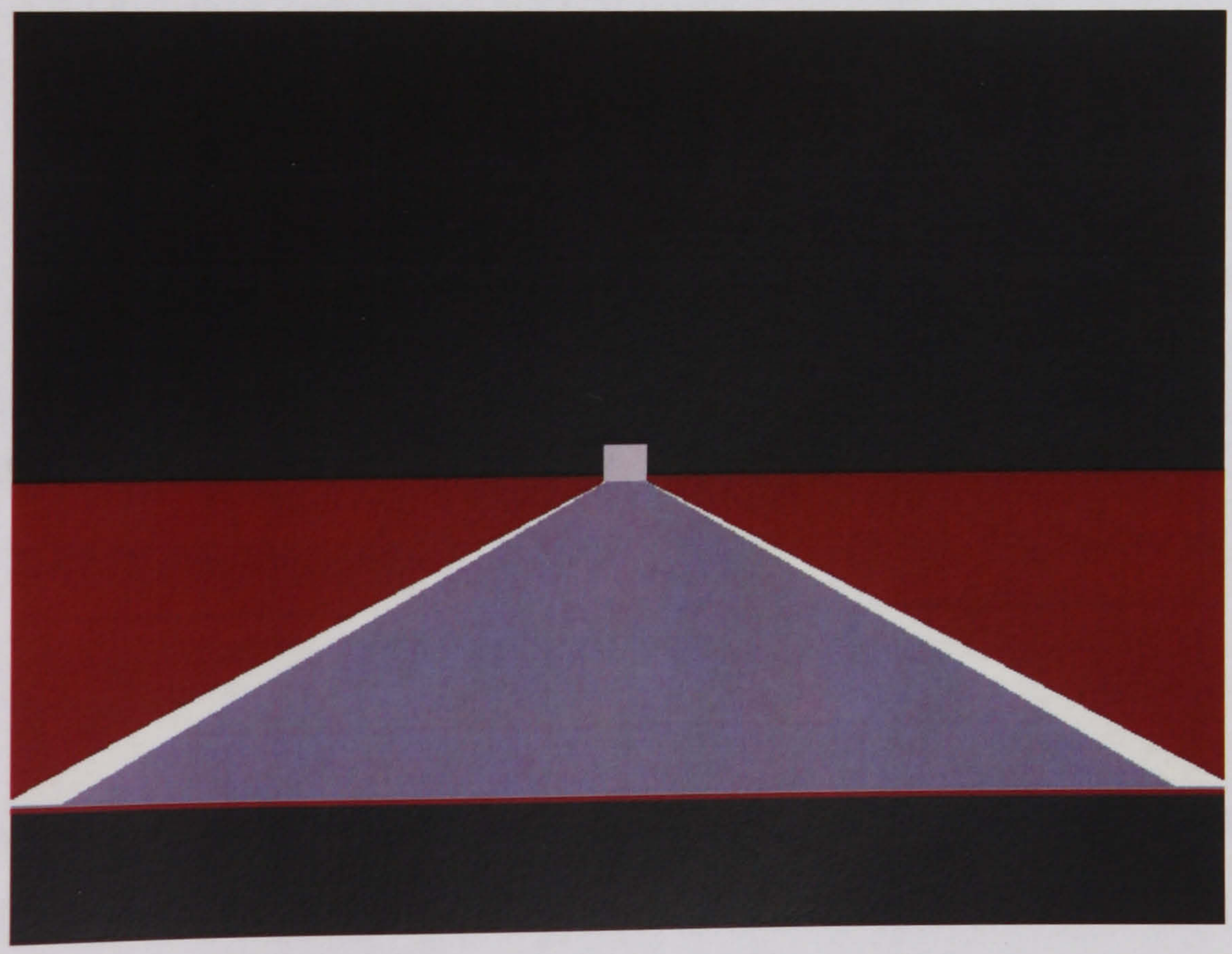


Figure 7.3: Track 1 Screen Capture

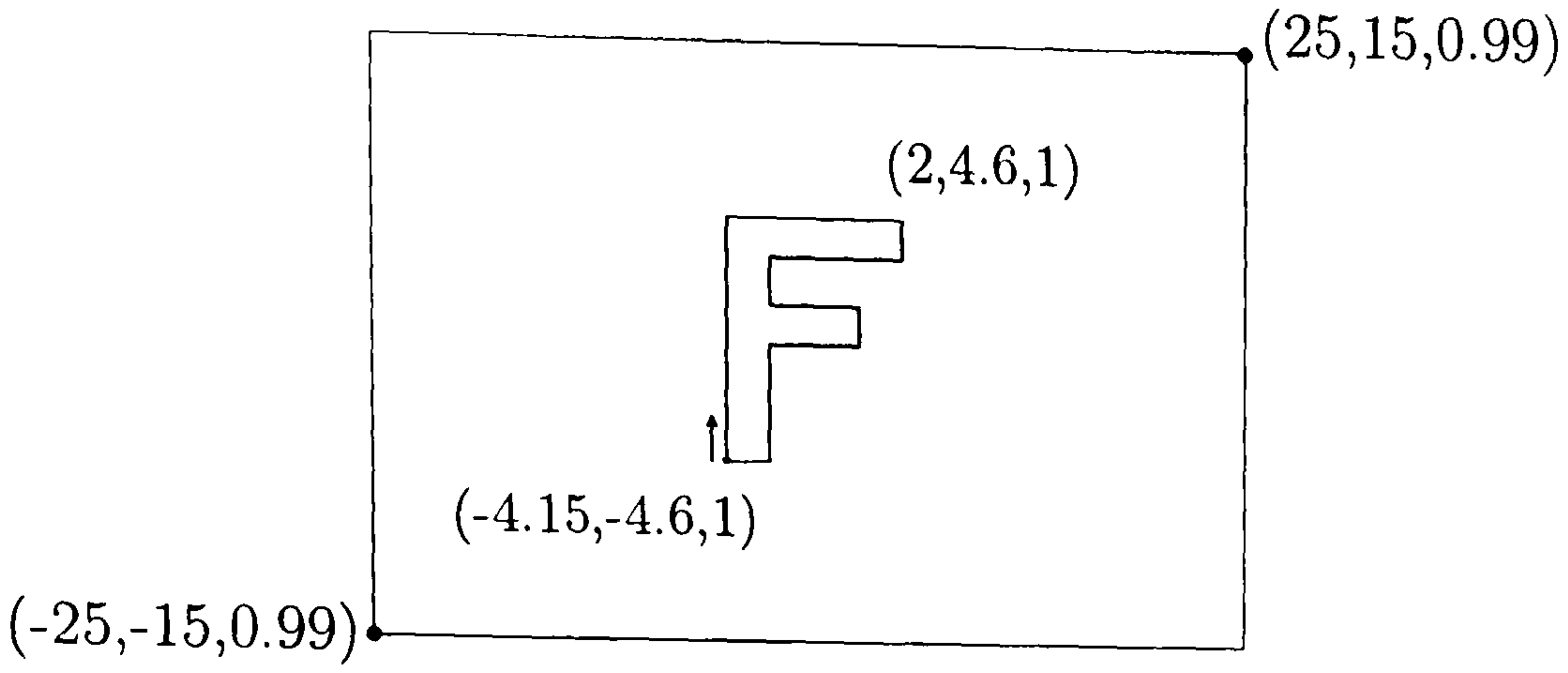


Figure 7.4: LetterF

7.2.3 Visual Interference Objects

LetterF

This object was visible in the environment as thick white lines on a dark grey rectangle with bottom left corner at (-25,-15,0.99) and top right corner at (25,15,0.99). The letter itself had a bottom left corner at (-4.15,-4.6,1) and top right corner at (2,4.6,1) as shown in Figure 7.4. However, it should be noted that the letter and background were 'attached' to the head of the user such that they appeared at (0,0.09,-0.7) with respect to the head. This meant that the user did not see the entire background rectangle and the letter appeared to be larger. The rectangle was designed to be larger than the visible area in order to block out the rest of the environment entirely as shown in Figure 7.5.

LetterG

This object was visible in the environment as thick white lines on a dark grey rectangle with bottom left corner at (-25,-15,0.99) and top right corner at (25,15,0.99). The letter itself had a bottom left corner at (-4.15,-4.6,1) and top right corner at (4.1,6.6,1) as shown in Figure 7.6. However, it should be noted that the letter and background were 'attached' to the head of the user as for letterF.

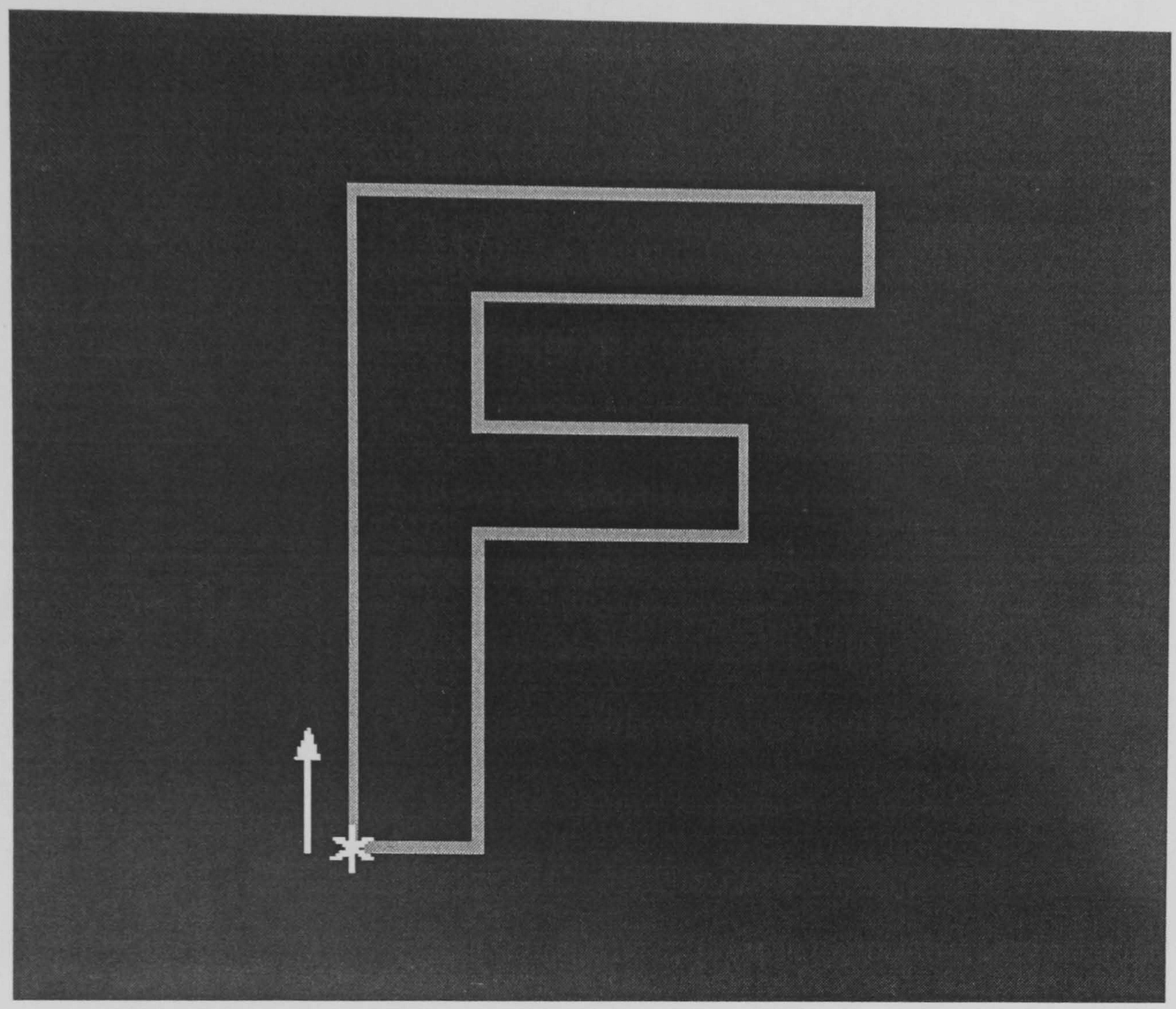


Figure 7.5: Letter F Screen Capture

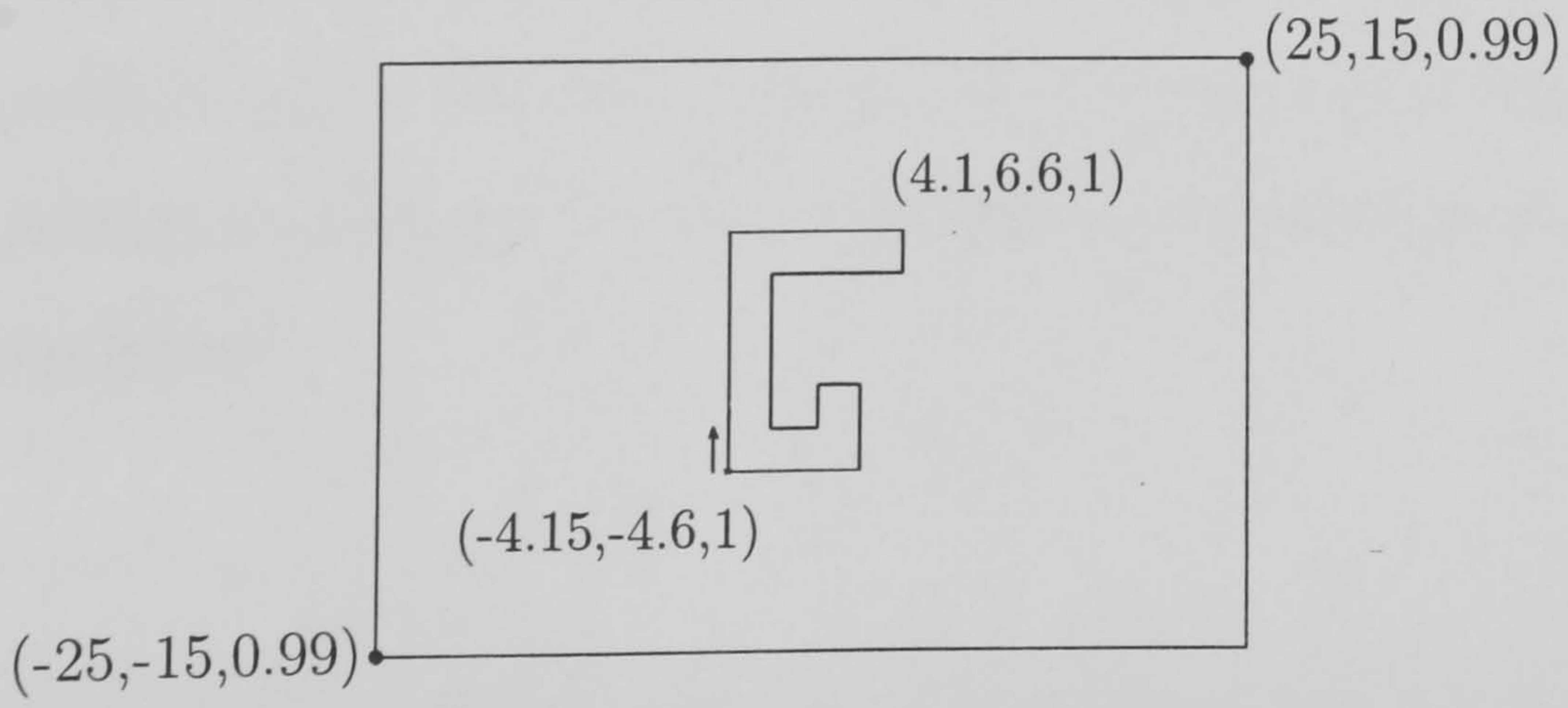


Figure 7.6: LetterG

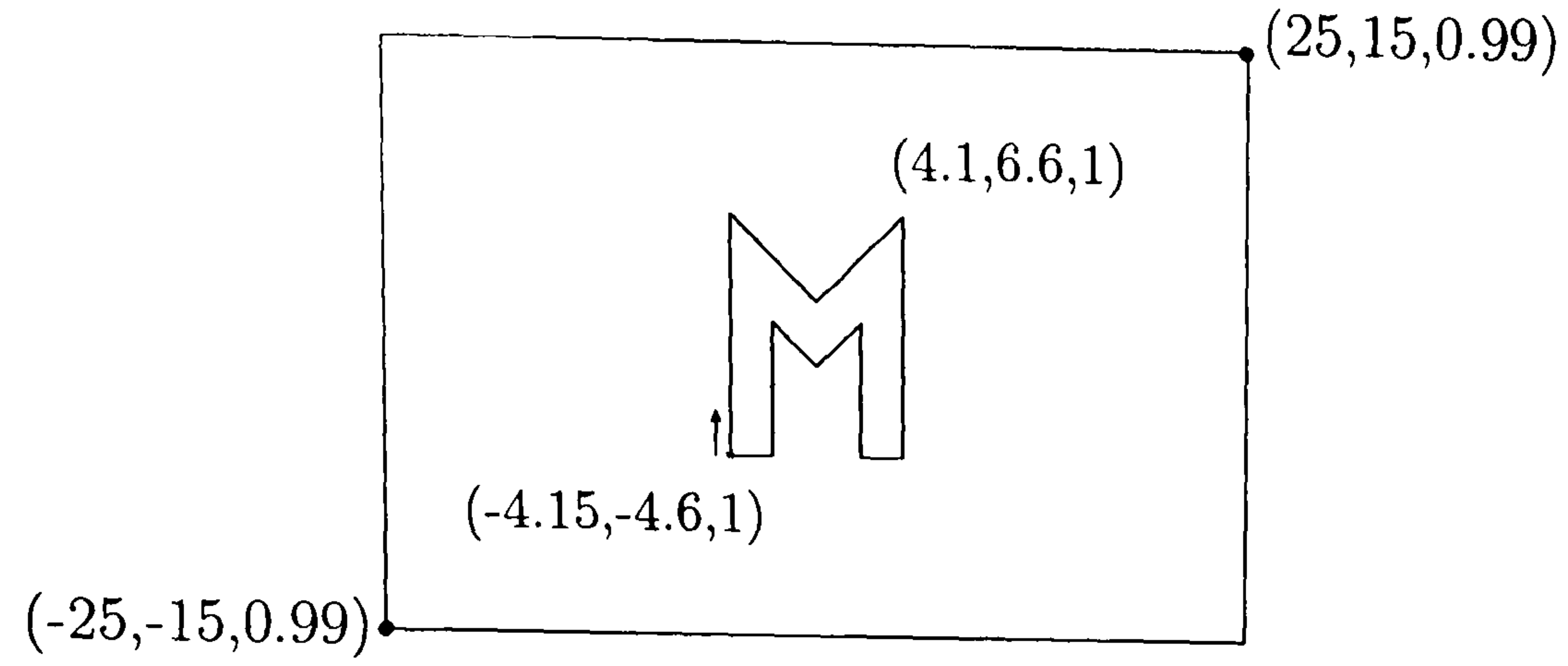


Figure 7.7: LetterM

LetterM

This object was visible in the environment as thick white lines on a dark grey rectangle with bottom left corner at (-25,-15,0.99) and top right corner at (25,15,0.99). The letter itself had a bottom left corner at (-4.15,-4.6,1) and top right corner at (4.1,6.6,1) as shown in Figure 7.7. As before the letter was positioned close to the head.

LetterN

This object was visible in the environment as thick white lines on a dark grey rectangle with bottom left corner at (-25,-15,0.99) and top right corner at (25,15,0.99). The letter itself had a bottom left corner at (-4.15,-4.6,1) and top right corner at (4.1,6.6,1) as shown in Figure 7.7. The letter was positioned close to the head as with previous letters.

LetterW

This object was visible in the environment as thick white lines on a dark grey rectangle with bottom left corner at (-25,-15,0.99) and top right corner at (25,15,0.99). The letter itself had a bottom left corner at (-3.15,-4.6,1) and top right corner at

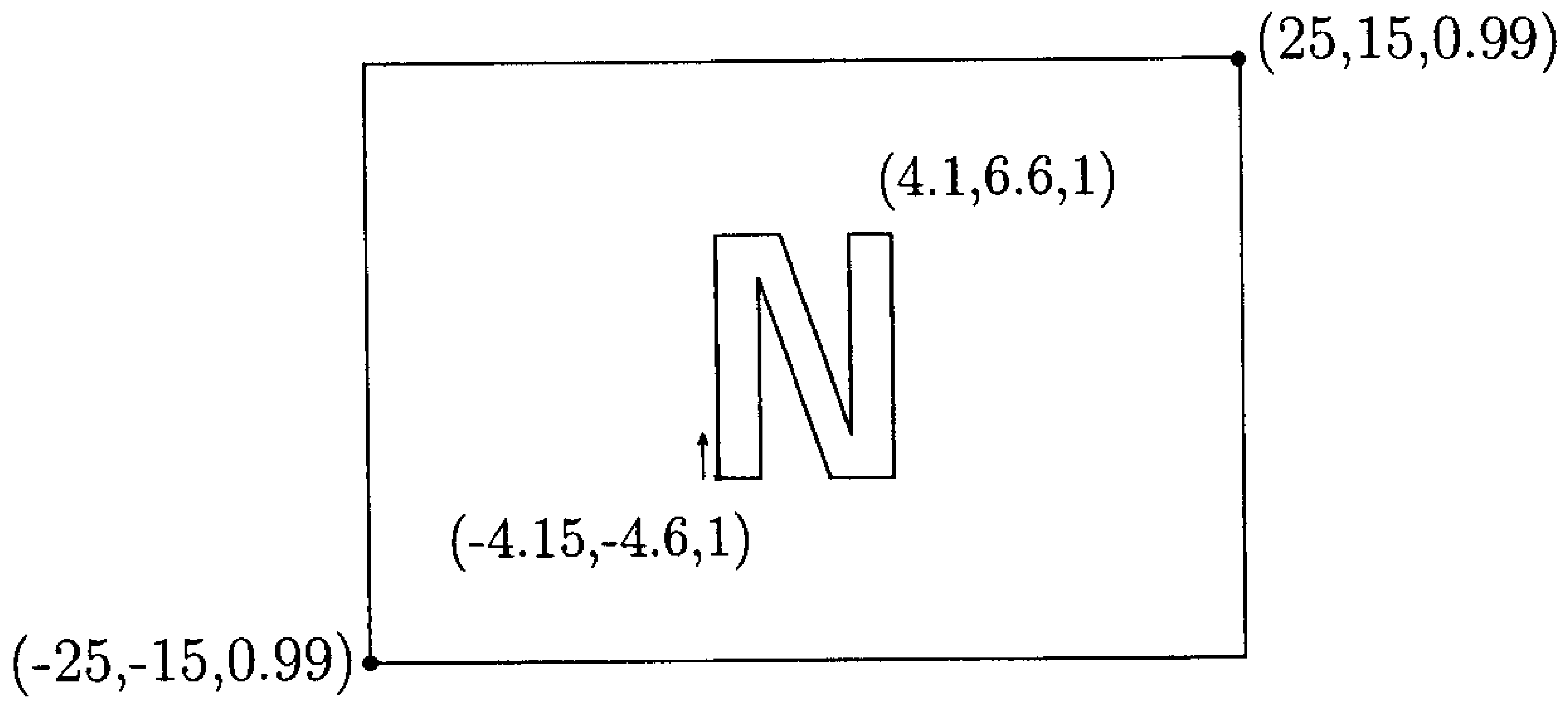


Figure 7.8: LetterN

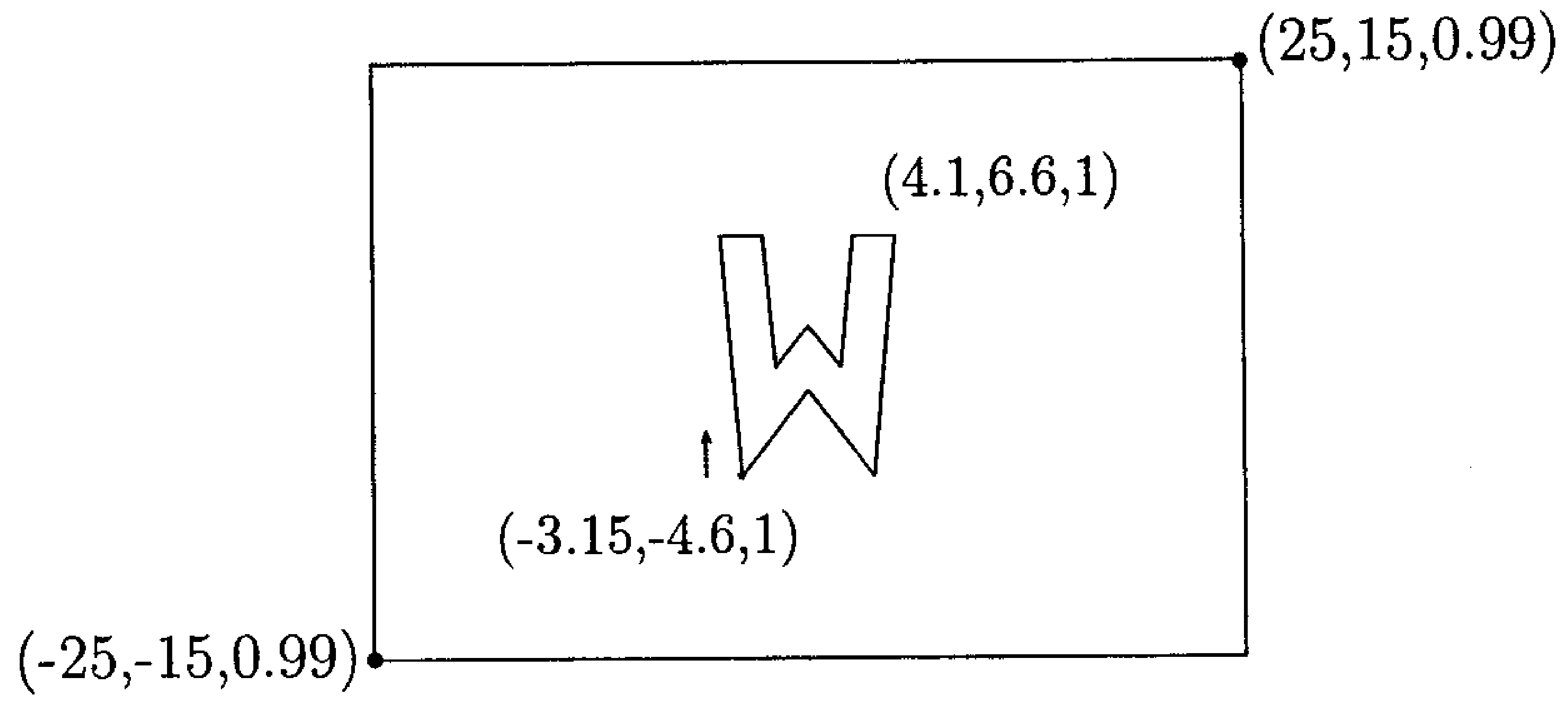


Figure 7.9: LetterW

(4.1,6.6,1) as shown in Figure 7.7. The letter was positioned close to the head as with previous letters.

LetterZ

This object was visible in the environment as thick white lines on a dark grey rectangle with bottom left corner at (-25,-15,0.99) and top right corner at (25,15,0.99). The letter itself had a bottom left corner at (-4.15,-4.6,1) and top right corner at (4.1,6.6,1) as shown in Figure 7.7. The letter was positioned close to the head as with previous letters.

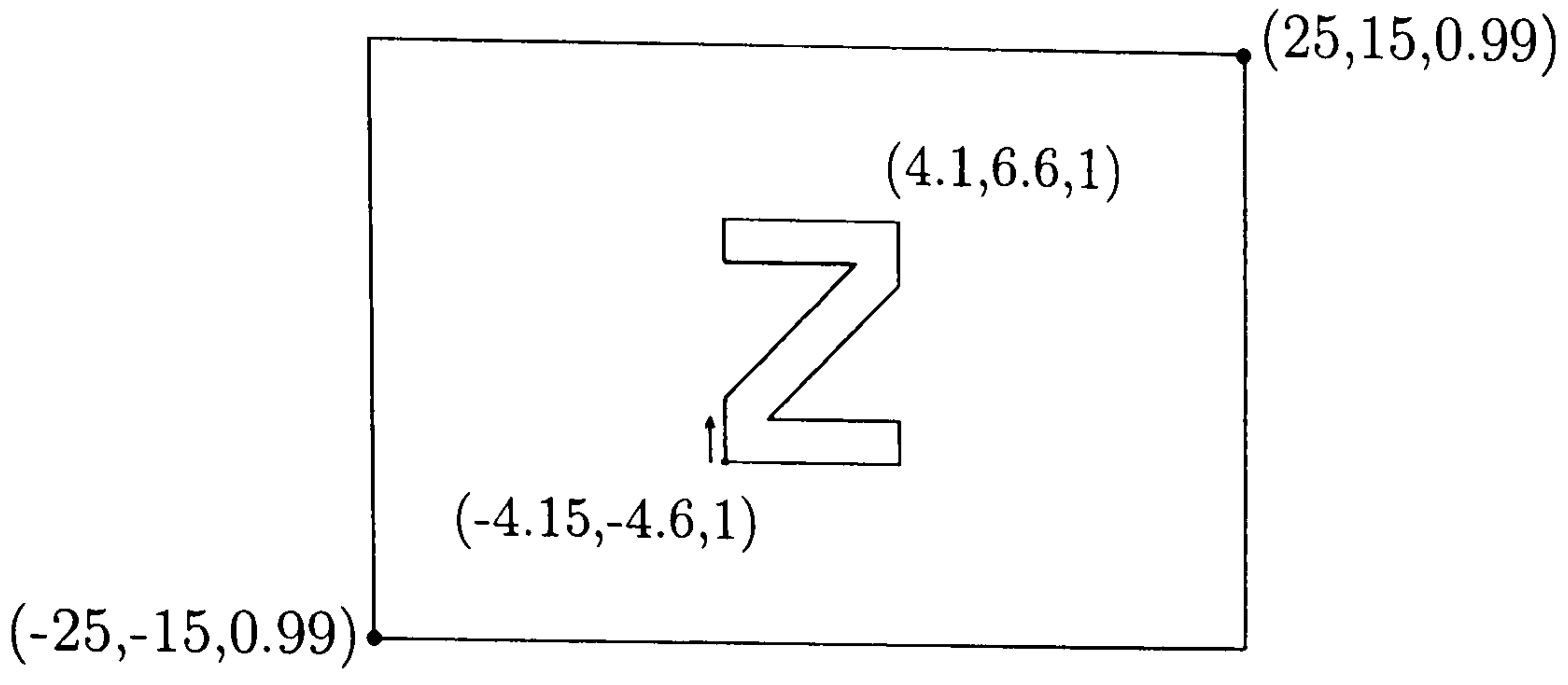


Figure 7.10: LetterZ

Visual_task1

This object was not visible in the environment but was used in order to detect collisions with the crosshair1 object in order to make a letter appear (one of F, G, M, N, W or Z).

The object visual_task1 was defined to be a rectangle with bottom left corner at (-200,-100,0) and top right corner at (200,100,0).

7.2.4 Startline

This object was not visible in the environment but was used in order to detect collisions with the crosshair1 object in order detect when the user had crossed the startline and record appropriate data in the output files.

The object startline was defined to be a rectangle with bottom left corner at (-100,-20,0) and top right corner at (100,20,0).

7.2.5 Tracks

Each of the tracks were rendered as a grey road 20 units wide and were placed on the dark red ground, with white edge lines being placed on top of the track. Each track started at (0,0,0) and extended in a negative z direction. A light grey target

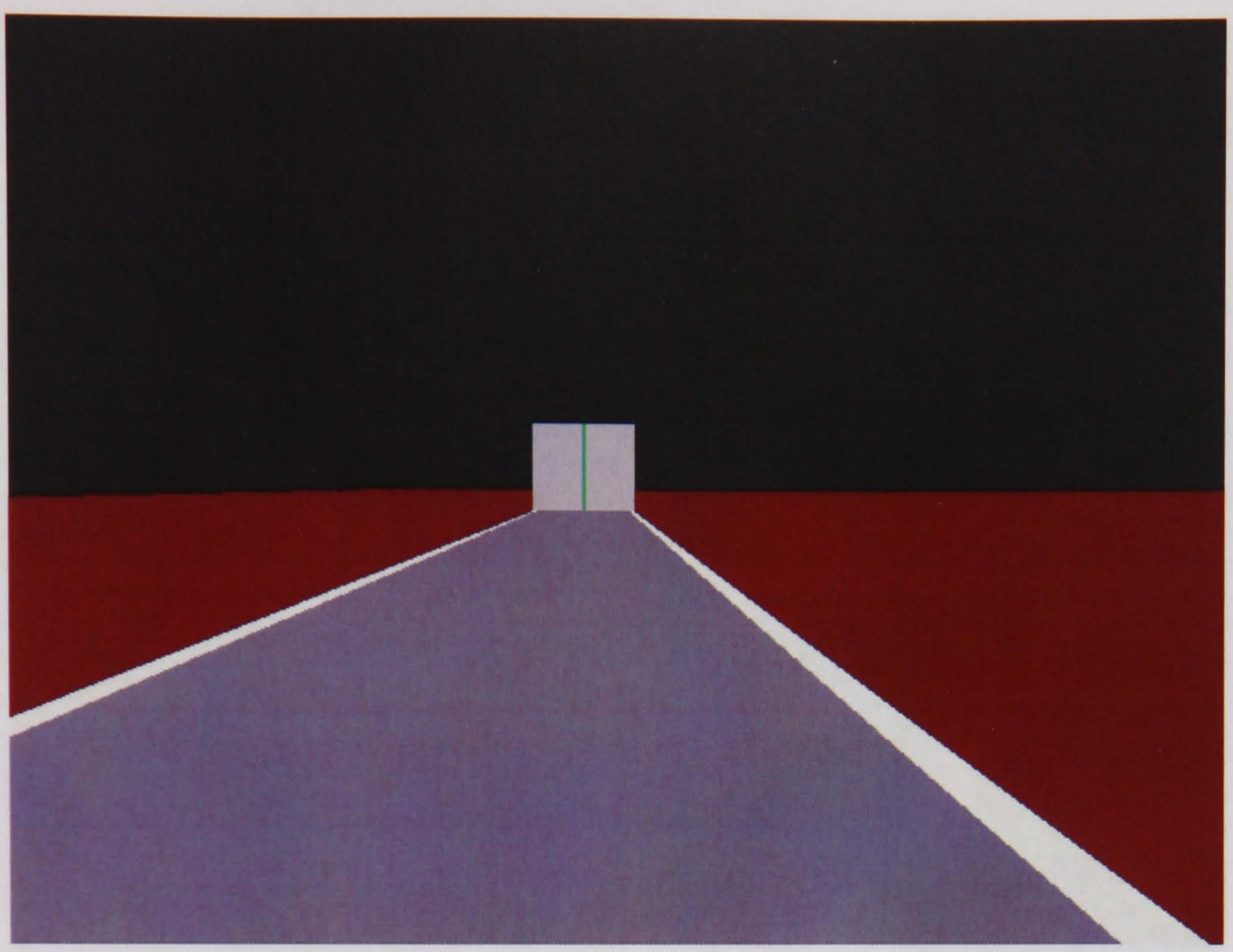


Figure 7.11: Target Screen Capture

with a green vertical centre line was placed at the end of the track (see Figure 7.11. As has been mentioned in Section 4.6, five tracks were implemented with 0, 1 or 2 turns respectively and can be seen in Figure 4.5.

Track1

This straight track was visible in the environment as a grey rectangle with bottom left corner at (-10,-16.99,0) and top right corner at (10,-16.99,-400). Please see Figure 7.3 for more details.

Track2

This track starts at (-10,-17,0) to (10,-17,0), bends to the left and finishes at (-290,-16.99,-180) to (-290,-16.99,-200). Please see Figure 7.12 for more details.

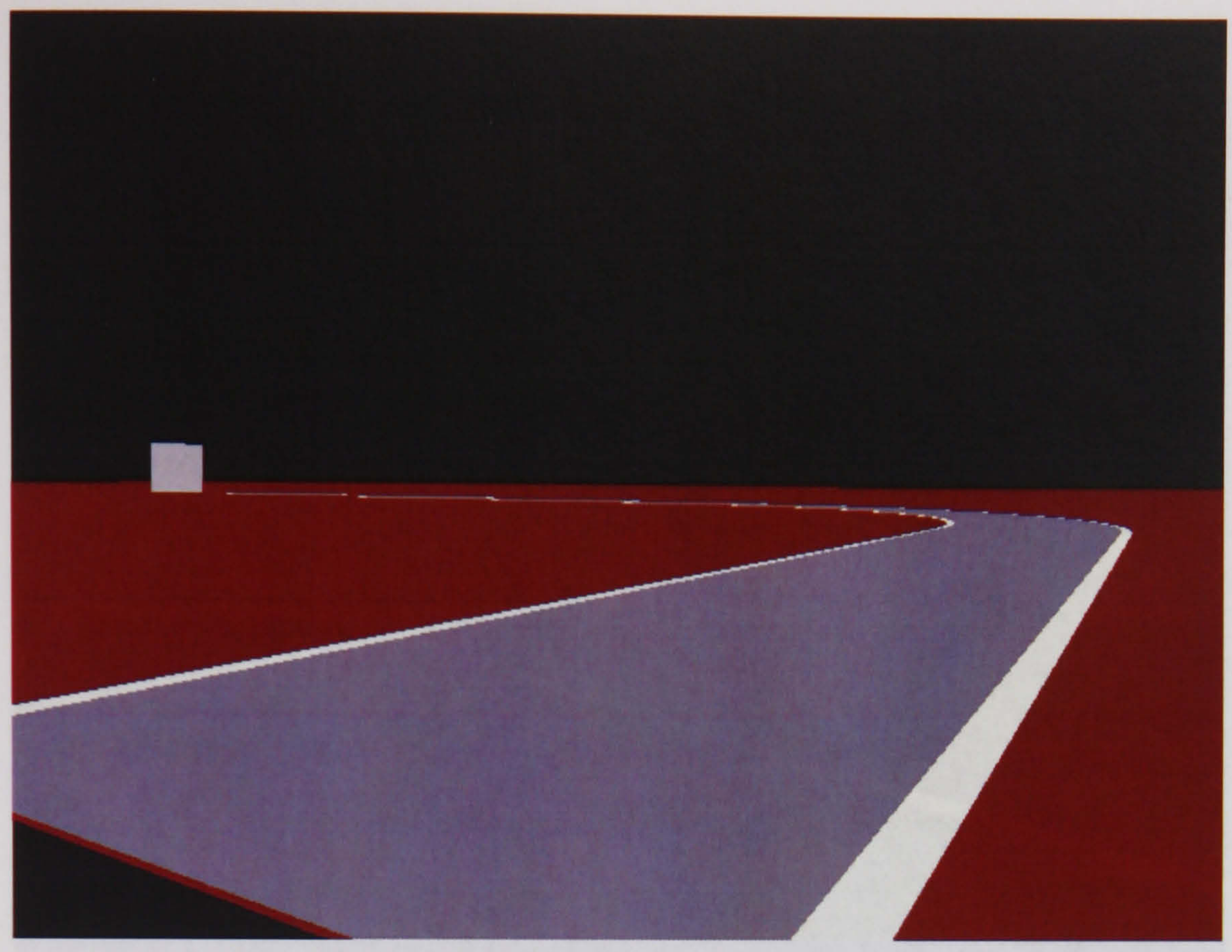


Figure 7.12: Track 2 Screen Capture

Track3

This track starts at (-10,-17,0) to (10,-17,0), bends to the right and finishes at (290,-16.99,-200) to (290,-16.99,-180). Please see Figure 7.13 for more details.

Track4

This track starts at (-10,-17,0) to (10,-17,0), bends to the left then back to the right before finishing at (-190,-16.99,-380) to (-170,-16.99,-380). Please see Figure 7.14 for more details.

Track5

This track starts at (-10,-17,0) to (10,-17,0), bends to the right then back to the left before finishing at (170,-16.99,-380) to (190,-16.99,-380). Please see Figure 7.15 for more details.

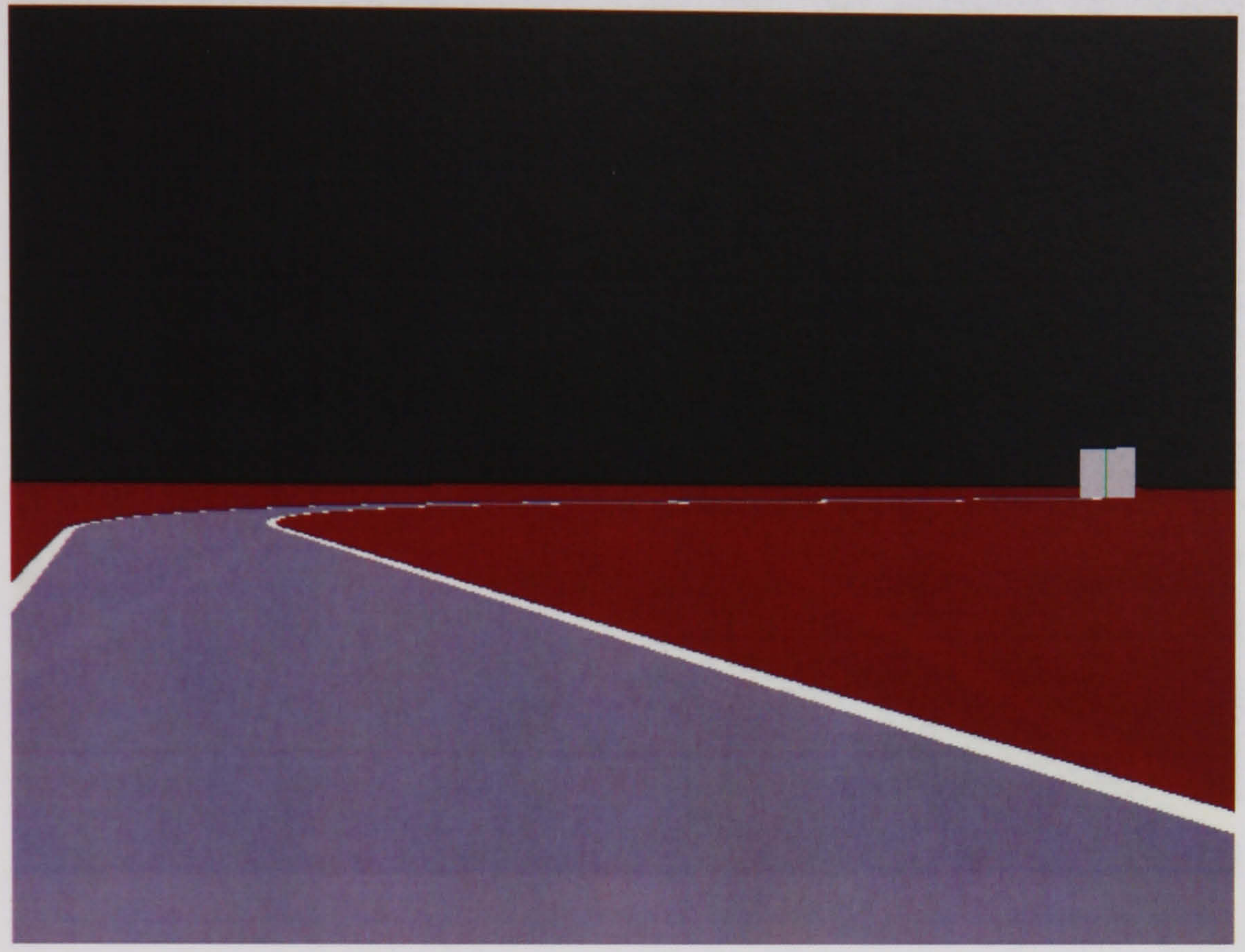


Figure 7.13: Track 3 Screen Capture

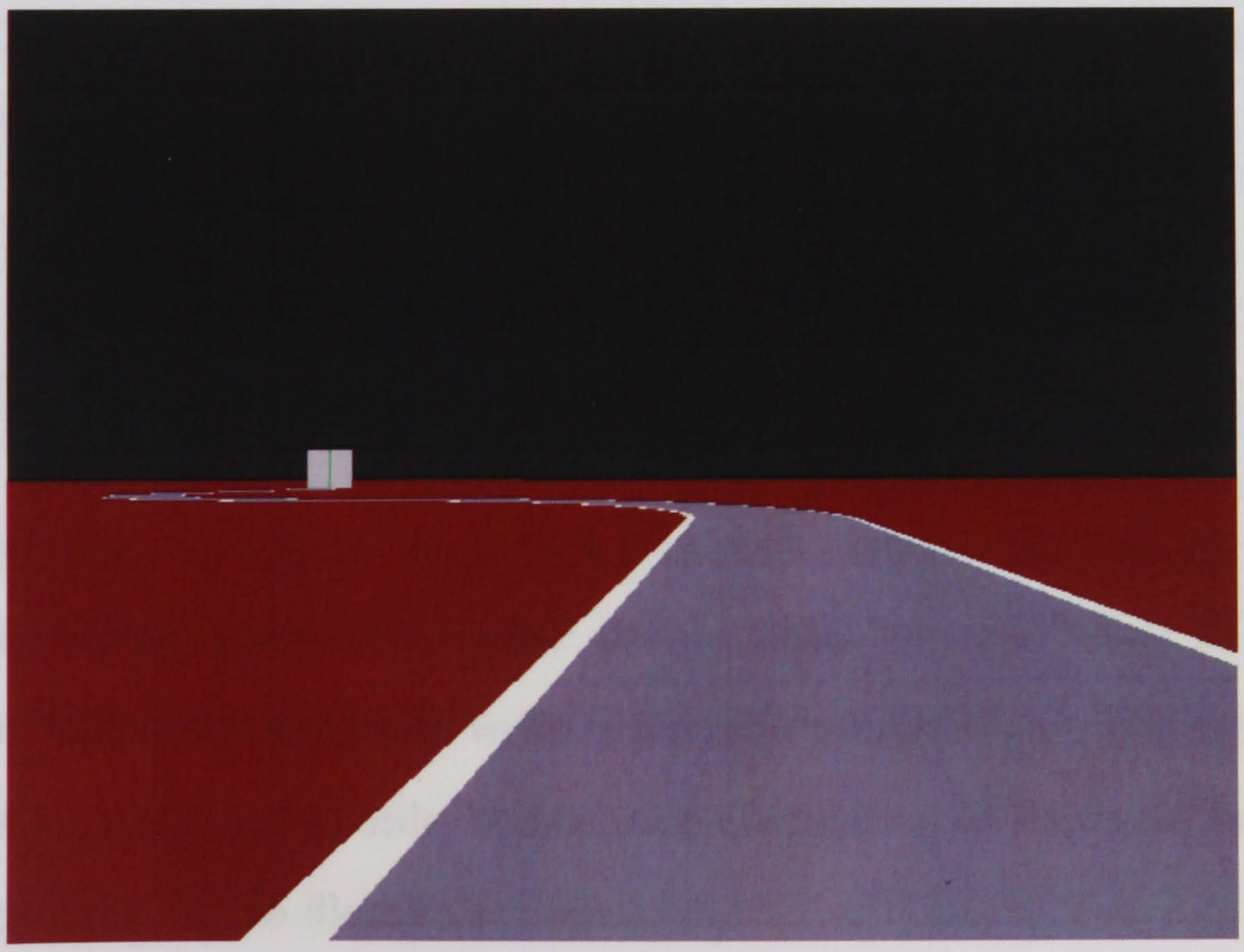


Figure 7.14: Track 4 Screen Capture

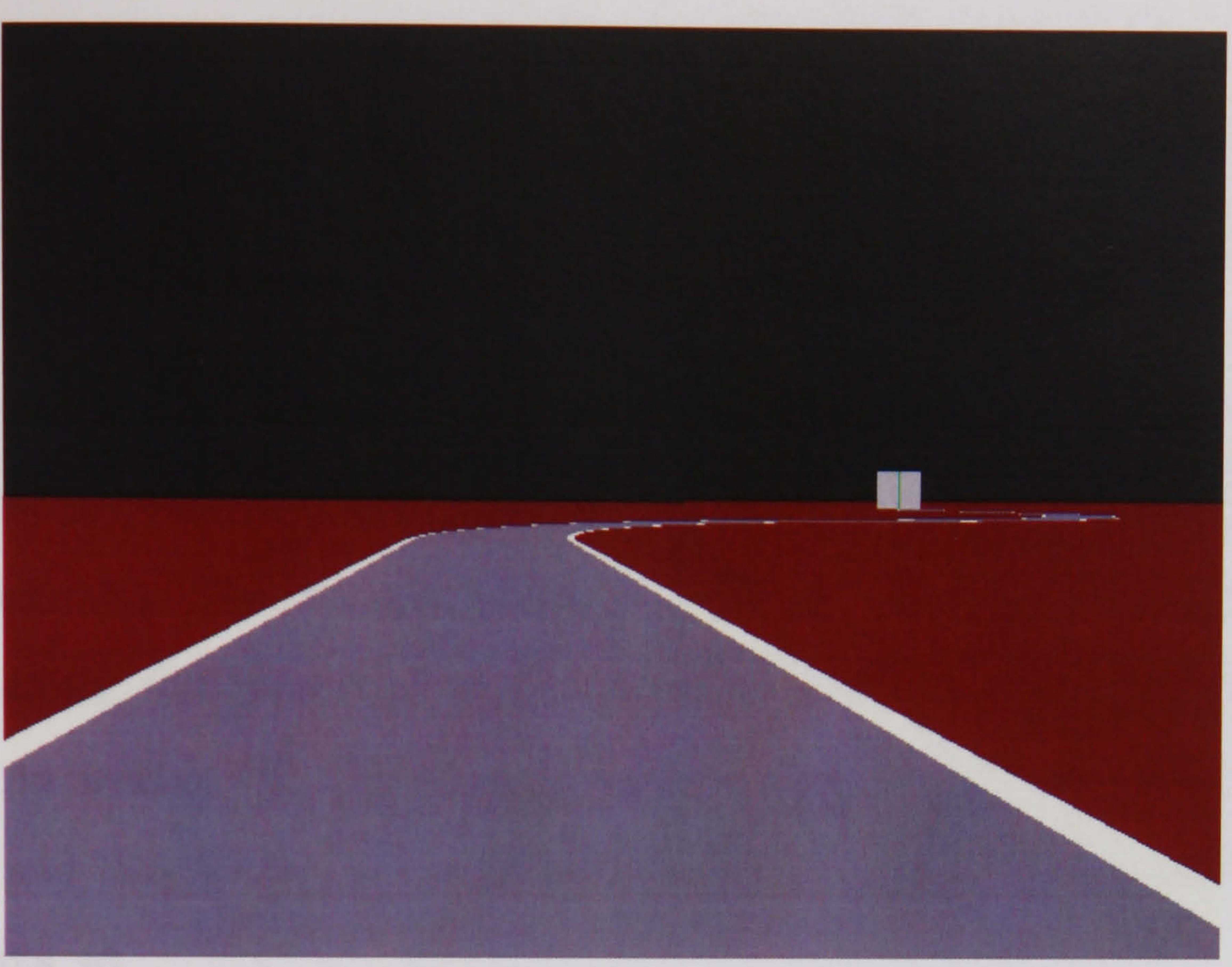


Figure 7.15: Track 5 Screen Capture

Condition	0–4	5–9	10–14	15–19	20–24	25–29
Interference?	N	N	N	Y	Y	Y
Delay	0 ms	400 ms	800 ms	0 ms	400 ms	800 ms
Track no	1–5	1–5	1–5	1–5	1–5	1–5

Table 7.1: Experimental Conditions

7.3 Implementation File Structure

In order to produce a virtual environment for each different experimental condition (such as no visual interference tasks, 400 ms delay, track4) it was decided that a separate VDI script would be written for each combination. The experimental conditions were encoded in order to facilitate automation as shown in Table 7.1.

This gave rise to 185 files of the form

$$\text{track}nxx \text{ where } 1 \leq n \leq 5 \text{ and } x \epsilon \{F, G, M, N, W, Z\}.$$

Although this may seem a rather inefficient method of implementation with much duplication of code, it was considered to be preferable to the alternative of creating a single, large environment with all the possible combinations defined within it. This alternative would require a considerable time to load each time and would therefore significantly lengthen the duration of each experiment.

The ordering of experimental conditions was randomised for each participant by using a short 'C' program with a randomly seeded pseudo-random number generator (see Appendix H). The choice of letters used in the visual interference tasks was also randomised, this time using truly random numbers from statistical tables (as mentioned in Section 4.6). These randomised orders were then stored in two files, exp_order and letter_order, and were consulted by the main experimental script, `experiments.pl`.

Other files required by dVISE such as the geometric and boundary definitions of objects along with materials and textures to be applied were all defined in a single set of common files which were used by all VDI files. These files were located in subdirectories within the directory from which the experiments were conducted.

In order to call dVISE with the relevant VDI file a Perl script was written. This perl script, `experiments.pl`, was also designed to aid the experimenter in running the experiments more easily by automating the data capture and displaying clear instructions as to what actions must be taken throughout the experiment. The data were recorded in output files with one file for each trial. Due to space constraints these files were not stored in the same location as the Perl script and dVISE files. The directory structure of all files used in the experiment is shown in Figure 7.16.

The script is briefly outlined in pseudo code in Table 7.2. (The full script can be found in Appendix C.) Output from the script (run with the dummy flag on so as to echo all commands rather than execute them) is given in Table 7.3.

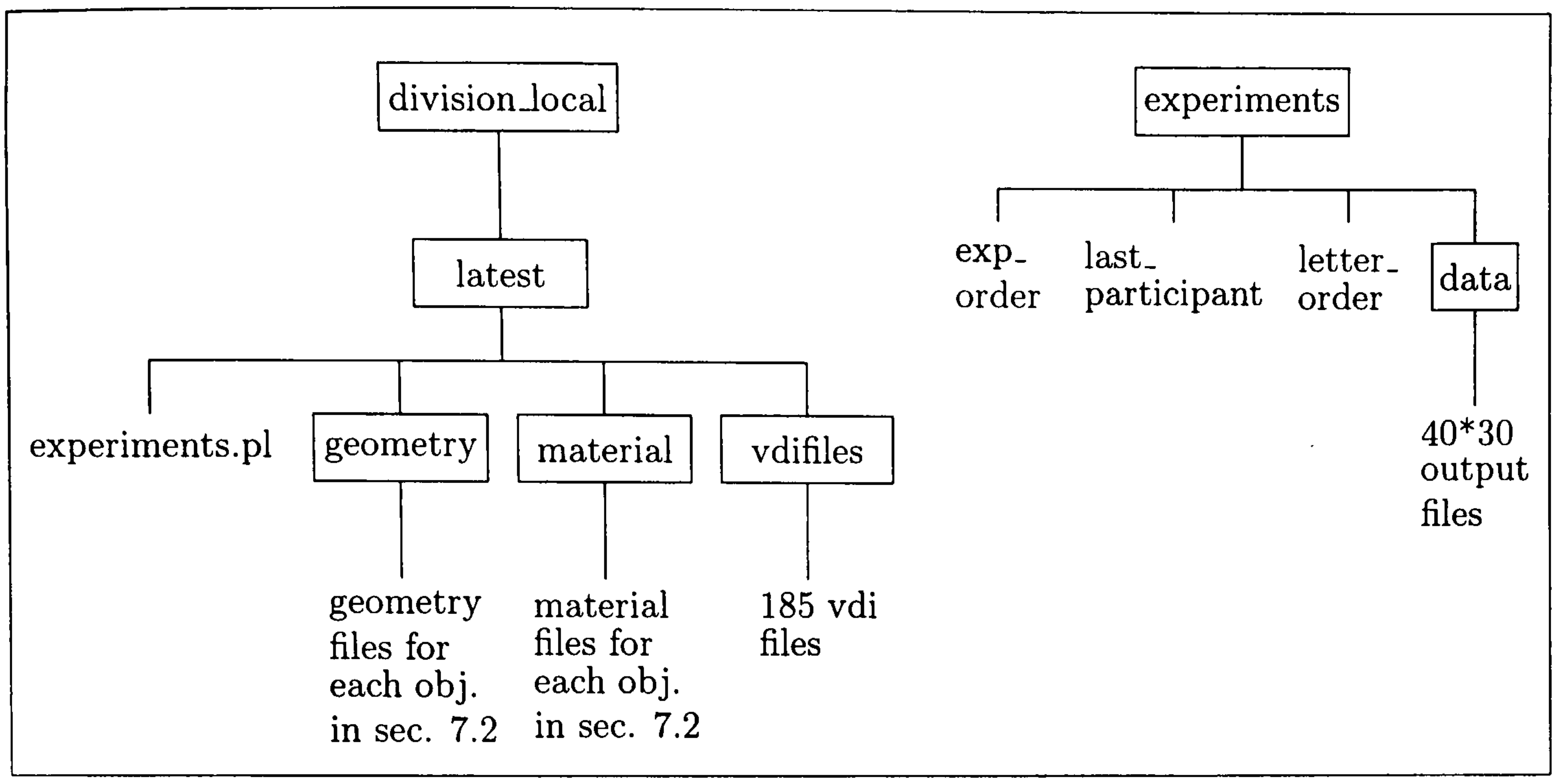


Figure 7.16: Directory Structure

(Framed entries are directories, non-framed are files.)

```
Display instructions for experimenter
Look up participant number from file and increment existing number
(to make next participant number)
Read order of conditions for current participant
For    each trial 1 to 30
       Read first condition and remove from order of conditions
       Display instructions for experimenter
       Call dVISE with relevant VDI file for current condition
       and output results to file
Next   trial
Display final instructions for experimenter
```

Table 7.2: Pseudo Code for Main Experimental Script

```
------------------------------------------------------------
 Delayed visual feedback experiment script: experiments.pl
                 Phil Day 21/08/2000
------------------------------------------------------------

** Dummy run - don't execute vcrun just print command syntax **

Generating new participant number...
Participant Number:6


Participant:6 Trial:1 Condition:25
/home/division/bin/killq
  (P6 T1 VI:WN Delay:800 ms Track:1)
-- Set delay, RESET delay h/w, <ENTER> to continue (B=back N=skip to next) --

vcrun -D PV10=enabled dvise vdifiles/track1WN.vdi -notoolbox > /home/division/exp
eriments/data/p6c25t1_track1WN_d800
```

[snip]

```
Participant:6 Trial:30 Condition:13
/home/division/bin/killq
  (P6 T30 VI: Delay:800 ms Track:4)
-- Set delay, RESET delay h/w, <ENTER> to continue (B=back N=skip to next) --

vcrun -D PV10=enabled dvise vdifiles/track4.vdi -notoolbox > /home/division/exper
iments/data/p6c13t30_track4_d800

-- End of experiment for participant 6 --
```

Table 7.3: Output of Experimental Script

7.3.1 dVISE Configuration

In addition to the design and implementation of a virtual world and the objects within it, the interaction of the user with the environment had to be defined. In order to prevent confusion the possible methods of interaction were kept to a minimum. For instance, the user always entered the environment at the same point (0, -0.3, 0.8) and could not climb in the Y plane at all (what dVISE terms *level flying*, i.e. they could only move in the X and Z planes thus giving an experience closer to driving). In a similar manner, the buttons on the 3D mouse were redefined such that only two of them had any functionality, namely movement forward or back, again removing the possibility of inadvertent control movements causing confusion.

7.4 Data capture and collection

As has been mentioned the main experimental script called dVISE with output being piped to a file. A new file was created for each trial thus meaning that there were 30 output files per participant, or 30*40 files in total.

In order to avoid confusion the filename for these output files was structured in the following manner:

$$\mathrm{p}\alpha\alpha\mathrm{c}\beta\beta\mathrm{t}\gamma\gamma\_\mathrm{track}\delta\Phi\Phi\_\mathrm{d}\zeta\zeta\zeta$$

where α=participant number, β=condition number, γ=trial number, δ=track number, Φ=visual interference letters and ζ=size of delay.

Data was stored in the files every 1/50 of a second with a single line being added to the file containing current position, orientation and current time and date stamp. In addition to this data comments were written to the file such as when the experiment began, when the user crossed the start line, when a visual interference letter appeared and disappeared and so on.

An extract from a sample output log, namely p34c21t24_track2NG_d400 is shown in Table 7.4.

Perl scripts were used to extract data from the output files in a form that could be read and analysed by SPSS Inc.'s SPSS for Windows v10.0.5. The scripts are as follows:

- `extract_completion_times.pl` (see Table 7.5 for summary and Appendix G.1)
- `extract_targeting_errors.pl` (see Table 7.6 for summary and Appendix G.2)
- `extract_trace_positions.pl` (see Table 7.7 for summary and Appendix G.3)
- `extract_tracking_errors.pl` (see Table 7.8 for summary and Appendix G.4)
- `summarise_tracking_errors.pl` (see Table 7.9 for summary and Appendix G.5)

These scripts are outlined using pseudo code. Full versions are also in Appendix G.

Additional scripts were written in order to generate plots of user traces using matlab (as shown in Section 9.3.1). These scripts used the data extracted by extract_trace_positions.pl and converted into a form that Matlab could read and plot with track boundaries.

The next chapter documents the design and implementation of the system used to introduce delays into the VR system described here.

```
dVS. Version 3.1. January 1996

Copyright Division Ltd 1992 - 1996. All rights reserved.

dVISE. Version 3.1. January 1996

Copyright Division Ltd 1992 - 1996. All rights reserved.

* Experiment begun at Wed Jan 24 10:57:33 2001


Key:    P = current Position

        O = current Orientation

        T = current Time (s)



P:(0, 0, 0) O:(0, 0, 0) T:0 D:Wed Jan 24 10:57:33 2001

[snip]

P:(0.0587654, -0.321002, -0.254314) O:(-15.1565, -9.89529, 3.3028) T:6.15644 D:W

ed Jan 24 10:57:39 2001


P:(0.0587654, -0.321002, -0.254314) O:(-15.1565, -9.89529, 3.3028) T:6.25637 D:W

ed Jan 24 10:57:39 2001


P:(0.0582777, -0.318528, -0.255552) O:(-14.4648, -9.51411, 3.19124) T:6.35649 D:

Wed Jan 24 10:57:39 2001
```

Table 7.4: Sample output log

```
For     each participant 1 to 40
        Write participant no to results file completion_times
        For         each trial 1 to 30
                    Write trial no to results file completion_times
                    Find time when start line crossed
                    Find time when target hit
                    Write completion time to results file completion_times
        Next        trial
Next    participant
```

Table 7.5: Pseudo Code for extract_completion_times.pl

```
For     each participant 1 to 40
        Write participant no to results file targeting_errors
        For         each trial 1 to 30
                    Write trial no to results file targeting_errors
                    Find position when target hit
                    Compare with centre of target for track
                    Write targeting error to results file targeting_errors
        Next        trial
Next    participant
```

Table 7.6: Pseudo Code for extract_targeting_errors.pl

```
For   each participant 1 to 40
      For       each trial 1 to 30
                Find position for each line between start line and target hit
                Write position to results files
      Next      trial
Next  participant
```

Table 7.7: Pseudo Code for extract_trace_positions.pl

```
For   each participant 1 to 40
      For       each trial 1 to 30
                Find position for each line between start line and target hit
                Compare position to centre line
                Write error to results files
      Next      trial
Next  participant
```

Table 7.8: Pseudo Code for extract_tracking_errors.pl

```
For   each participant 1 to 40
      For       each trial 1 to 30
                Read errors
                Calculate square of each error and add to
                running total for each condition 1 to 30
      Next      trial
Next  participant
Write totals to IS_tracking_errors
```

Table 7.9: Pseudo Code for sumamrise_tracking_errors.pl

Chapter 8

Delay hardware design and implementation

8.1 Delay hardware design

The design and implementation of the delay box was carried out in the Computing and Electrical Engineering department (see Acknowledgements for details).

As has been mentioned in Section 6.2, the delay hardware was designed to delay signals on the two serial lines between the integrated peripherals unit (IPU) and the HP workstation as illustrated in Figure 6.4 (on page 114).

Please note, some of the documentation given below refers to the revised version of the delay hardware (with thumb switches and different increments). However, due to this version not being built in time, the experiments were conducted using an earlier prototype which produced delays of 0-800 ms in 100ms increments. The layout of the prototype delay box can be seen in Figure 8.1 and the modified box (which was not used for the experiments) is shown in Figure 8.2.

8.1.1 Tasks undertaken

1. Analyse serial port communications between HP-UX host computer and Division IPU (integrated peripheral unit) to see what types of signal are received and transmitted.

2. Provide hardware to record, store and playback signals. Incorporate a delay of 0 to 1.35 sec. in 50ms steps and 0 to 2.9s in 100ms steps.

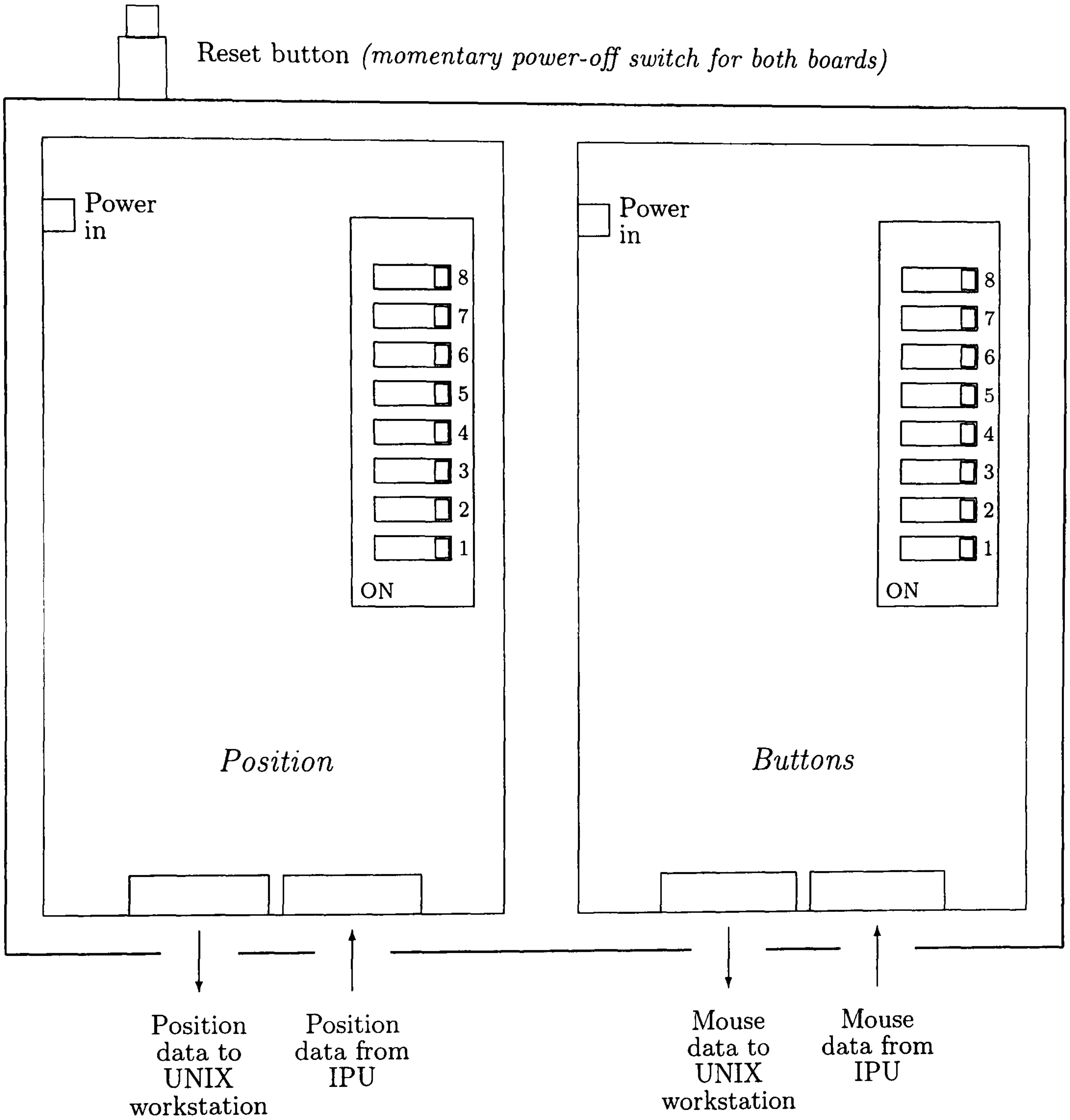


Figure 8.1: Prototype delay hardware layout

3. Signals to be delayed: all mouse clicks and all mouse/headset movements.

8.1.2 Analysis of serial port communications

It was found that the serial signals between the host computer and IPU were in RS232 ASCII code format with an 8-bit data word, no parity bit and 1 stop bit. The system settings file can be found in the file `home/division/etc/input/ipu.inp` and can be seen in Appendix I.2. In the event of a communications lock-out, the system can be shutdown and restarted by logging out, logging in again as '`lroot`', entering the password and typing the command '`shutdown -h now`'. Select '`n`' for no messages when prompted.

The setup starts with the host computer sending a burst of initialisation data to the IPU. A more detailed explanation of the system commands can be found in the POLHEMUS 3-SPACE user manual, which comes with the system. The summary of the burst is as follows:

```
o1152,N,8,0

Sfull,

O1,18,20,1

O2,18,20,1

PPPPPPP......
```

The meaning of this burst is described below.

Line 1 `o`= output port, 115.2 k baud, no parity bit, 8 bit words and no handshake.

Line 2 `S`= Status request required from IPU, `f`=binary format, u=measurement in cm, `l1`=station on.

Line 3 & 4 `O`=output list request from ipu, 1=station no., 18 = x,y,z 16 bit values, 20= q0-q3 quaternion values, 1 = carriage return/linefeed.

Update rate	baud rate	period cycle	burst time	bit time
(10 or 40)	9600	15.6 ms	3.6 ms	104 us

Table 8.1: **Buttons data stream settings**

Line 5 onwards `P` = continuous poll command.

The IPU then replies with the status information as follows:

```
22S3F3  0  102.03factory default cpg2030-003-05
```

This status information has the following meaning: `22`=record type and station no., `S3F3`=Status-continuous off, compensation off, units cm, output binary. `0`=output format ASCII, `102.3`= software issue, factory defaults set and system identification code.

Buttons data stream

This part of the system is the mouse-click section connected from a 25-way IPU SERIAL_MOUSE port at the IPU to a 9-way D-type connection at the host computer. This has a 3-byte data burst. The first byte contains the mouse-buttons data and bytes 2 and 3 contain a fixed output, not affected by movement of the 3D mouse. Pressing the mouse buttons changes the corresponding bit in the first byte. This can be seen with an oscilloscope probing at pin 3 of the SERIAL_MOUSE connector. Pin 2 of this connector is a constant ready signal of 11V dc. Changes to the software does not change the period of this burst, as would be expected. The reason for this is unknown at present. The mouse buttons data burst remains fixed and is not changed with changes to the `ipu.inp` file. Data settings are shown in Table 8.1.

Update rate	baud rate	period cycle	burst time	bit time
10/sec	115.6 kb	100 ms	1.65 ms	8.5 μs
40/sec	115.6 kb	50 ms	1.64 ms	8.5 μs

Table 8.2: Position data stream settings

Position data stream

This is the headset and mouse positional data. This can be seen with an oscilloscope probing at pin 3 of the SERIAL_MOUSE connector. Pin 2 of this connector is a polling command (ASCII 'P') from the 25-way IPU SERIAL port to a 9-way D-type connector at the host computer. Changing the update rate in the configuration file inp.ipu does alter the period of this burst. Data settings are shown in Table 8.2

The headset and mouse positional data are comprised of 2 bursts of data per cycle (1 for the headset,1 for the mouse position). These bursts are made up of 19 bytes of data. Bytes 1,2 and 3 are comprised of a letter O (output data list), the station number (1=headset, 2= mouse) and an error code (ASCII 'space' if no error). Bytes 4 and 5, 6 and 7 and 8 and 9 represent 16-bit Cartesian co-ordinates of position values x, y and z. Bytes 10 and 11, 12 and 13, 14 and 15 and 16 and 17 represent 16-bit binary spatial-orientation quaternion values q0, q1, q2 and q3. Bytes 18 and 19 represent the ASCII characters carriage return and line feed.

8.1.3 Hardware design

A circuit board was designed and made by the Department of Computing and Electrical Engineering. A copy of the circuit diagram can be found in Appendix I.1. Appendix I.3 shows the input pin settings for 50ms resolution. Appendix I.4 shows the input pin settings for 100ms resolution. Appendix I.5 shows the data memory locations used for each setting. Programs labelled `hset.asm` (Appendix I.6) for the headset and mouse positional data and `bttns.asm` (Appendix I.7) for the push-button data were created and compiled using MPLAB and Quickstart Plus for the PIC18C452 microchip. Switch SW3, connected to Portb RB1 (pin 34), selects either 50ms resolution with max. delay time of 1.35 sec. or 100ms resolution with a max. delay time of 2.9 sec. The PIC program looks for an input low on Portb pins RB7-RB2 (pins 40-35). This selects the appropriate delay. Two delay lines were fitted, one in the headset and mouse position communications path and one in the mouse buttons communications path. The setting of thumbwheel switch SW2 multiplied by the resolution switch SW3 gives the actual delay time. The thumbwheel outputs are in BCD format.

8.1.4 Delaying signals

The PIC18C452 microchip has 32k-x8 program RAM, with 1536 bytes of data RAM and a MAX232 line driver/receiver for the delay routine. There is a reset vector at 00h, a high priority interrupt vector at 0008h and a low priority interrupt vector at 0018h. The FSR pointer is used to access the memory storage locations across all banks without the need for the BSR (Bank select Register). This method uses an "access bank" made up of the lower section of bank 0 (00h - 07Fh) and the upper section of bank 15 (F80h-FFFh) to store commonly used values and SFRs respectively.

The program is summarised as follows:

- Set variable addresses and vector addresses.
- Initialise all required registers.
- Check for a delay switch setting.
- If no delay selected, loop data in and straight out of the PIC.

- If a delay is selected then start a routine to receive and send out the first 165 bytes of data, which contains the current status information, from the IPU to the host computer.

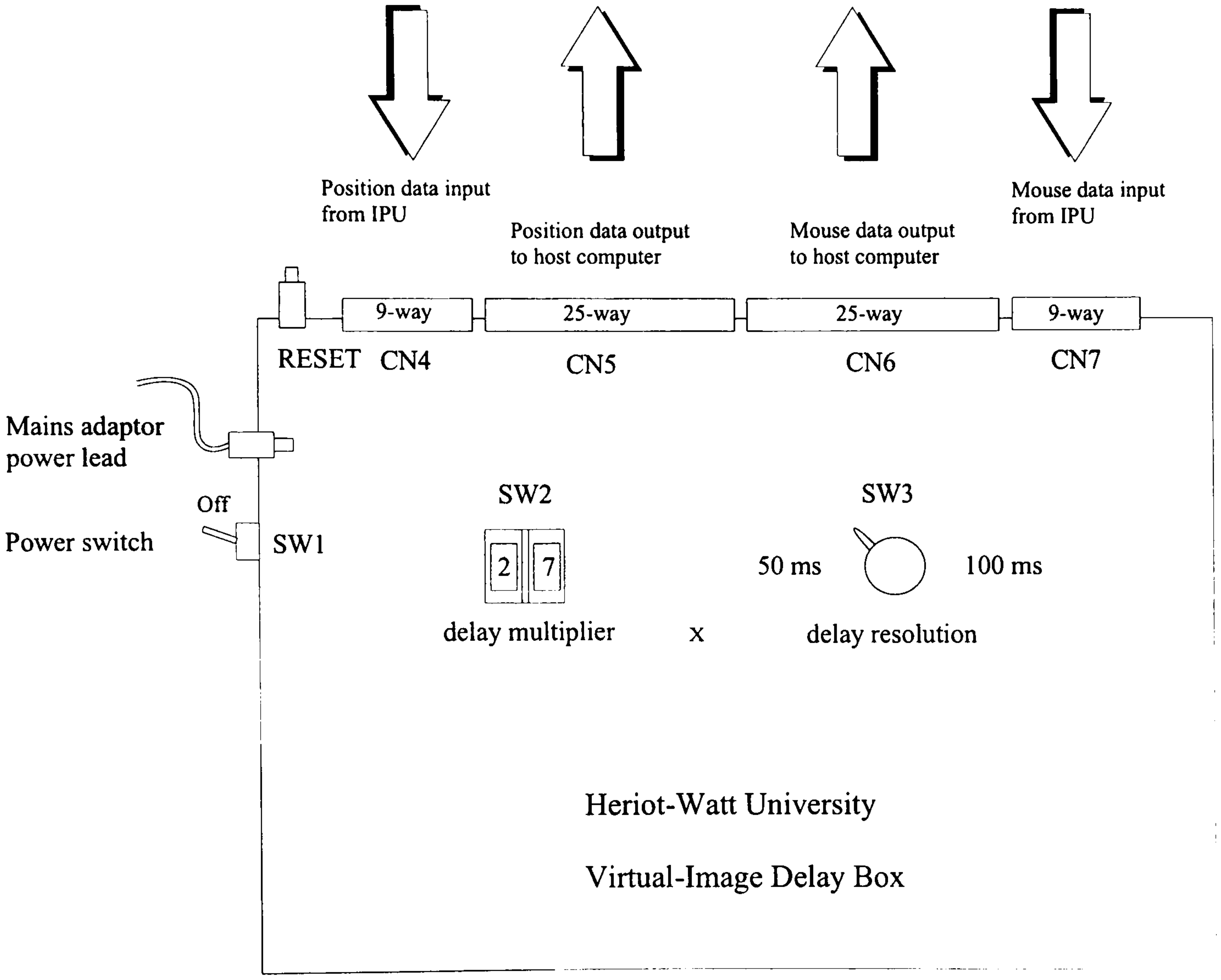
- Check which delay value is called for and call the sub-routines for this. The subroutines will receive a block of data, save it in the register locations, while at the same time sending this data back out to the host computer. The data must continue to be sent out in order for the system not to stall.

- After the required amount of data is stored then the program moves on to the next set of subroutines. These will recall the first block of data and send it to the host computer. The new incoming block of data will then be saved in the now empty memory location. This process will be repeated for remaining blocks (See Appendix I.5).

8.2 Delay hardware implementation

The delay box and onboard software was implemented according to the designs outlined in Section 8.1. As has already been mentioned, due to the final version not being ready in time, the experiments were performed using the prototype version with delays of 0–800ms being added in 100ms increments. The design hardware is shown attached to the VR equipment in Figure 8.3.

Diagram 1. Heriot-Watt University
Virtual-Image Delay Box



PROPOSED LAYOUT FOR PIC 18C452 SYTEM

Figure 8.2: Delay hardware layout

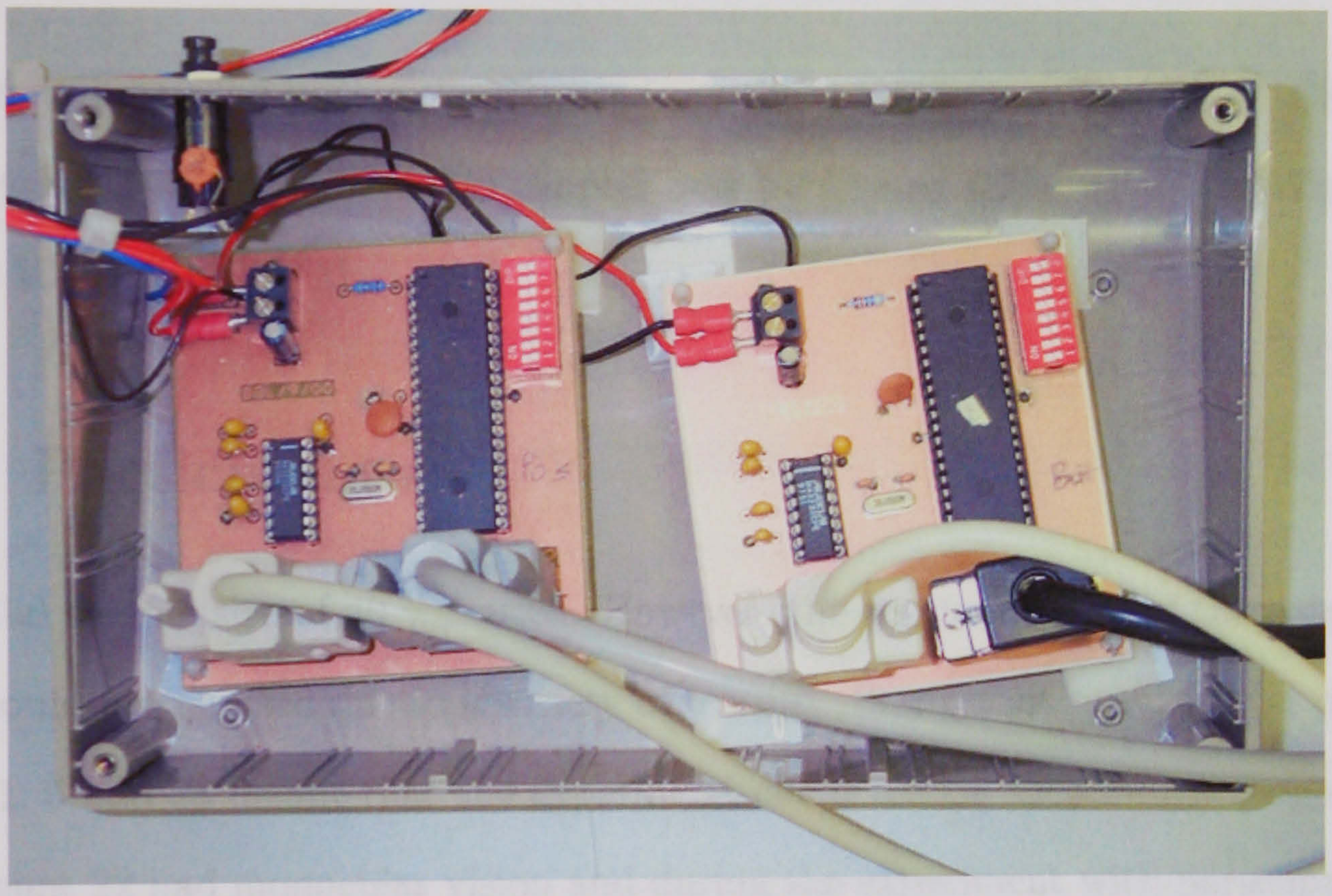


Figure 8.3: Delay hardware

Chapter 9

Experimental Results: Visuo-spatial WM disruption

9.1 Overview

The results presented in this chapter are from the experiments described in Chapter 4. All statistical analysis in this chapter was performed using SPSS for Windows version 10.0.5 (SPSS Inc).

9.2 Participants

An initial sample size of 40 was used. However, the results for five of these participants could not be used due to a variety of reasons. Equipment problems for participants 1, 5 and 28 meant that the experiment could not be successfully completed, participant 22 had monocular vision and during the experiment with participant 34 there was a lot of noise in the laboratory.

This gives rise to a sample size of 35 participants. Of these 35, 27 were male and 8 female. Ages of participants are shown in Table 9.1. Age and gender were not used in analysis as it was thought that these would have little relevance to the results.

34 participants were right-hand dominant and 1 was left-hand dominant. 16 participants had normal vision, with 19 requiring correctional lenses. All participants had normal or corrected-to-normal vision for the experiment. No participant reported any physical disabilities that could affect their ability to control a vehicle.

Age range:	<21	21–30	31–40
Number of participants:	10	22	3

Table 9.1: Participant Age

The majority of participants were students in the Computing and Electrical Engineering department with 13 being undergraduate students and 14 postgraduate students. 2 participants were staff in the Computing and Electrical Engineering department, 2 were postgraduate students in other departments at Heriot-Watt University and 2 were software engineers in industry. The remaining 2 participants were a pharmacist and an administrator.

9.2.1 Graphics Experience

The majority of participants reported a high level of computer usage (recorded on a 5 point rating scale with a rating of 1 being equivalent to '*little*' and 5 meaning '*lots*'). The mean response was 4.5 on the scale with a standard deviation of 0.62.

Most participants reported that they had very little experience of video editing and video production. This data was gathered as it was felt that those participants who were highly experienced at manipulating video may be more able to compensate for disparities in the timeline. However, as all participants had a similar level of experience this was not analysed in detail. The mean response was 1.6 on the scale (where 1 represented '*no experience*' and 5 '*very experienced*') with a standard deviation of 0.76. By contrast, the mean rating for experience with immersive graphics (such as VR or computer games) was 2.5 (using the same scale for experience) with a standard deviation of 1.20.

Experience:	None	< 1 year	1–5 years	6–10 years	> 10 years
No. of participants:	2	8	12	10	3

Table 9.2: Amount of Driving Experience

9.2.2 Driving Experience

Driving experience is summarised in Table 9.2.

24 participants reported that they had never had a driving accident. Of the 11 that had, 3 had an accident less than a year ago, 5 between 1 and 5 years ago, 1 from 6 to 10 years ago and 2 over 10 years ago.

Most participants had slightly positive feelings about driving, with a mean rating of 3.5 (where 1 means '*love it*' and 5 '*hate it*') and a standard deviation of 1.17.

The majority of participants reported little experience of controlling remotely operated vehicles or computer based simulations with a mean rating of 2.0 (where 1 meant '*little*' and 5 '*lots*' of experience) and a standard deviation of 0.98.

9.3 Overall Performance

Please note, the procedure that was followed for these experiments is recorded in Chapter 4, Section 4.6.5 (page 101).

Operator performance was measured by completion times (time taken from start line to hitting target), targeting errors (distance from the centre of target) and integral of squared tracking error (ISE) where tracking error is the distance away from the centre of the track. The success of the letter tracing tasks was also measured with a count being taken of all correct corners for the two letters (giving a total out of 20 with 20 being all corners correct i.e. no errors).

The integral of squared tracking error (ISE) was used as the main measure of error. ISE is commonly used in control systems engineering as a measure of system

	No visual interference			*Visual interference*		
	0 ms	400 ms	800 ms	0 ms	400 ms	800 ms
Mean times (s)	21.08	22.29	25.50	23.43	24.44	25.89
SD times	3.51	3.76	5.58	6.31	6.24	9.11
Mean targ. errs. (m)	0.1522	0.1121	0.1850	0.4197	0.4024	0.7756
SD targ. errs.	0.3695	0.0457	0.3332	0.7559	0.7612	1.1925
Mean ISE	1593.5	1712.0	2021.8	2043.0	2343.4	2738.4
SD ISE	173.8	283.5	500.9	843.7	1694.9	1562.1
Mean letter trace	n/a	n/a	n/a	15.49	15.35	15.01
SD letter trace	n/a	n/a	n/a	2.89	2.70	3.35

Table 9.3: Performance summary

(where targ. errs. = targeting errors, ISE = Integral of Squared tracking Error and SD = Standard Deviation)

performance and was therefore considered as an appropriate indicator of human performance. ISE is defined as $\int \epsilon^2 dt$ where ϵ is tracking error in this case. As the data was recorded at discrete time periods this then becomes $\sum \epsilon^2$.

As one might expect performance decreased (i.e. times and errors increased) for both visual delays and the interpolated visual interference tasks of letter-tracing as summarised in Table 9.3 and Figures 9.1, 9.2, 9.3 and 9.4.

Results showed that visual interference tasks had significant effects on targeting errors ($F = 11.85, p < .005, df = 1, 34$) and ISE tracking errors ($F = 10.96, p < .005, df = 1, 34$). (Analysed using the General Linear Model of SPSS for repeated measures with univariate statistics. The test had three main effects or factors; visual interference (with two levels), delays (with three levels), and track type (five levels) giving 30 interactions in total.) Please see Appendix J for full results of this test. Completion times were not significantly affected by the visual interference tasks.

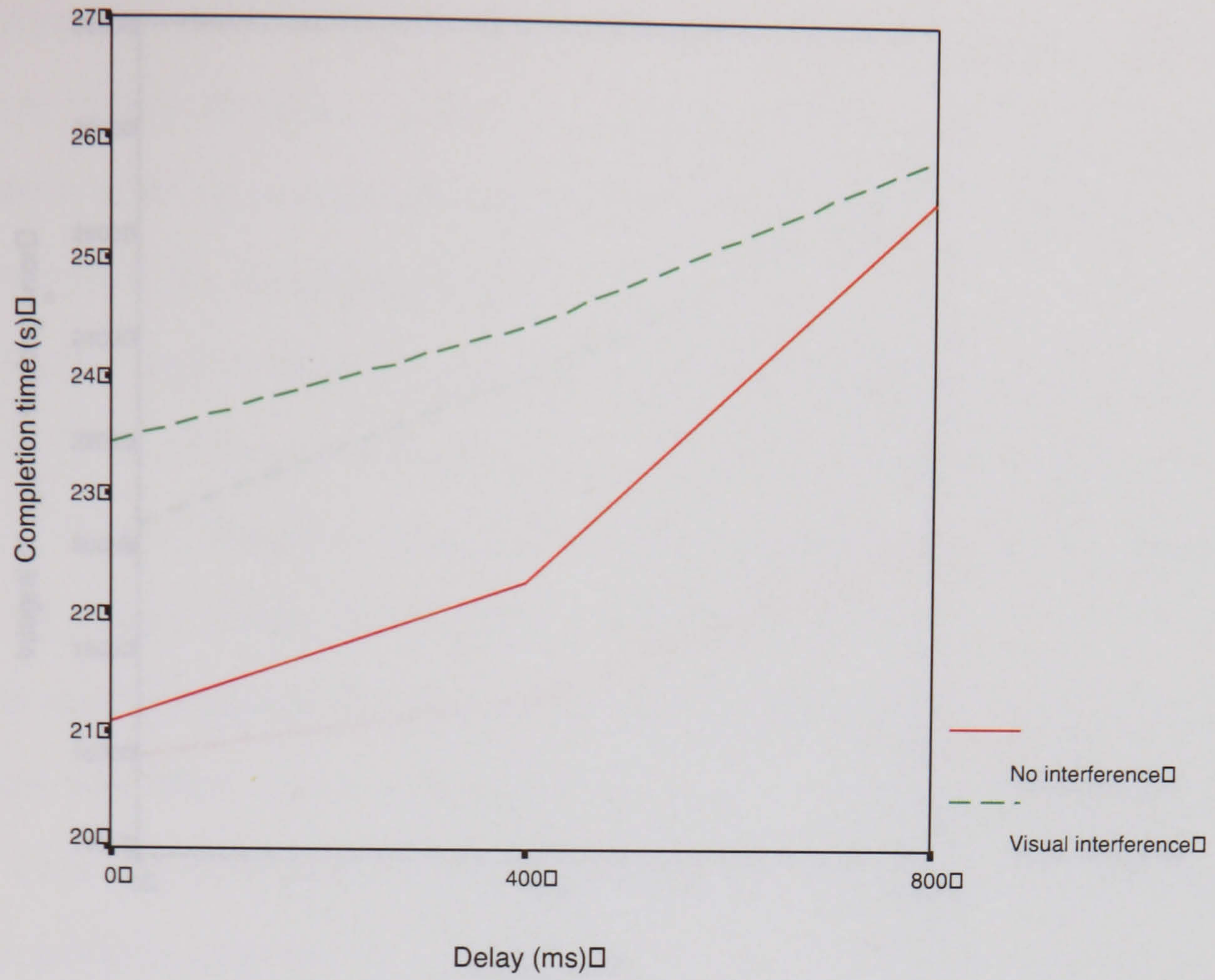


Figure 9.1: Mean completion times

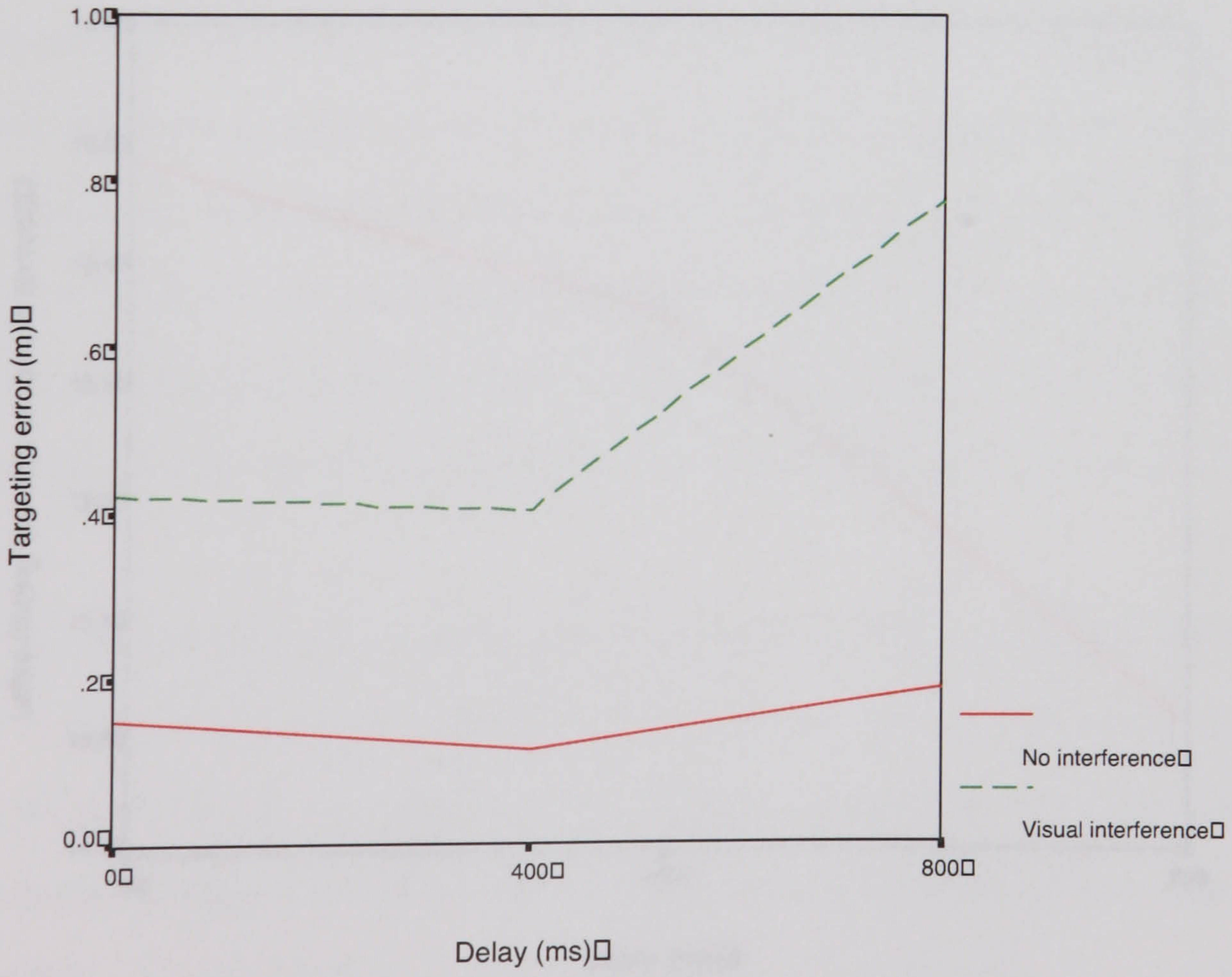


Figure 9.2: Mean targeting errors

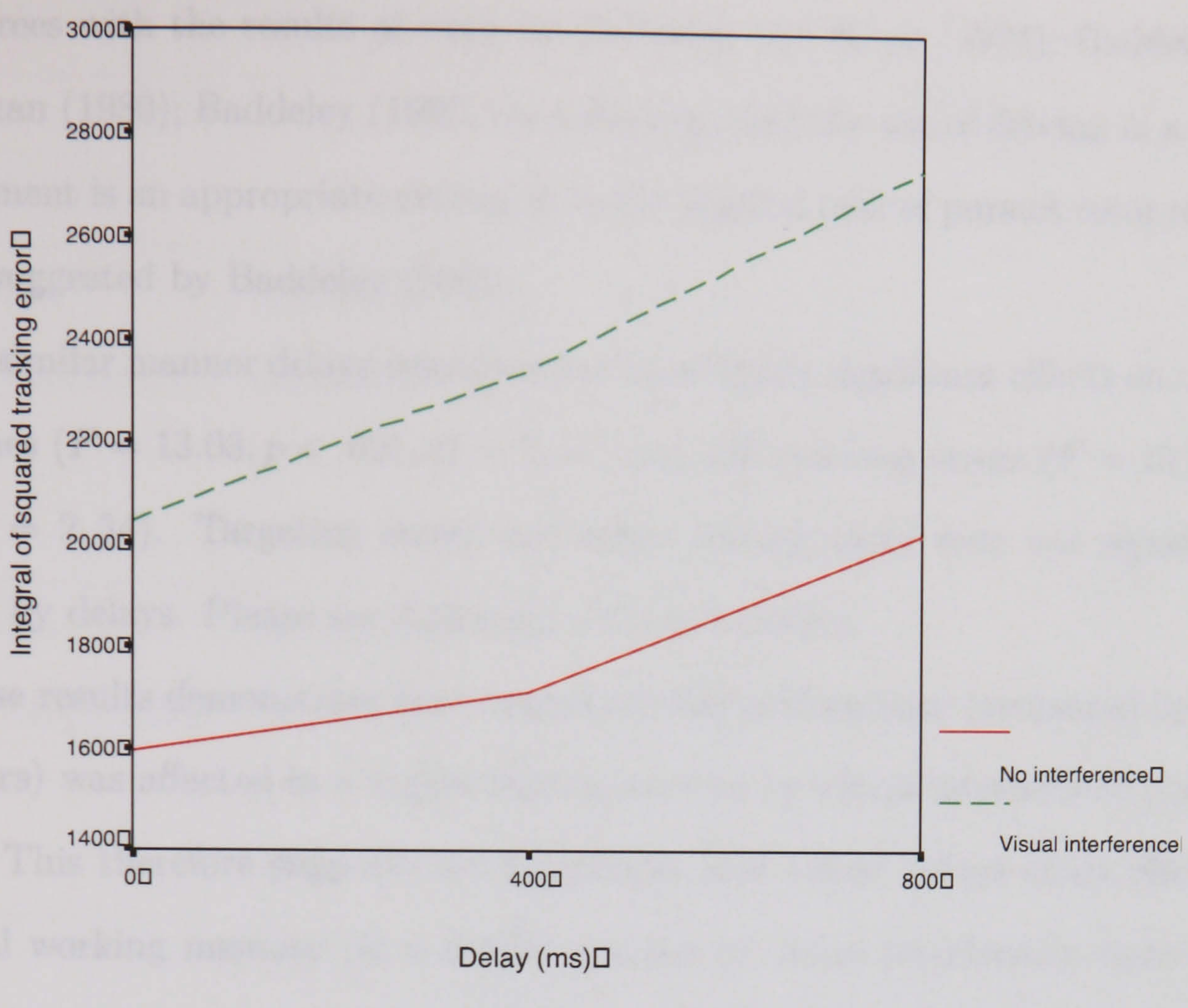


Figure 9.3: Integral of Squared Tracking Errors

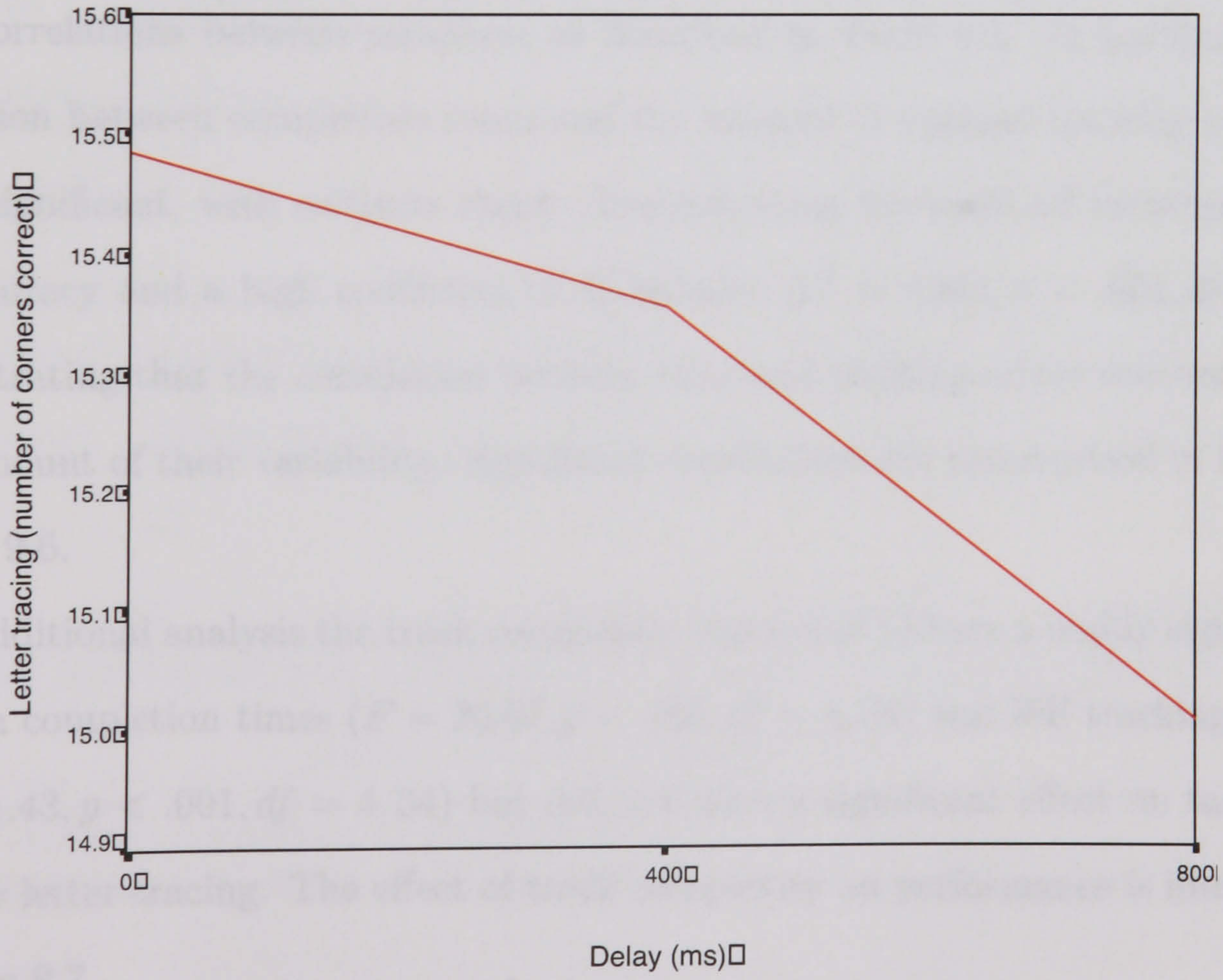


Figure 9.4: Letter Tracing - number of corners correct

This agrees with the results of work by Baddeley and Hitch (1974); Baddeley and Lieberman (1980); Baddeley (1986) thus showing that the use of driving in a virtual environment is an appropriate extension to the original task of pursuit rotor tracking as was suggested by Baddeley (2001).

In a similar manner delays were found to have highly significant effects on completion times ($F = 13.03, p < .001, df = 2, 34$) and ISE tracking errors ($F = 10.25, p < .001, df = 2, 34$). Targeting errors and letter tracing tasks were not significantly affected by delays. Please see Appendix J for full results.

These results demonstrate that overall driving performance (measured by tracking errors) was affected in a highly similar manner by visual interference tasks and delays. This therefore supports the hypothesis that visual delays cause disruption of visual working memory (in a similar manner to visual interference tasks). The results also suggest that people sacrificed speed for accuracy in the presence of visual delays but did not under visual interference. This premise is supported by analysis of correlations between measures as described in Table 9.4. In particular the correlation between completion times and the integral of squared tracking errors is highly significant, with subjects clearly demonstrating the trade-off between speed and accuracy and a high coefficient of correlation ($r^2 = 0.801, p < .001, df = 34$) demonstrating that the correlation between time and tracking errors accounts for a large amount of their variability. Significant correlations are summarised in Figures 9.5 and 9.6.

In additional analysis the track complexity was found to have a highly significant effect on completion times ($F = 26.67, p < .001, df = 4, 34$) and ISE tracking errors ($F = 71.43, p < .001, df = 4, 34$) but did not have a significant effect on targeting errors or letter tracing. The effect of track complexity on performance is illustrated in Figure 9.7.

The interaction between visual interference tasks and delays was not found to

		Targ. err. vs. Time	ISE vs. Time	Letter tracing vs. Time
No interference	Correlation (r)	-0.365[a]	0.895[b]	n/a
	Significance	0.031	0.000	n/a
	df	35	35	35
	r^2	0.133	0.801	n/a
Visual interference	Correlation	0.008	0.638[b]	-0.359[a]
	Significance	0.963	0.000	0.034
	df	35	35	35
	r^2	0.000	0.407	0.129

		ISE vs. Targ. err.	Letter tracing vs. Targ. err.	Letter tracing vs. ISE
No interf.	Correlation (r)	-0.248	n/a	n/a
	Significance	0.150	n/a	n/a
	df	35	35	35
	r^2	0.062	n/a	n/a
Visual interf.	Correlation (r)	0.430[b]	-0.271	-0.581[b]
	Significance	0.010	0.115	0.000
	df	35	35	35
	r^2	0.185	0.073	0.338

All correlations were calculated using 2-tailed, multivariate Pearson's product-moment correlation tests.

---

[a] Correlation is significant at the 0.05 level.

[b] Correlation is significant at the 0.01 level.

Table 9.4: Correlations between measures

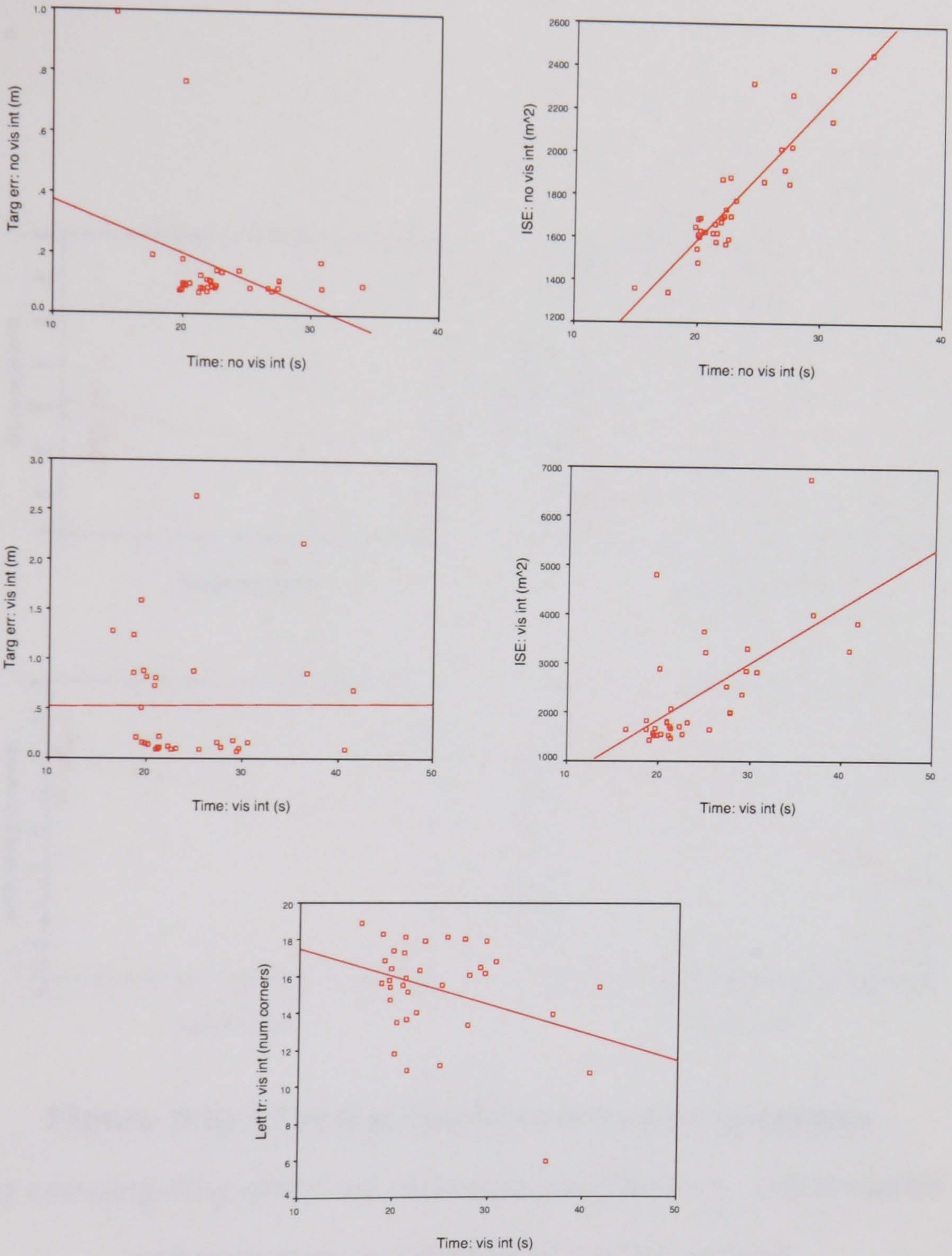


Figure 9.5: Correlations between time and other measures

where targ err=targeting error, vis int=visual interference, lett tr=letter tracing and num corners=number of corners correct.

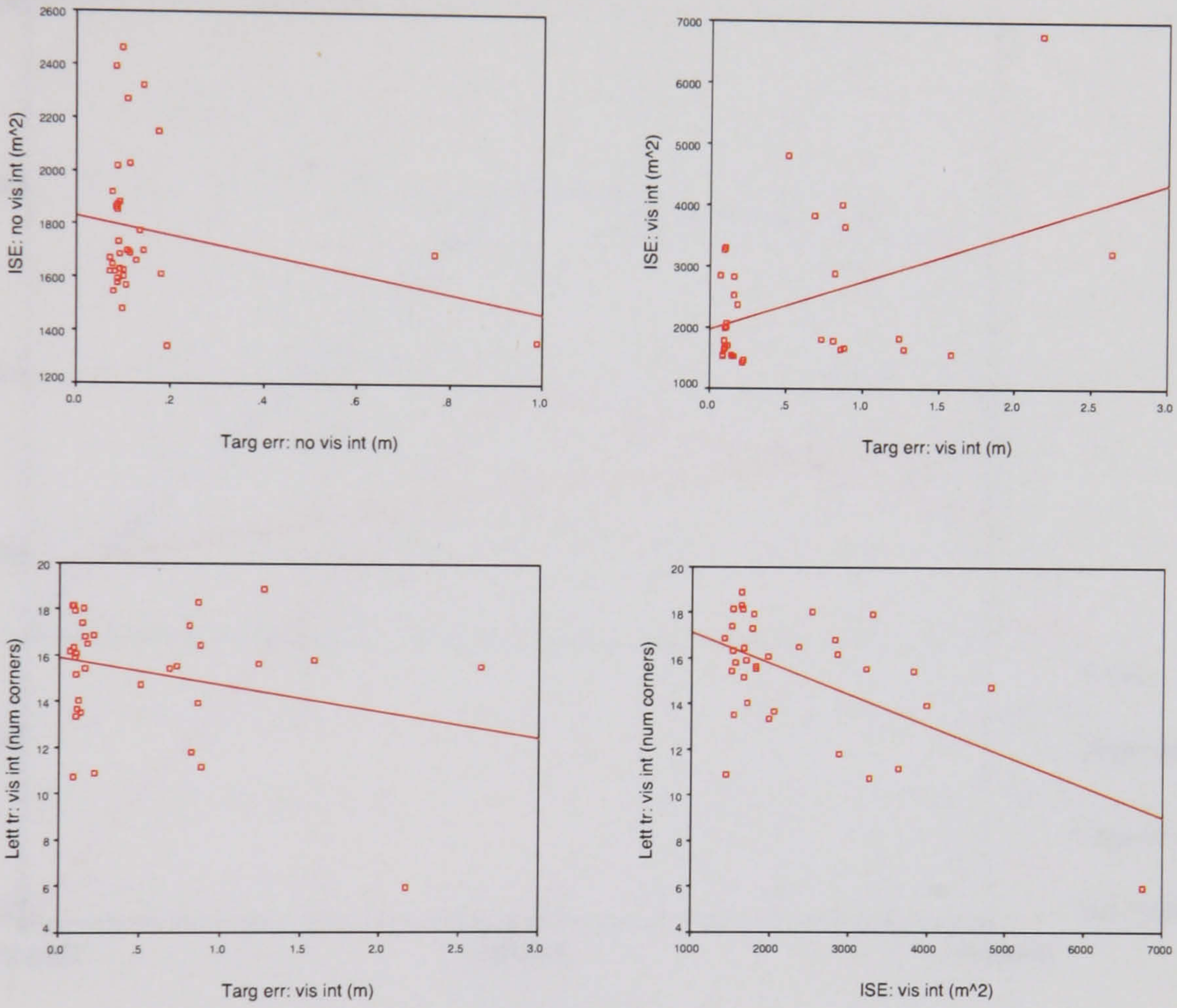


Figure 9.6: Correlations between error measures

where targ err=targeting error, vis int=visual interference, lett tr=letter tracing and num corners=number of corners correct.

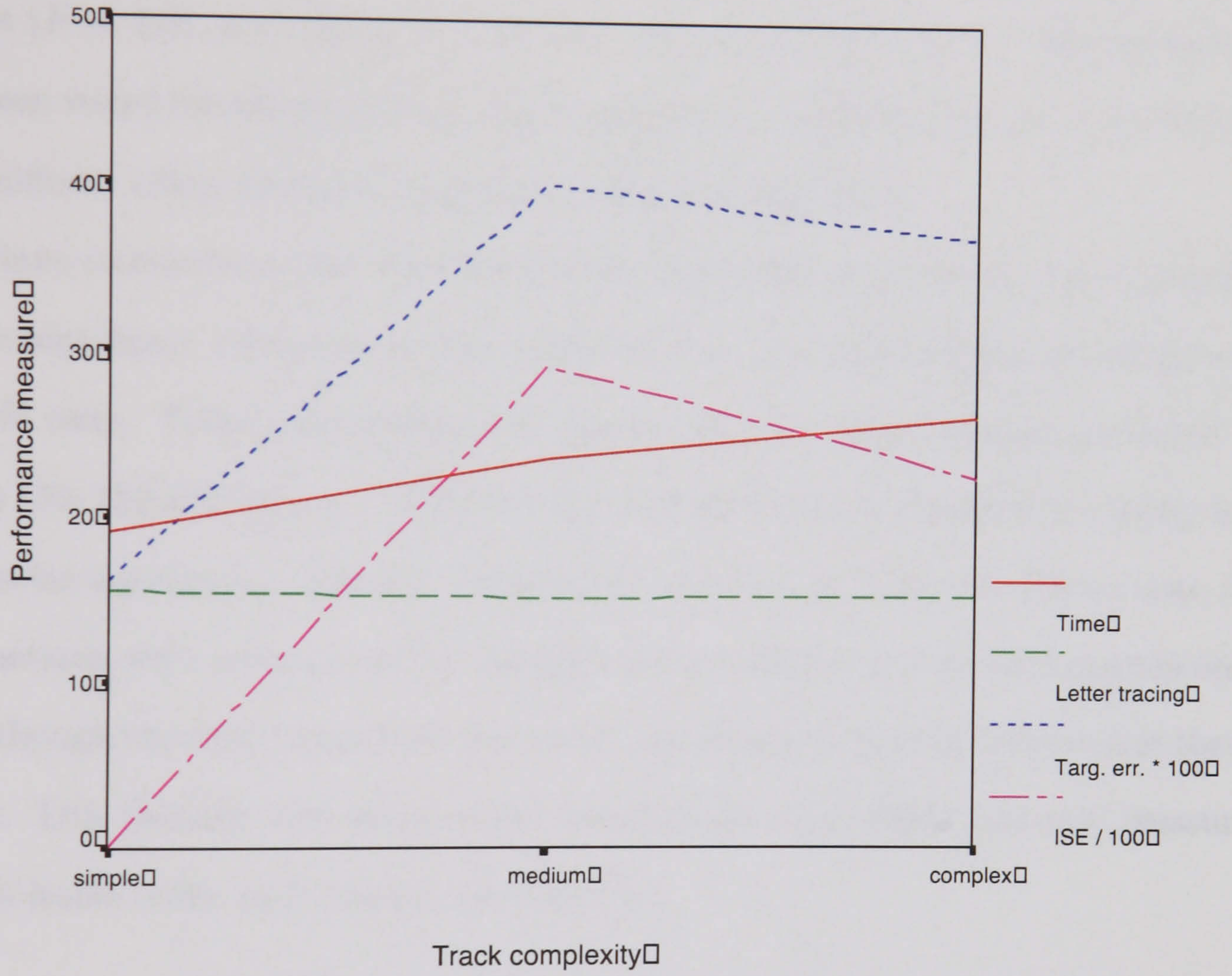


Figure 9.7: Effect of Track Complexity on Performance

(N.B. measures have been scaled to fit on same axes)

have a significant effect on times, targeting or ISE tracking errors. The interaction between visual interference tasks and track complexity did not have a significant effect on times or targeting errors, but did have a significant effect on ISE tracking errors ($F = 5.31, p < .005, df = 4, 34$).

The interaction between delays and track complexity was found to have a significant effect on completion times ($F = 3.49, p < .005, df = 8, 34$) and ISE tracking errors ($F = 2.01, p < .05, df = 8, 34$) but not on targeting errors. The interaction between visual interference tasks, delays and track complexity was not found to have a significant effect on times, targeting or ISE tracking errors.

Those interactions that were found to be significant are illustrated in Figure 9.8. These significant interactions were analysed with post-hoc testing calculated with Scheffé tests. These calculations were performed using the approach presented on pages 150–152 of Edwards (1972) with the formula shown in Equation 9.1 being used to test for significance. Results of these tests are given in Table 9.5. Please note, the interactions were summarised as low-high for all effects for ease of comprehension even though the delay magnitude and track complexity were both measured at threee levels. This decision was taken as the visual interference effect was only measured at two levels (with and without interference).

$$t_{\text{Scheffé}} = \frac{d_i}{s_{d_i}} \quad \text{where} \quad d_i = a_{1i}\bar{X}_1 + a_{2i}\bar{X}_2 + \cdots + a_{ki}\bar{X}_k \qquad (9.1)$$

$$\text{and} \quad s_{d_i} = \sqrt{\frac{s^2}{n}\sum a_{\cdot i}^2}$$

From the post-hoc testing of interactions it can be seen that track complexity interacts significantly with both delay magnitude and the presence of visual interference with respect to ISE errors. Interestingly, this interaction is only significant with low delays or no visual interference and is no longer significant with high levels of delay or interference. From the interaction diagrams shown in Figure 9.8 one might

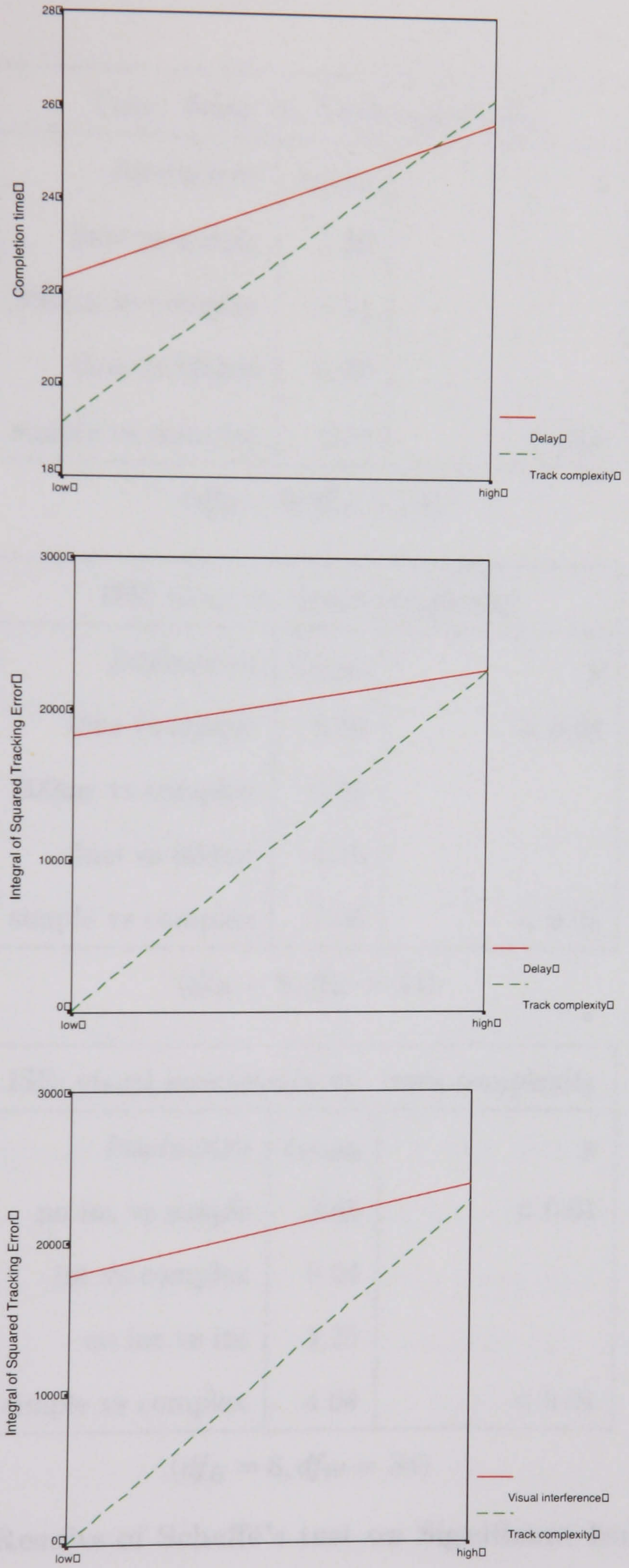


Figure 9.8: Interactions between factors

Time: delay vs. track complexity

Interaction	$t_{\text{Scheffé}}$	p
0ms vs simple	1.80	
800ms vs complex	0.31	
0ms vs 800ms	1.99	
simple vs complex	4.10	< 0.01

$(df_B = 8, df_W = 34)$

ISE: delay vs. track complexity

Interaction	$t_{\text{Scheffé}}$	p
0ms vs simple	5.69	< 0.01
800ms vs complex	0.38	
0ms vs 800ms	1.76	
simple vs complex	7.08	< 0.01

$(df_B = 8, df_W = 34)$

ISE: visual interference vs. track complexity

Interaction	$t_{\text{Scheffé}}$	p
no int vs simple	3.65	< 0.01
int vs complex	0.24	
no int vs int	1.23	
simple vs complex	4.64	< 0.01

$(df_B = 8, df_W = 34)$

Table 9.5: Results of Scheffé's test on Significant Interactions

	low		high	
Time: delay/track	*0ms*	*simple*	*800ms*	*complex*
Variance	17.52	10.06	44.79	44.60
ISE: delay/track	*0ms*	*simple*	*800ms*	*complex*
Variance	213812.41	58.83	811573.66	550784.32
ISE: vis int/track	*no int.*	*simple*	*vis. int.*	*complex*
Variance	213812.41	75091.42	811573.66	1346856.51

Table 9.6: Variance of factors

expect the interaction between delay and track complexity to be significant at low levels due to the distance between the line representing delay and that representing track complexity. However, this distance is almost certainly due to the error being high at this point.

Variance was also calculated for each of the values to give an indication of the effect that each factor had on the measure. These results are summarised in Table 9.6.

It can be seen from Table 9.6 that delays caused a larger variance than track complexity in timings and errors and therefore it can be inferred that delays had a stronger effect on performance than track complexity did. This result is important as it shows that these experiments do indeed demonstrate the effects of delays rather than the effects due to other factors such as track complexity. A comparison of variance due to visual interference and track complexity gave inconclusive results with visual interference having more effect at low levels (no visual interference vs. simple tracks), and track complexity resulting in a large variance in ISE errors at high levels (visual interference vs. complex tracks).

9.3.1 User Traces

These can be seen in Figure 9.9 for experimental conditions 0–14 (without visual interference) and Figure 9.10 for conditions 15–29 (with visual interference tasks). Please see Table 7.1 (page 132) for details of what each condition represents.

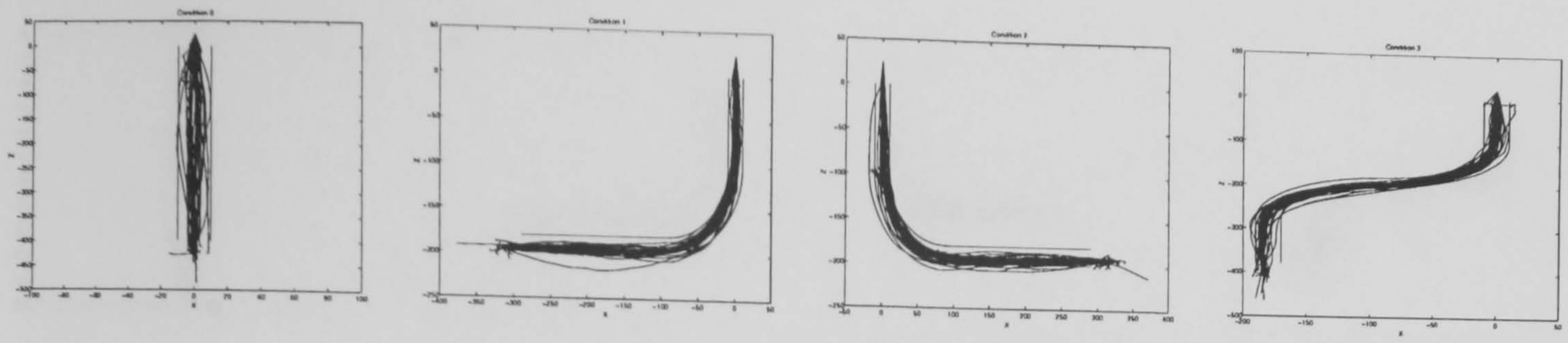
9.4 Subjective measures of effects

On completion of the experiments participants completed a questionnaire giving their judgement of what happened during the experiment. From the answers to the questionnaires the following points can be made.

Most participants thought that the delays had affected their ability to control the vehicle. The mean response was 3.8 on the scale (where 1 represented '*little effect*' and 5 '*lots*') with a standard deviation of 0.89. In a similar manner, most participants also thought that the delays had affected their enjoyment of the driving task, although this was less marked than delays affecting ability. The mean response was 3.3 with a standard deviation of 1.10 using the same scale.

In order to ascertain whether the results were distorted by equipment difficulties participants were asked to give their opinion of how easy the controls were to use. The 3D mouse (used for moving forward and back) was found to be easy to use with a mean response of 4.0 and a standard deviation of 0.76 (where 1 represented '*very difficult*' and 5 '*very easy*'). The immersive headset (used for display and steering to the left and right) invoked a less clear opinion with some finding it easy, and some finding it rather difficult to use. The mean response was 3.1 with a standard deviation of 0.88 on the same scale.

Participants gave four ratings on whether the system was frustrating, confusing, tiring and difficult. The system was considered with and without delays, and with and without visual interference tasks. Mean responses are given in Table 9.7.

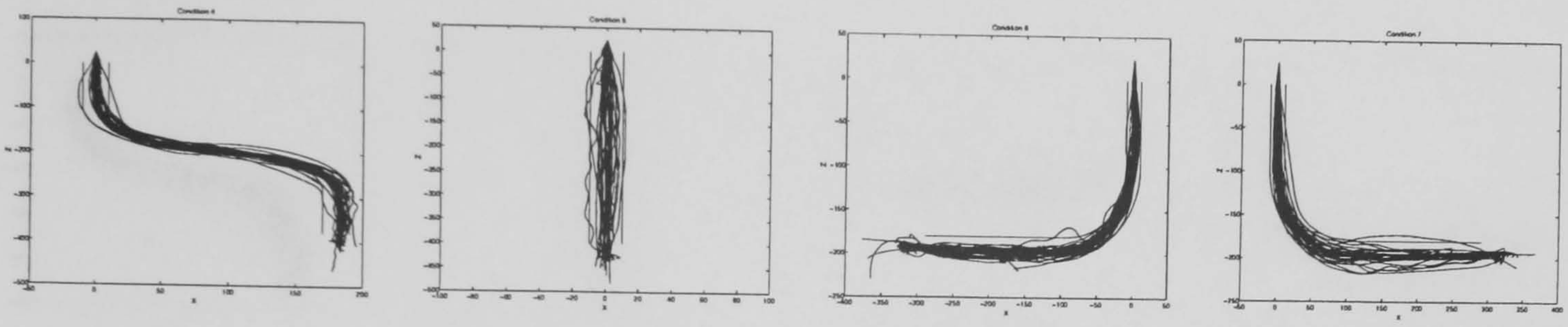


(0) no interference, delay 0, track 1

(1) no int, delay 0, track 2

(2) no int, delay 0, track 3

(3) no int, delay 0, track 4

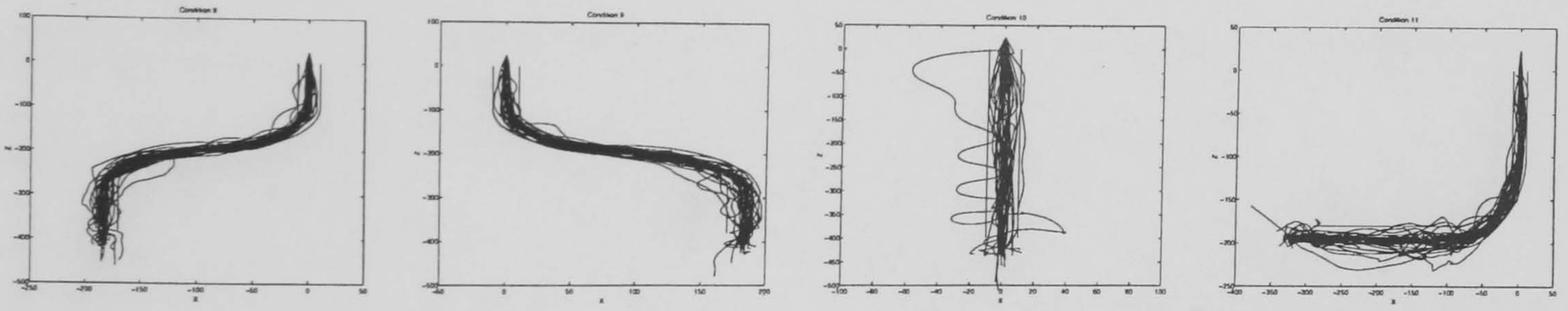


(4) no int, delay 0, track 5

(5) no int, delay 400, track 1

(6) no int, delay 400, track 2

(7) no int, delay 400, track 3

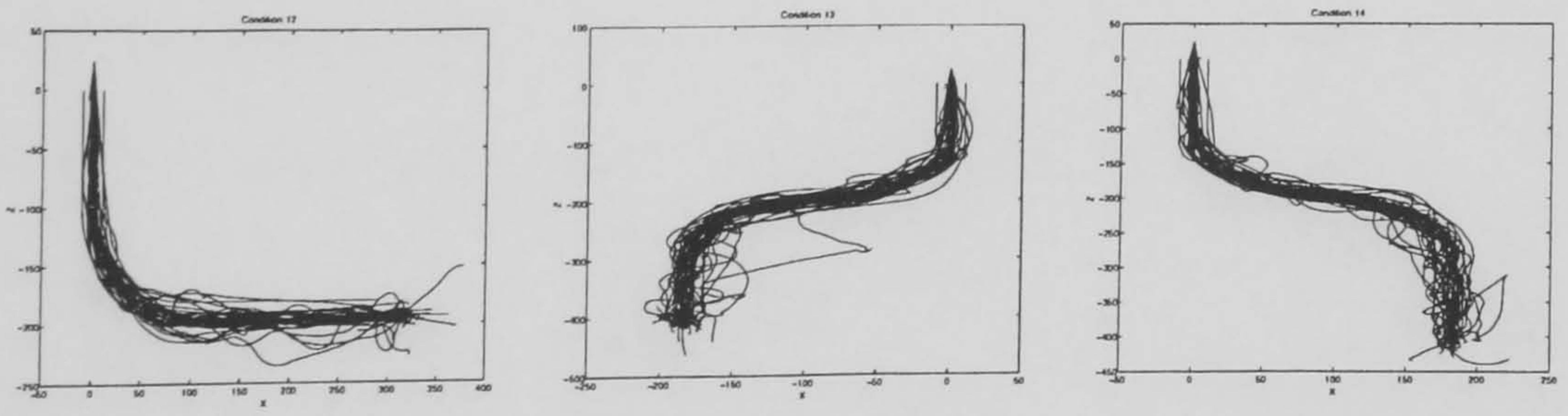


(8) no int, delay 400, track 4

(9) no int, delay 400, track 5

(10) no int, delay 800, track 1

(11) no int, delay 800, track 2

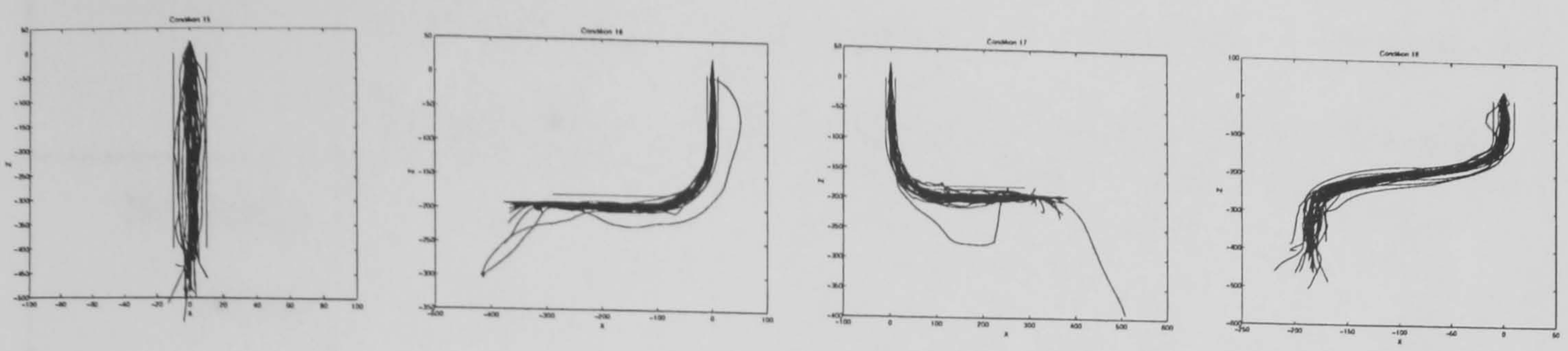


(12) no int, delay 800, track 3

(13) no int, delay 800, track 4

(14) no int, delay 800, track 5

Figure 9.9: User Traces - No Visual Interference

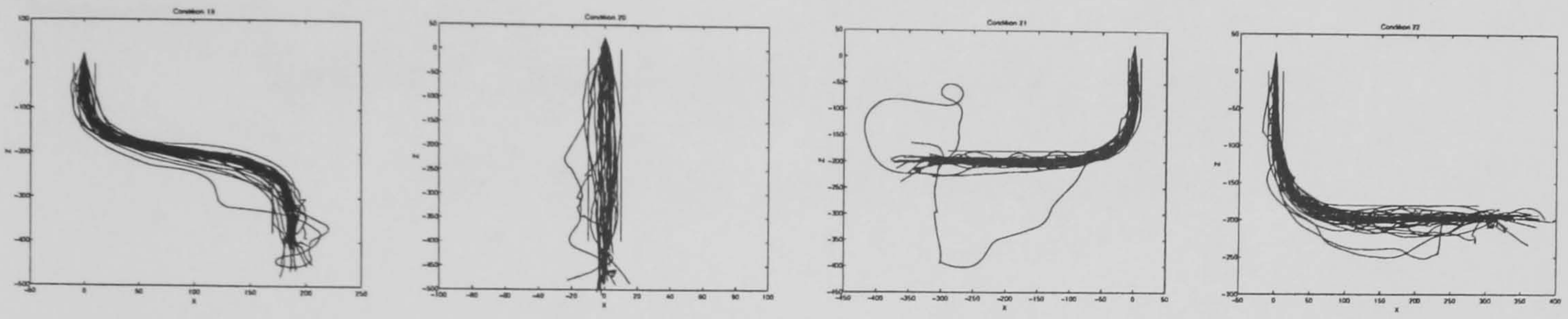


(15) Interference, delay 0, track 1

(16) Int, delay 0, track 2

(17) Int, delay 0, track 3

(18) Int, delay 0, track 4

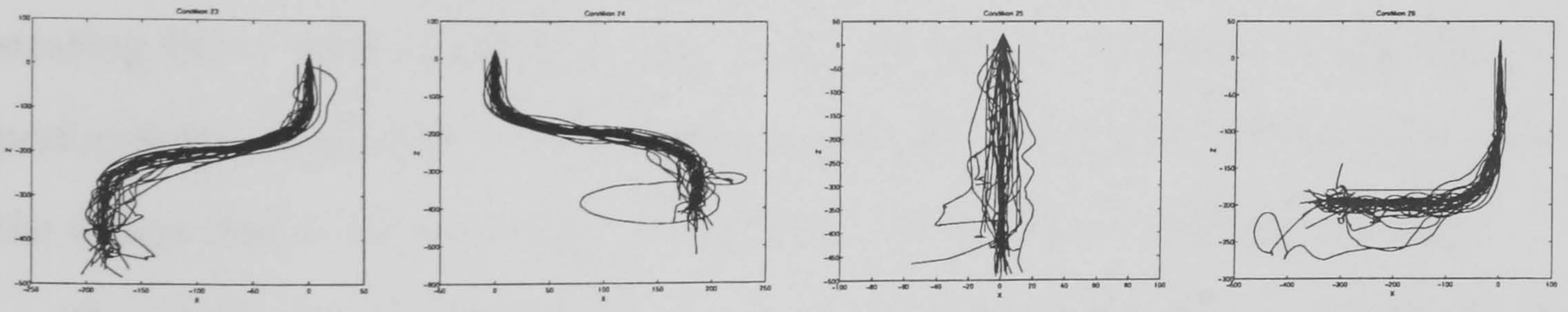


(19) Int, delay 0, track 5

(20) Int, delay 400, track 1

(21) Int, delay 400, track 2

(22) Int, delay 400, track 3

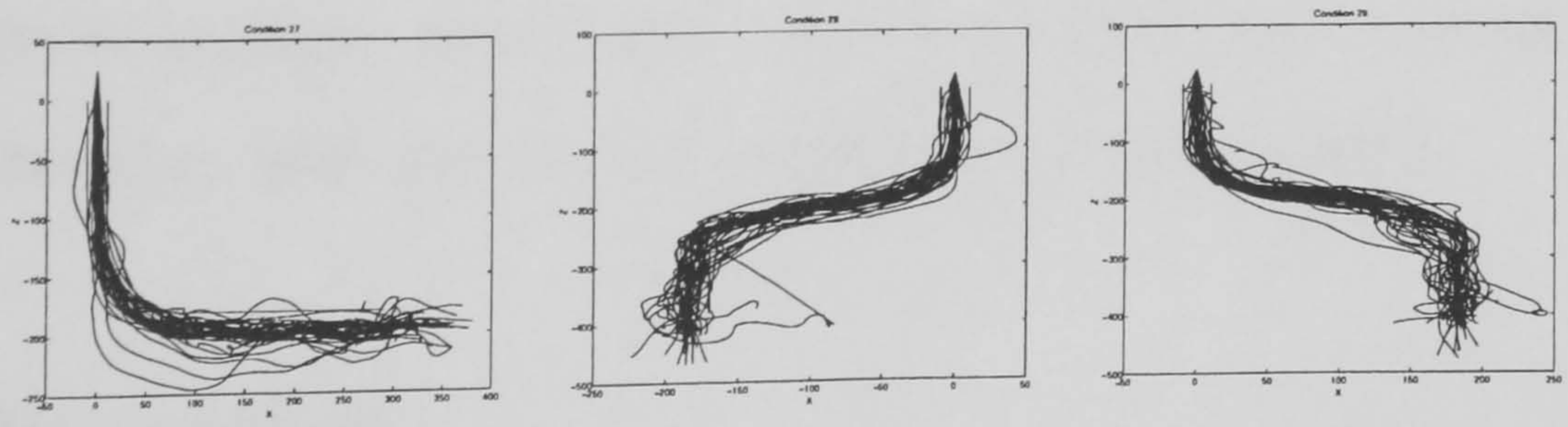


(23) Int, delay 400, track 4

(24) Int, delay 400, track 5

(25) Int, delay 800, track 1

(26) Int, delay 800, track 2



(27) Int, delay 800, track 3

(28) Int, delay 800, track 4

(29) Int, delay 800, track 5

Figure 9.10: User Traces - Visual Interference

	1=*frustrating*, 5=*satisfying*	1=*confusing*, 5=*not confusing*	1=*tiring*, 5=*not tiring*	1=*difficult* 5=*easy*
No delays	3.8	4.3	3.4	3.7
Delays	2.5	2.7	2.6	2.3
No visual int.	4.1	4.4	3.8	4.0
Visual int.	2.4	2.2	2.3	1.7

Table 9.7: Overall impressions (mean responses)

(*N.B. visual int. = visual interference*)

Various categories were ranked in order to ascertain what, in the participant's opinion, had a strong effect on their ability to control the vehicle. The ranked categories (averaged across all participants) are given in Table 9.8 clearly demonstrating that visual interference and delays were found to have a strong effect on performance. It should be noted that participants sometimes did not even notice the delays due to the extremely strong effects of the visual interference tasks.

23 participants expressed a desire for less delay in the display, even if that meant reducing the size, resolution or complexity of it, while the remaining 12 participants did not prefer this.

As might be expected, delays were noticed more when maneouvering (29 participants) rather than while driving in a straight line (6 participants).

9.5 Discussion

This experiment, although yielding significant results, had a number of limitations associated with it. In particular, the limited number of delay settings that were considered (0, 400 and 800 ms) meant that the hypothesis concerning the presence

Overall ranking	Category	Mean rank	SD
1	Letter tracing tasks	2.6	2.4
2	Delay in display	2.7	2.3
3	Frame rate of display	3.9	2.6
4	Difficulties in using the VR equipment	4.7	2.8
5	Angle of view	4.8	2.6
6	Resolution of display	5.1	2.7
7	Realism of simulation	5.3	2.8
8	Size of display	6.1	2.6
9	Colour of objects in simulation	6.6	2.4

Table 9.8: Influence of categories on vehicle control

(N.B. 1=very important, 9=not important)

of a minimum and maximum threshold delay magnitude could not be tested. In addition, the interface used for controlling the vehicle involved steering with head movements (controlling the heading of the vehicle) and controlling velocity with mouse button presses. This interface is not completely natural and it would therefore be useful to compare this method with a more conventional interface such as a joystick.

However, even with these limitations, the experiment yielded many useful and interesting results. As was described in Section 9.3, an increase in delay magnitude was found to have a significant effect on driving performance (measured by times and tracking errors). For this reason the null hypothesis H00 was rejected and the alternate hypothesis H11 accepted, i.e. an increase in delay magnitude does have an effect on driving performance. This replicates the findings of the work previously outlined in Chapters 2 and 3.

These results did not show significant evidence of threshold values exisiting, mainly due to the limited number of cases investigated as previously discussed, with only three delay settings being used. For this reason the alternate hypotheses H12 and H13 could not be conclusively accepted.

Track complexity had a significant effect on performance (measured by times and tracking errors) thus the null hypothesis H03 was rejected and H16 accepted. In particular, from the post-hoc testing of interactions, track complexity was found to interact significantly with both delay magnitude and the presence of visual interference with respect to ISE errors. Interestingly, this interaction is only significant with low delays or no visual interference and is no longer significant with high levels of delay or interference. It is suggested that this is due to performance being severely degraded at high levels of delay and interference therefore the interaction between these and track complexity is no longer observed. Future work should therefore be carried out in studying at what point between 0 and 800ms performance is degraded to the extent of masking the effect of the interaction between track complexity and the other independent variables (delay magnitude and visual interference).

From the interaction diagrams shown in Figure 9.8 (page 162) one might expect the interaction between delay and track complexity to be significant at low levels due to the distance between the line representing delay and that representing track complexity. However, this distance is almost certainly due to the error being high at this point.

From the analysis of variance within the results the trade-off between speed and accuracy can clearly be seen, with some participants sacrificing accuracy for an increase in speed. This behaviour is often seen in experimental work and therefore to be expected in such a control task.

Visual interference tasks had a significant effect on driving performance (measured by targeting and tracking errors). As a result of this the null hypothesis H01 was rejected and the alternate hypothesis H14 accepted. In addition, the visual interference tasks and delays had a similar effect on performance thus H02 was rejected and H15 accepted. Delays in visual feedback were therefore found have a similar effect on performance as visual interference, thus supporting the claim that both cause confusion due to disruptions in visuo-spatial working memory.

In fact, many of the participants commented that the tasks that had both visual interference and delays were extremely difficult and a significant number admitted to adopting the strategy of ignoring the letter tracing task in order to be able to cope with the driving task. This subjective result further strengthens the argument that delays and visual interference affect the same cognitive mechanisms; namely visuo-spatial working memory.

However, it was recognised that this argument may be flawed, for example, if the whole premise of working memory being used for visuo-spatial tasks was inaccurate and some other cognitive mechanism was involved, then both delays and interference could cause similar performance decrements as was seen, but not because they disrupted working memory. In addition it was recognised that the effects of visual delays may be to increase working memory load (i.e. place more load on the central executive) rather than to specically disrupt visuo-spatial working memory. For this reason, it was decided to extend the experiments outlined in this chapter to consider central executive disruption, as described in the following chapter (Chapter 10.

It was also decided to construct a simulation (a control system model was used) that uses mechanisms that resemble working memory and see if that simulation shows similar effects with performance being adversely affected by both delays and visual interference tasks. If visuo-spatial working memory is indeed being disrupted by delays and visual interference then this simulation should exhibit similar behaviour as it will also use this mechanism. The modelling work and results of using the model are described in detail in the Chapter 11.

Chapter 10

Experimental Results - Central Executive Disruption

10.1 Overview

The results presented in this chapter are from the experiments described in Chapter 5. All statistical analysis in this chapter was performed using SPSS for Windows version 11.0.1 (SPSS Inc).

10.2 Participants

An initial sample size of 31 was used. However, the results for one of these participants could not be used due to equipment problems. This gives rise to a sample size of 30 participants. Of these 30, 22 were male and 8 female. Ages of participants are shown in Table 10.1. Age and gender were not used in analysis as it was thought that these would have little relevance to the results.

27 participants were right-hand dominant and 3 were left-hand dominant. 18 participants had normal vision, with 12 requiring correctional lenses. All participants had normal or corrected-to-normal vision for the experiment. No participant

Age range:	<21	21–30	31–40	41–50
Number of participants:	4	21	4	1

Table 10.1: Participant Age

Experience:	None	< 1 year	1–5 years	6–10 years	> 10 years
No. of participants:	0	6	14	5	5

Table 10.2: Amount of Driving Experience

reported any physical disabilities that could affect their ability to control a vehicle.

All participants were students or staff from the School of Mathematical and Computer Sciences at Heriot-Watt University. 13 participants were undergraduate students, 14 were postgraduate students and 3 were research staff.

10.2.1 Graphics Experience

The majority of participants reported a high level of computer usage (recorded on a 5 point rating scale with a rating of 1 being equivalent to '*little*' and 5 meaning '*lots*'). The mean response was 4.5 on the scale with a standard deviation of 0.66.

Most participants reported that they had very little experience of video editing and video production. This data was gathered as it was felt that those participants who were highly experienced at manipulating video may be more able to compensate for disparities in the timeline. However, as all participants had a similar level of experience this was not analysed in detail. The mean response was 1.8 on the scale (where 1 represented '*no experience*' and 5 '*very experienced*') with a standard deviation of 0.92. By contrast, the mean rating for experience with immersive graphics (such as VR or computer games) was 2.8 (using the same scale for experience) with a standard deviation of 1.08.

10.2.2 Driving Experience

Driving experience is summarised in Table 10.2.

19 participants reported that they had never had a driving accident. Of the 11

that had, 1 had an accident less than a year ago, 7 between 1 and 5 years ago and 3 from 6 to 10 years ago.

Most participants had slightly positive feelings about driving, with a mean rating of 3.9 (where 1 means '*love it*' and 5 '*hate it*') and a standard deviation of 0.62.

The majority of participants reported little experience of controlling remotely operated vehicles or computer based simulations with a mean rating of 2.1 (where 1 meant '*little*' and 5 '*lots*' of experience) and a standard deviation of 0.94.

10.3 Overall Performance

Please note, the procedure that was followed for these experiments is recorded in Chapter 5, Section 5.3.4 (page 107).

Operator performance was recorded with the same measures as the previous experiment; namely completion times, targeting errors and integral of squared tracking error (ISE). The success of the random number generation tasks was also measured with an indication of whether any tasks were failed (i.e. no valid number given) and in the case of valid numbers, analysis of how well the responses match a normal random distribution.

As one might expect performance decreased (i.e. times and errors increased) for the interpolated central executive interference tasks of random number generation as summarised in Table 10.3 and Figure 10.1.

The performance of the random number generation task is summarised in Table 10.4.

Results showed that central executive disruption tasks (of random number generation) had no significant effect on completion times, targeting errors or ISE tracking errors. (Analysed using the General Linear Model of SPSS for repeated measures with univariate statistics.) Please see Appendix K for full results of this

	No interference	*Interference*
Mean times (s)	16.79	16.90
SD times	1.53	1.29
Mean targeting errors (m)	0.169	0.176
SD targeting errors	0.328	0.312
Mean ISE	1312.85	1421.81
SD ISE	123.18	544.20

Table 10.3: Performance summary

(where ISE = Integral of Squared tracking Error, SD = Standard Deviation)

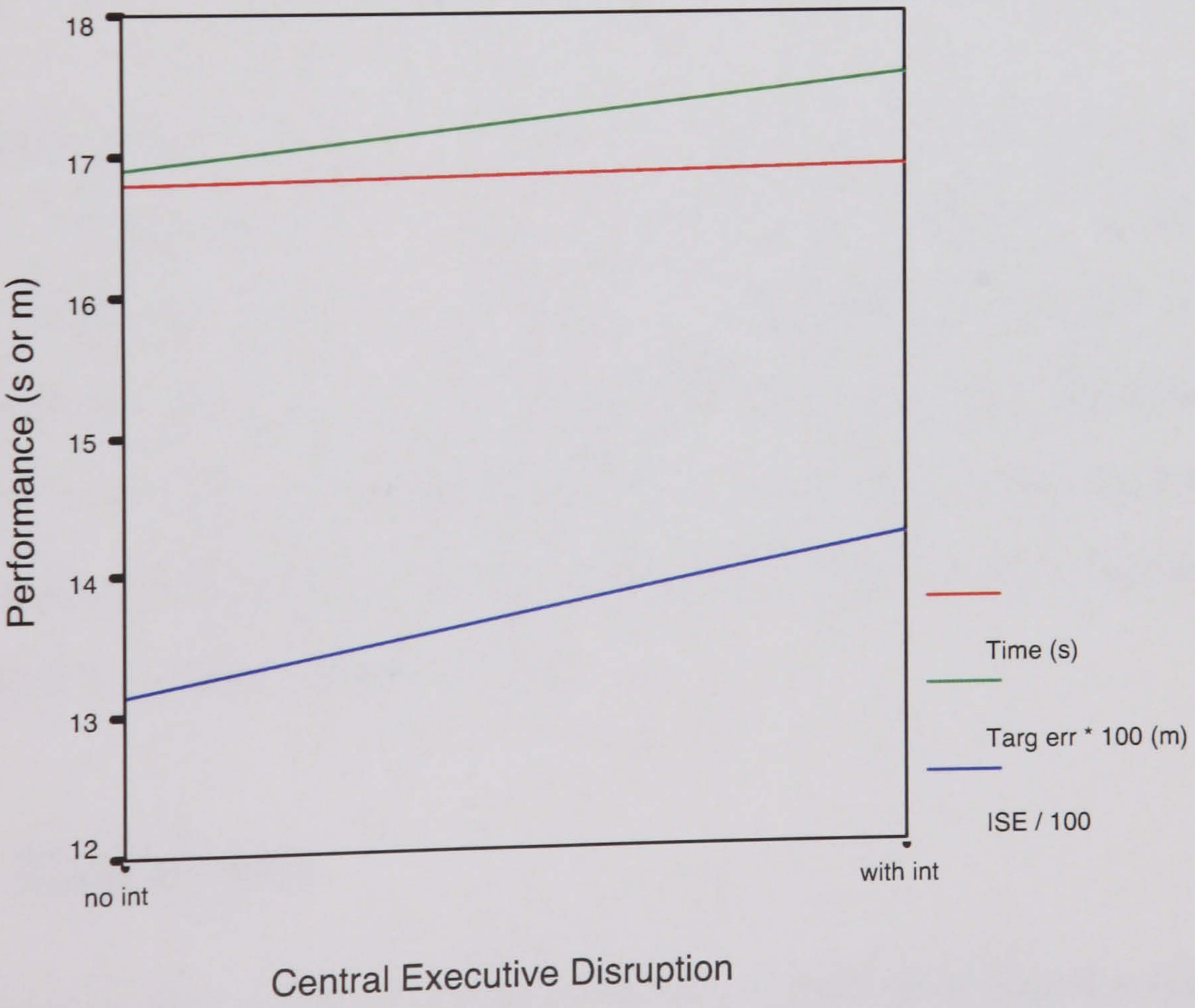


Figure 10.1: Performance summary

Number	*Mean*	*SD*
1	5	2
2	5	2
3	5	1
4	4	2
5	4	2
6	4	2
7	5	1
8	4	2
9	4	2
10	3	2
Missed prompt	1	1

Table 10.4: Random number generation performance summary

test. However, track complexity did have a highly signifant effect on completion times ($F = 51.78, p < .001, df = 2, 30$) and ISE tracking errors ($F = 205.17, p < .001, df = 2, 30$). In additional analysis, track complexity was found to have a highly significant effect on the performance of random number generation tasks ($F = 746.88, p < .001, df = 2, 30$). Performance of the random number generation task was measured as a ratio of numbers said by total number of prompts. Please see Appendix K.1 for full results of this test.

10.4 Discussion

This experiment demonstrated that the presence of tasks that placed a demand on central executive resources (i.e. random number generation tasks) did not have any significant effect on performance. For this reason null hypothesis H01 could not be rejected, i.e. the presence of random number generation tasks has no significant effect on driving performance. In addition, because this lack of effect on performance was in such marked contrast to the highly significant effects elicited by visual interference and visual delays, the null hypothesis H02 could also not be rejected, i.e. the presence of random number generation tasks has a negligible effect on driving performance when compared with the letter tracing tasks.

This finding also supports alternate hypothesis H15 in the previous experiment, namely that delays in visual feedback cause disruption in visuo-spatial workng memory. This result supports the assumption that visual delays cause specific disruption to visuo-spatial working memory rather than placing a general load on working memory resources (i.e. disruption of the central executive). In particular it demonstrates that a task that disrupts visuo-spatial working memory (such as letter tracing) produces a similar performance decrement as visual delays do, whereas a general central executive task (such as random number generation) has no such effect on performance.

Further investigation regarding the cognitive nature of the effects of delayed visual feedback made use of a simple computational model that was analagous to working memory. These investigations are described in the following chapter (Chapter 11).

Chapter 11

Control System Model

11.1 Introduction

As was discussed in Chapter 1 the model proposed in this chapter began as a means of simulating and predicting the behaviour of the experimental system involved in investigating delayed visual feedback. This model is shown by means of a brief schematic diagram in Figure 11.1 and more fully in Figure 11.2.

This model attempts to quantify the control actions associated with the driver of a vehicle. This driver (or operator) is within the vehicle control loop. It is proposed that the operator closes the feedback loop through the visual assessment of the position and velocity of the vehicle within the confines of the required trajectory of the vehicle.

Two fundamental characteristics of the operator are modelled. Firstly, a pure delay due to the need to assess the situation with respect to maintaining the vehicle on track, whilst simultaneously undertaking a secondary cognitive task (i.e. the visuo-spatial task). This is referred to as the *Reasoning Delay* and is a function of the complexity and duration of the secondary cognitive task. Then secondly, the driver reaction time which is modelled as an exponential lag. This varies with the skill of the operator.

The modelling work was carried out in order to understand better what cognitive mechanisms fail with delayed visual feedback, in particular, to investigate the hypothesis that visual delays cause working memory disruptions. In addition to testing this hypothesis, it was expected that the model could be used to make predictions

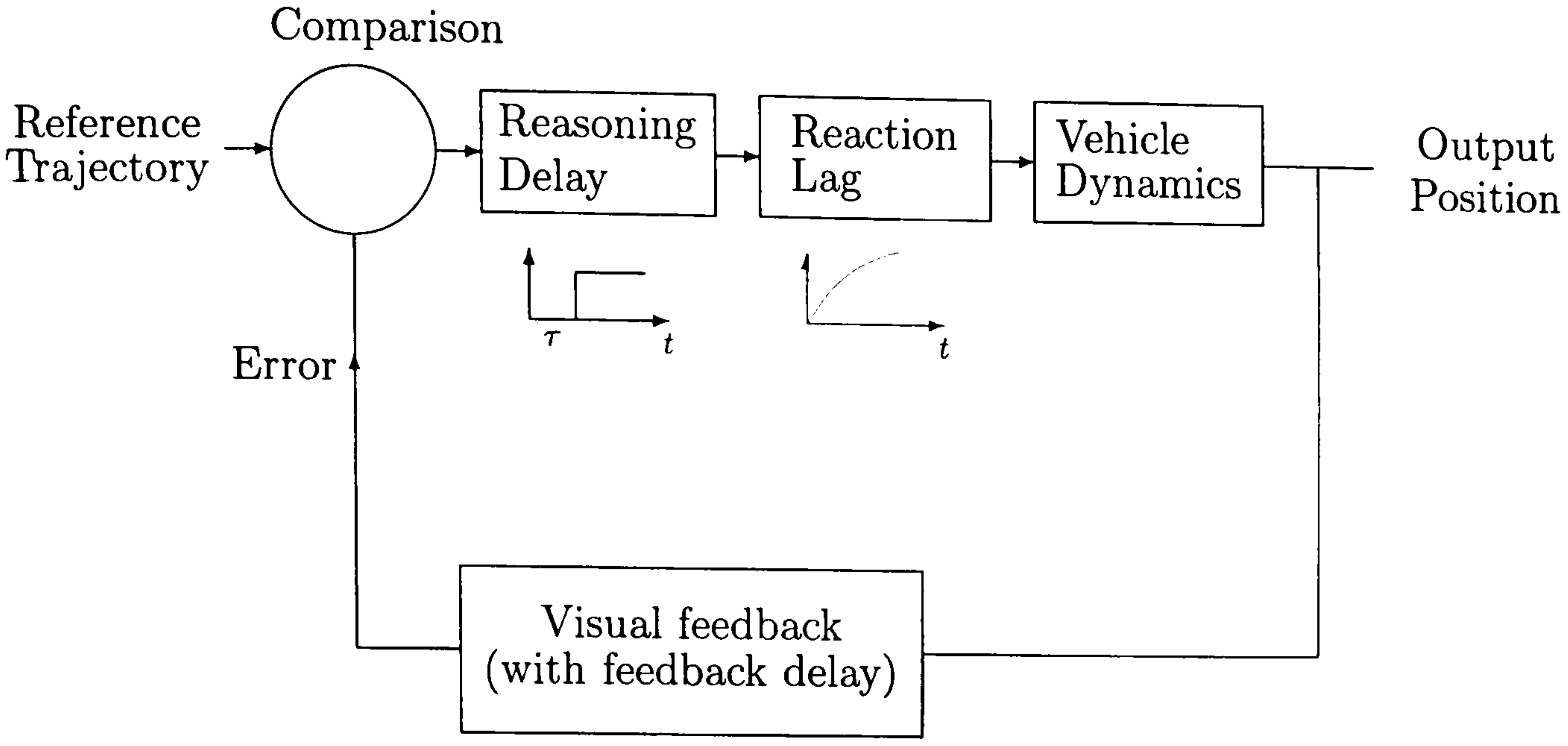


Figure 11.1: Schematic Diagram of Experimental Structure

and to test empiric data obtained from observations (including the pilot work and main experiment). The model placed the operator in the loop with elements of the cognition of the operator being modeled in the context of the whole system (including the vehicle to be controlled and feedback mechanisms used) and was found to act in a similar manner to human operators.

This model was then implemented as a control system using mechanisms that resembled the use of working memory by human operators with delayed feedback. In particular, use was made of a temporary storage area in which calculations were performed, these calculations depending on the *complexity* and *duration* of a given task (analagous to the letter tracing task). In addition to this the control system also navigated along a target track. The model that is proposed in this chapter models the reasoning involved in driving with delayed visual feedback as a delay. The calculations to give this delay have two parameters, namely task complexity and duration. The model therefore calculates a quantity of (reasoning) delay from the task complexity and duration.

This use of a temporary storage area for spatial calculation bears close resemblance to the definition of working memory that has been adopted for this thesis (as

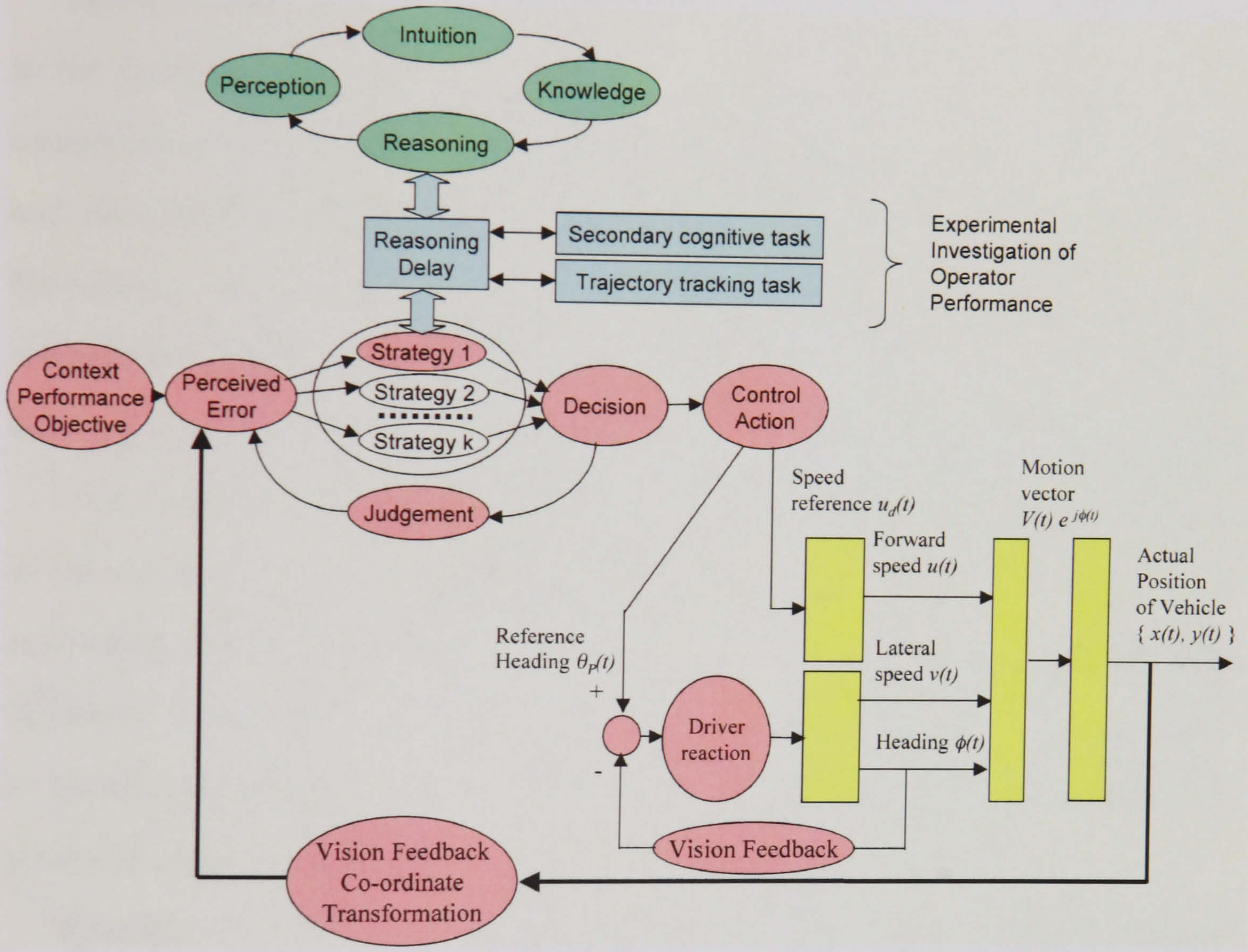


Figure 11.2: Experimental System Structure

Please note, the inner vision feedback loop (from heading to reference heading) refers to the actual heading i.e. not relative to current position. The outer vision feedback loop refers to the relative measure of current position compared to required position, i.e. the vehicle position within the environment.

outlined in Section 2.7):

> *'the temporary storage of information that is being processed in any of a range of cognitive tasks'.* (Baddeley et al., 1999)

This definition is of a generic nature and includes any cognitive task. However, in the modelling work that was carried out, only a limited part of memory was considered in the context of specific tasks (driving with delayed visual feedback and visuo-spatial interference) and other features such as the emotional state of the operator were excluded from the model. For this reason specific features were considered in detail and modelled. The key feature to be modeled was the finding that visuo-spatial tasks (such as driving and letter tracing) conflict with each other.

This approach, of modelling a limited part or set of functions of human memory in the context of a number specified tasks, has been found to be a useful way of performing detailed tests without the need to construct extrememly complex models of human cognition. For example, Newell and Simon (1972) used this approach in modelling working memory in the context of problem solving and proposed a production-system architecture for cognitive processes.

Interestingly, this system (Newell and Simon, 1972) acted in a similar manner to people, but, even more importantly, also failed in a similar manner to people. The model that is outlined in this chapter also appears to fail in a similar manner to human operators (although derived using ideas from control systems engineering rather than production systems). In particular the model uses a temporary storage area in a manner akin to a human operator using working memory to perform the tasks.

11.2 Modelling human behaviour - an overview

Due to the complex nature of operators' reactions to delayed feedback various attempts have been made to model human behaviour in specific application areas. The vast majority of these models are mathematical in nature and do not consider the cognition of the user as part of the system but are included as examples of current methods and knowledge in this area.

Allen and DiMarco (1985) in their investigations into the effects of transport delays on manual control system performance were particularly concerned with digital flight control systems and flight simulators. In order to explain the effects of various delays they presented a generic manual control system model of tracking behaviour derived from models of driving behaviour as well as flying behaviour. The delays modelled were 0, 75, 100 & 250 ms.

Bryson and Fisher (1990) were also concerned with system lag in virtual environments, and particularly in defining, modelling, and measuring this lag. In their studies they found that the overall system lag can be broken down into transmission lag time and position lag (the difference between actual position and displayed position). They also noted that position lag can be understood in terms of transmission lag so optimising system for small transmission lags also optimises for small position lags.

Anderson and Spong (1989) were concerned with bilateral control of teleoperators with time delay. For this reason they investigated the use of haptic feedback under delay and used network theory to derive a new control theory for a teleoperator system. They defined the teleoperator system as an operator, master, communication block, slave, environment. Using this model they showed that instability occurs due to a nonpassive communication block.

Namiki and Ishikawa (1996) also investigated teleoperations using visual and tactile feedback in the presence of delay. They were particularly concerned with developing a control method for a robot that uses visual and tactile feedback for grasping. In their experiments there was no feedback delay but a low frame rate in the visual feedback. In fact, the algorithm was written such that visual feedback was only given once in every 600 steps, with tactile feedback once in every 300. Results showed that the system was robust against errors due to compensation by sensor feedback. A review of modelling manual control and tracking is given by Hess (1997).

In addition to this modelling work in the engineering disciplines, work has been performed in modelling the effects of feedback delays from a neurological perspective. Beuter and Bélair (1989, 1990, 1993) proposed a model to describe the oscillations that they observed in their studies into feedback and delays in neurological diseases (observed in terms of finger tracking). An additional point that they made was that if the gain of the finger was increased (for example, 1 mm movement gives 10-18 mm movement on screen), this increased the accuracy of tracking (for intentional movements). Bélair and Beuter (1995) extended this work and discovered that an increase in time delay induces different oscillations (in finger position in a tracking exercise). The influence of delays in 2 feedback loops was considered.

Barto et al. (1996) proposed a predictive switching model of cerebellar movement control. In this work they presented the hypothesis that the cerebellum might participate in regulating movement in the presence of feedback delays without resorting to a forward model of the motor plant. The model uses prediction, but instead of predicting sensory input, it regulates movement by reacting in an anticipatory fashion to input patterns. It is closely related to direct predictive adaptive controllers.

Miall (1996) performed a frequency analysis of human manual tracking. These experiments were particularly concerned with the frequency spectra of human movement, with visual delay just being used as a tool. Miall found that the feedback loop delay decreased from around 341 to 264 ms as the task speed doubled. This implies that the subjects 'tune' their feedback system to suit the demands of each individual task.

Lazzari et al. (1997) devised a computer simulation of a coordination model while investigating eye tracking with a self-moved target compared with eye-alone tracking. Results were shown to fit human data.

An attempt was made by Gordon and Subramanian (1996) to produce a cognitive model that explains how humans acquire skills. This model used the idea of action models (internal models of actions and consequences).

Numerical simulations by Dorizzi and Grammaticos (1991) have shown that delayed feedback has a desynchronising influence on neuronal oscillations.

Van de Vegte et al. (1990) modelled a manually-controlled teleoperator system mathematically. The operator was considered to be an optimal controller and results from the model were compared to experimental results using a simulated submersible. Results show that this model responded to time delays in a similar manner to a system with a human operator in the loop thus implying that it might be of use in design and analysis of future teleoperator systems.

11.3 Design of Model

11.3.1 Introduction

A control system model was designed in collaboration with Professor George T. Russell. This model arose from results obtained from the pilot work outlined in Chapter 3 and was extended to include the findings of the the virtual reality based driving experiments described in Chapter 9.

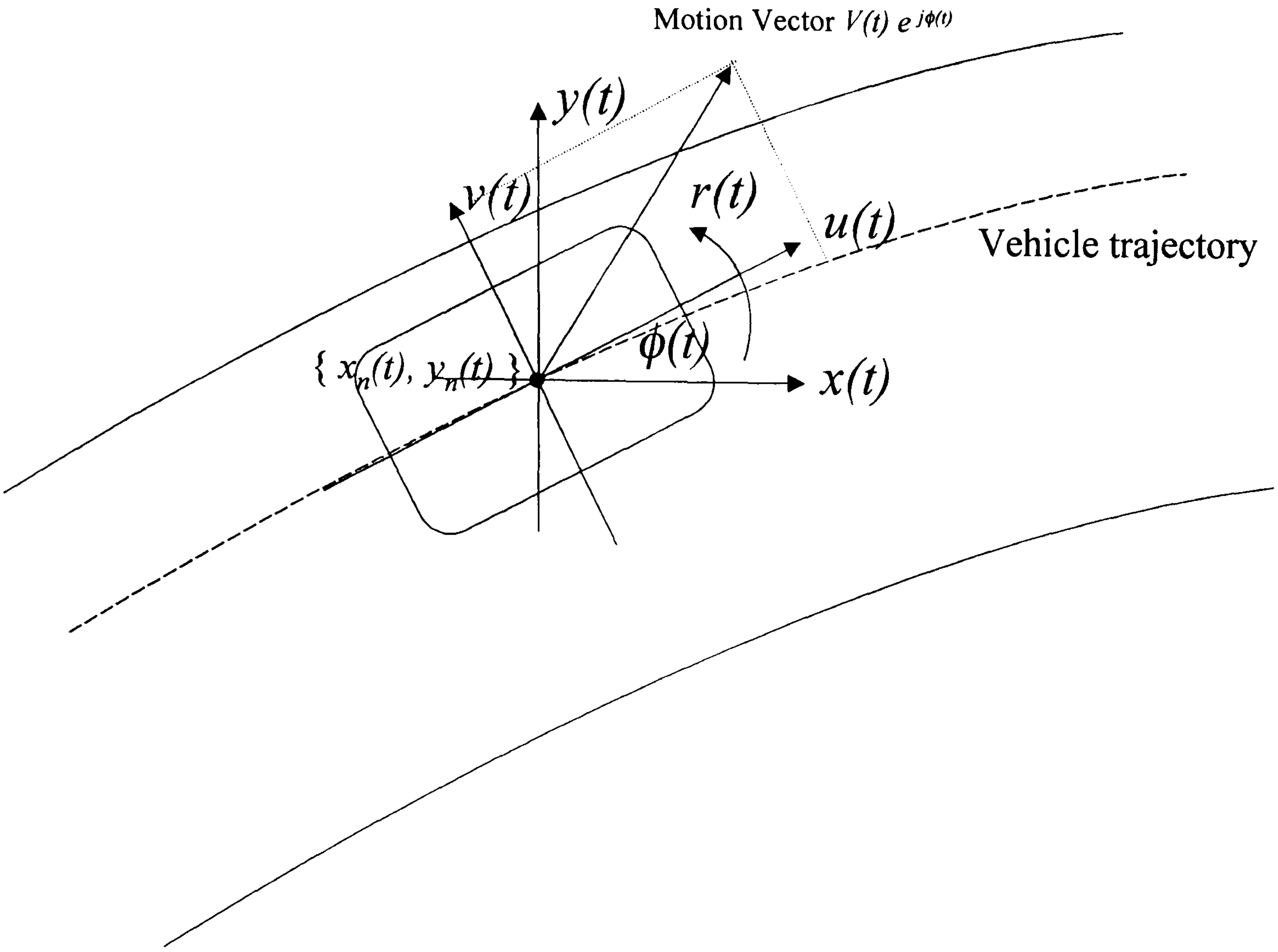


Figure 11.3: General vehicle movement

11.3.2 Overview

In designing a control system to model the behaviour discovered in the VR based driving experiments the vehicle was considered to travel along a path with motion vectors as defined in Figure 11.3. The model was of a simple vehicle, moving with three degrees of freedom, together with an operator controlling it.

11.3.3 Underlying driver strategy

The operator strategy modelled within the vehicle control system is shown in Table 11.1. This strategy is, of course, naive and is proposed to produce an initial quantitative model to test against experimental results. The strategy assumes that the operator can change the following variables:

```
Look ahead a certain distance to point on path
Calculate required heading with respect to current heading
Repeat
        Delay representing user cognition
        (increases with task complexity, duration and number of tasks)
        Exponential lag while user responds
        Vehicle dynamics react to control action
        Feedback delay until see result
        Calculate new required heading
Until   perceived result = final required location
```

Table 11.1: Driver strategy

1. look ahead dimension (R in diagram)
2. velocity of vehicle ($u(t)$ in diagram).

This leads to the steering algorithm described in Section 11.4.2.

11.3.4 System model outline

The model of the system takes the form of a general feedback loop as shown in Figure 11.1. The human operator is modelled in terms of a Reasoning Delay and a Reaction Lag within the context of a specific driving strategy. In effect, two loops are operating simultaneously. The primary loop is the vehicle control and the secondary loop involves the operater undertaking a secondary cognitive task. This secondary loop determines the magnitude of the Reasoning Delay in the primary loop as is shown in Figure 11.4.

The loops are implemented by using a temporary storage area and performing calculations using that area in a manner similar to working memory usage in human

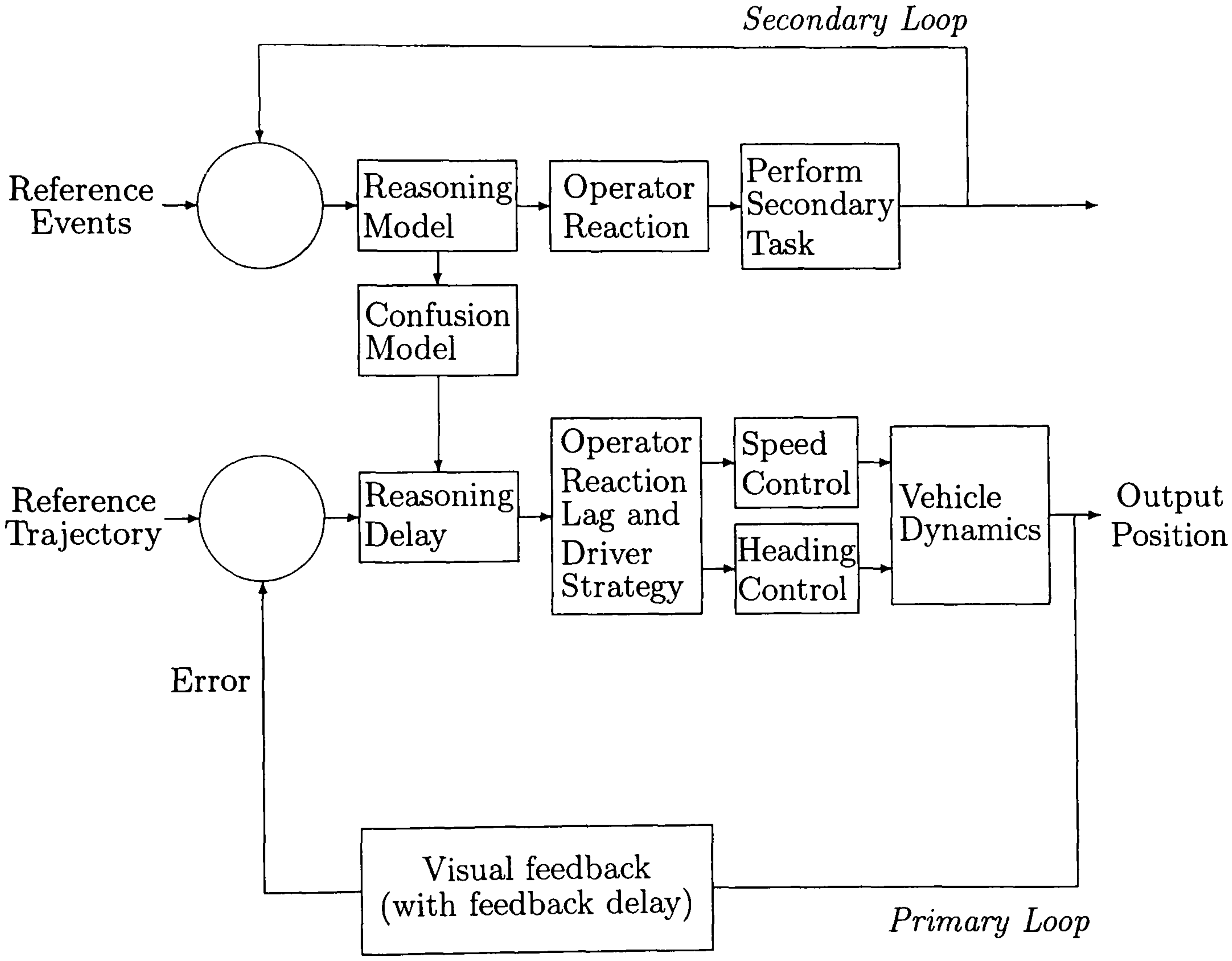


Figure 11.4: Control System: Description of Main Loops

cognition. This process is a primitive attempt to produce a temporary effect while a task is being performed that provides a delay in the feedback. This temporary effect is of the form of a temporary storage area being used for calculations (analagous to working memory being used for visuo-spatial cognition). The effect seen in the model is dependent on the task as was seen in the human performance results outlined in Chapter 3.

The final stage in modelling the system is to include the visual feedback of the system (feedback of the vehicle's current heading and position) which in the experiments was a pure delay.

11.4 Detailed Description of Control System

The model is made up of the following portions:

1. Vehicle dynamics including human reaction time (constant delay).
2. Steering algorithm.
3. Confusion due to working memory disruption:
    (a) Confusion due to interpolated tasks (increases with complexity of task until task is achieved).
    (b) Confusion due to navigating with delayed visual feedback (constant complexity dependant on delay magnitude).

11.4.1 Modelling vehicle dynamics

An overview of the approach taken is given in Figure 11.5. More detail is given in Figures 11.6 and 11.7. A detailed description of the control system is also included in Appendix L.1.

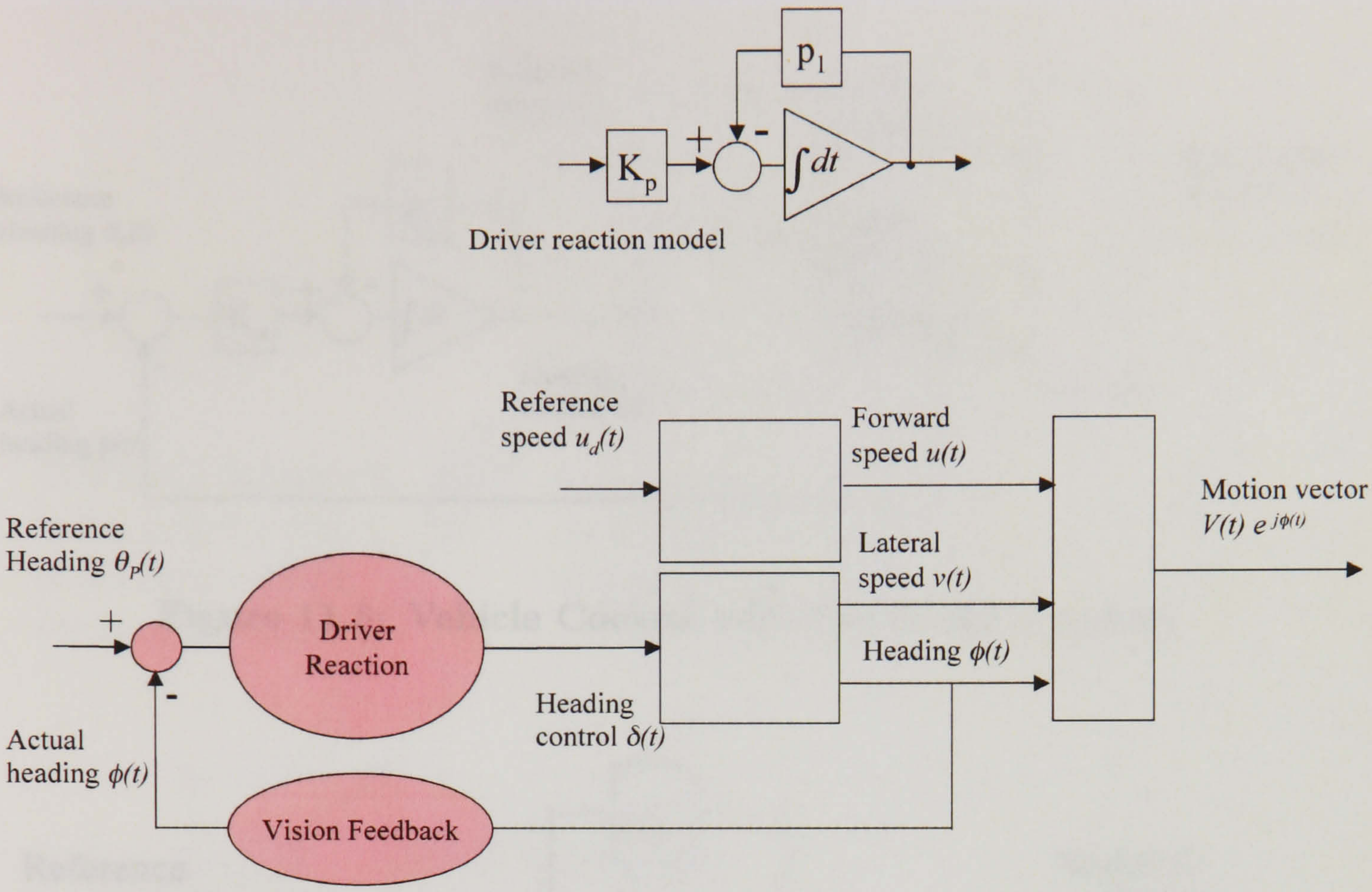


Figure 11.5: Vehicle Control with Driver RT - overview

Please see Table 11.3 (on page 201) for a list of constants used both in the design and in the corresponding implementation.

It should be noted that the reaction time of the human operator is included in the consideration of vehicle dynamics. In addition, lateral and forward speed are considered separately. The reason for this is that when a vehicle turns it does not respond immediately and therefore when turning has both a forward speed and an additional lateral speed.

11.4.2 Steering algorithm

As has been mentioned in Section 11.3.3 the navigational strategy adopted is a rather simple one as is illustrated in Figure 11.8. However, similar strategies have been incorporated into models and successfully used by Allen and DiMarco (1985)

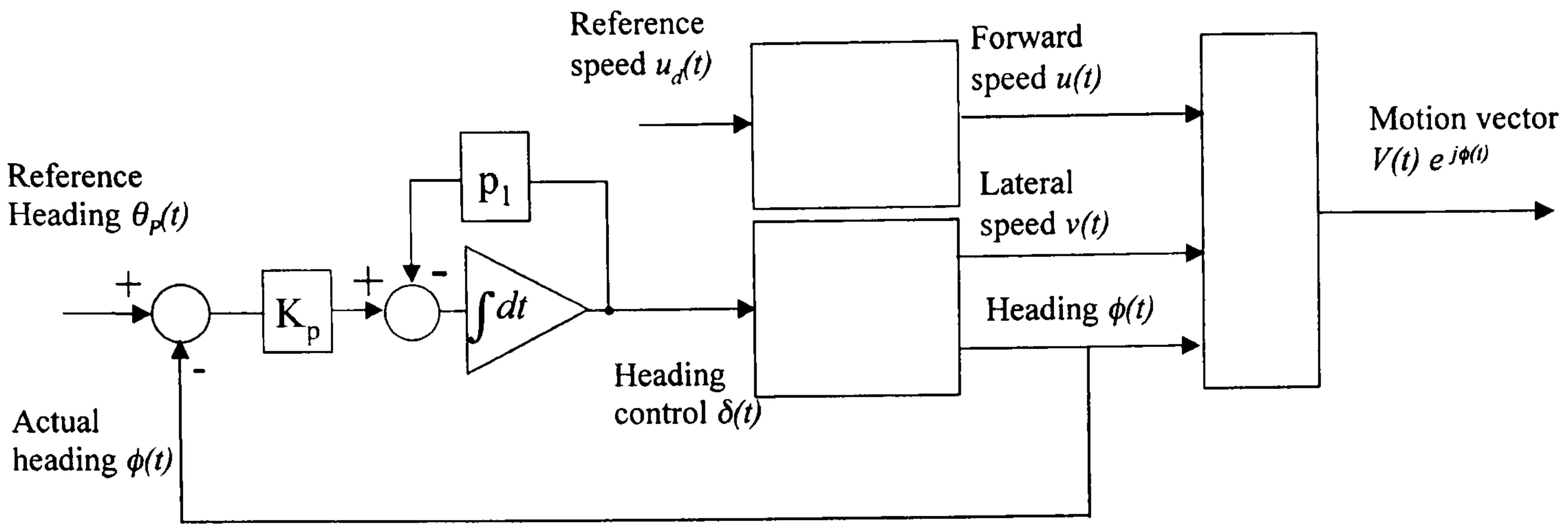


Figure 11.6: Vehicle Control with Driver RT - system

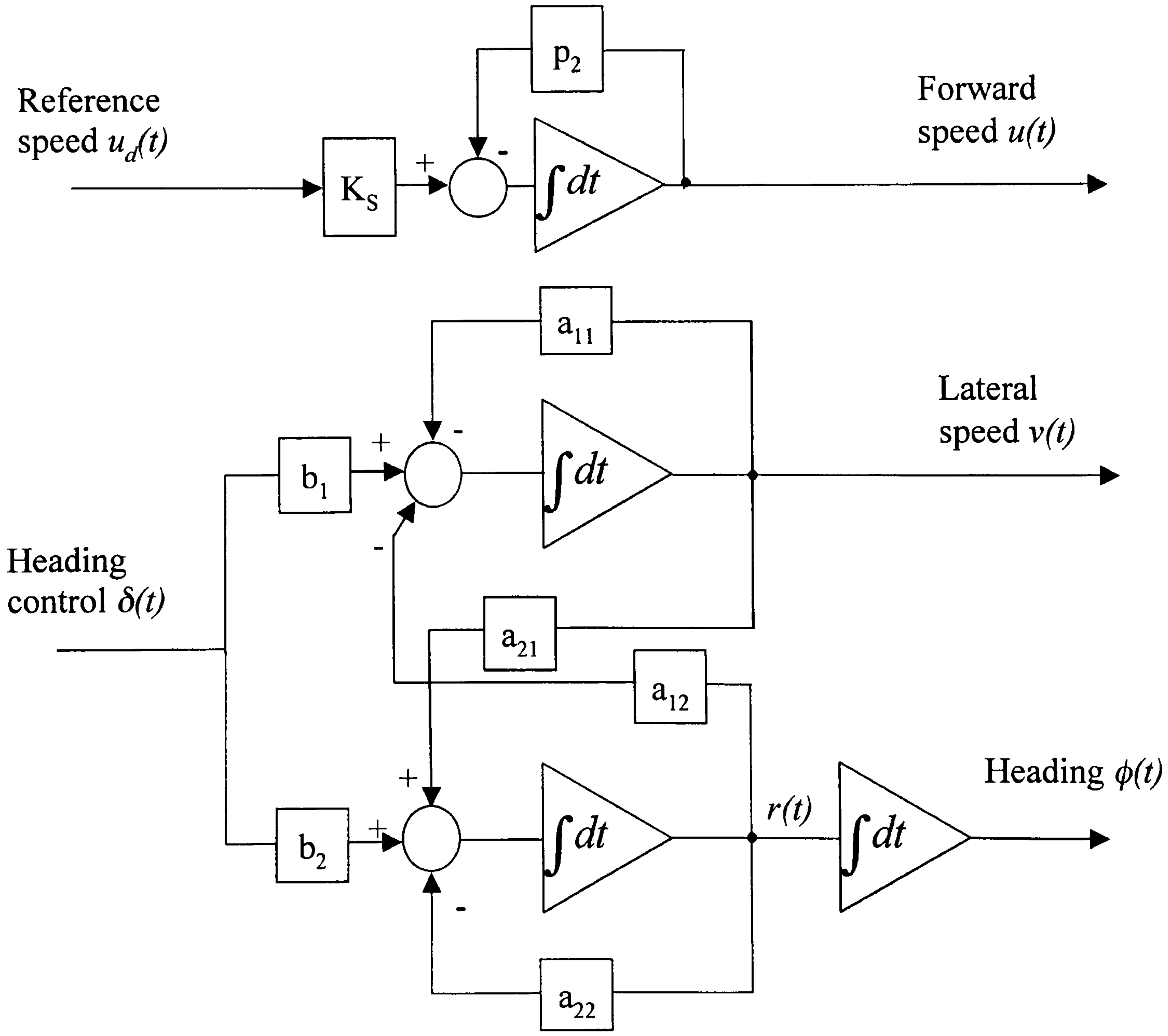


Figure 11.7: Vehicle Control - detail

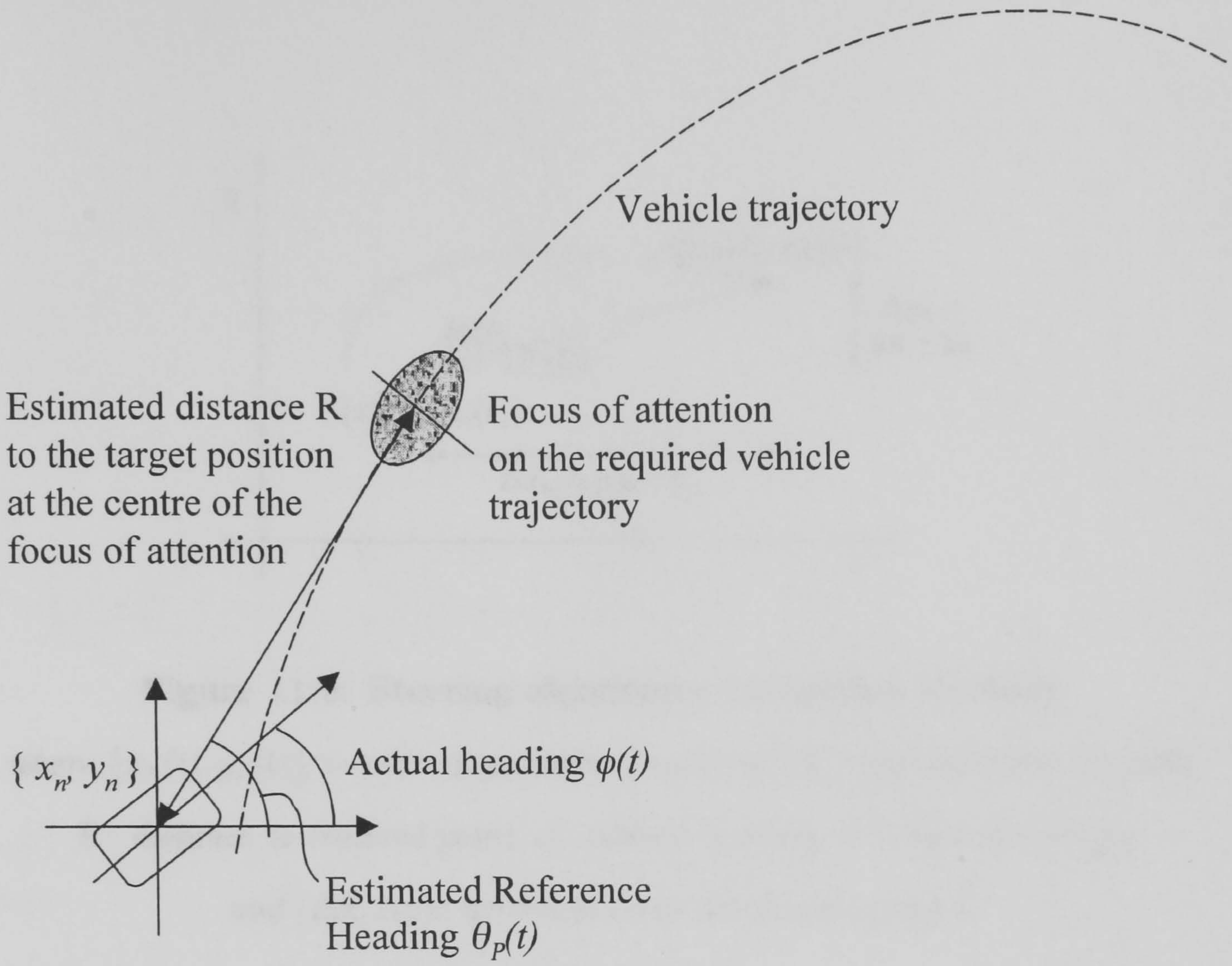


Figure 11.8: Steering Outline

among others. The algorithm calculates the required reference heading θ_R to a point on the path knowing the range R and the current location $\{x_n(t), y_n(t)\}$ as shown in Figure 11.9. The algorithm is described in Table 11.2 and is implemented as the control system shown in Figure 11.10.

11.4.3 Modelling confusion

The main cognitive tasks that were undertaken by participants in the experiments consisted of a primary task of steering and navigation with a secondary, interpolated task of letter tracing. The confusion that this caused is modelled as a number of exponential lags as expressed in Equation 11.1. This model includes both the driving

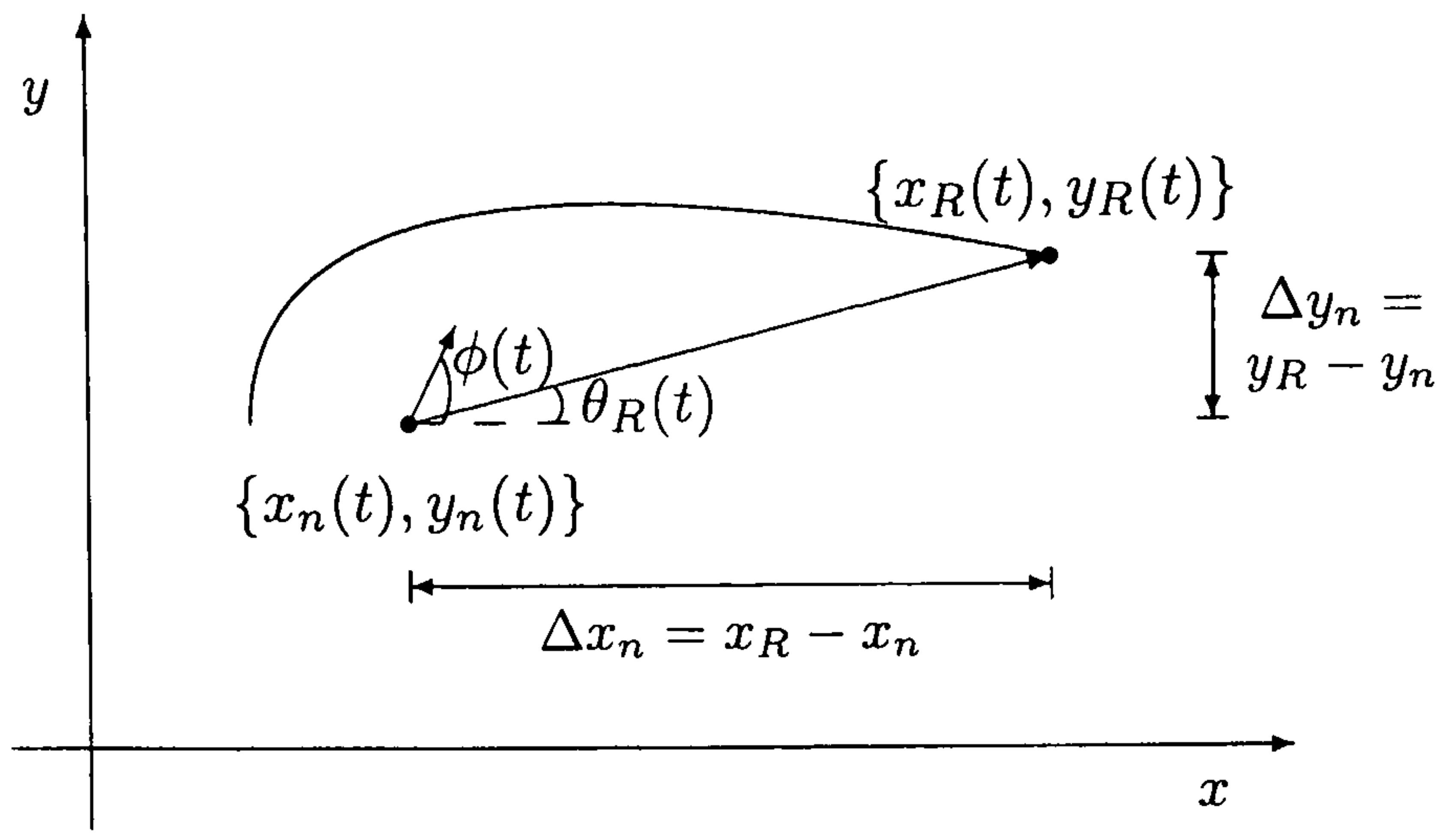


Figure 11.9: Steering algorithm: navigation strategy

where $\{x_n(t), y_n(t)\}$ = *current position,* $\{x_R(t), y_r(t)\}$*: required point on path,* R*: distance to required point,* ϕ*: current heading,* θ*: required heading and* $(\Delta x, \Delta y)$*: perceived error all at some time* t*.*

`Find the value of` $x_R(t)$ `such that` $\int e_R(t)dt \Rightarrow 0$ `where` $e_R(t) = R^2 - ((\Delta x_R(t))^2 + (\Delta y_R(t))^2)$ `and the trajectory parameters` y_R `and` x_R `are related through the expression` $y_R(t) = f_R(x_R(t))$

Table 11.2: Steering Algorithm Details

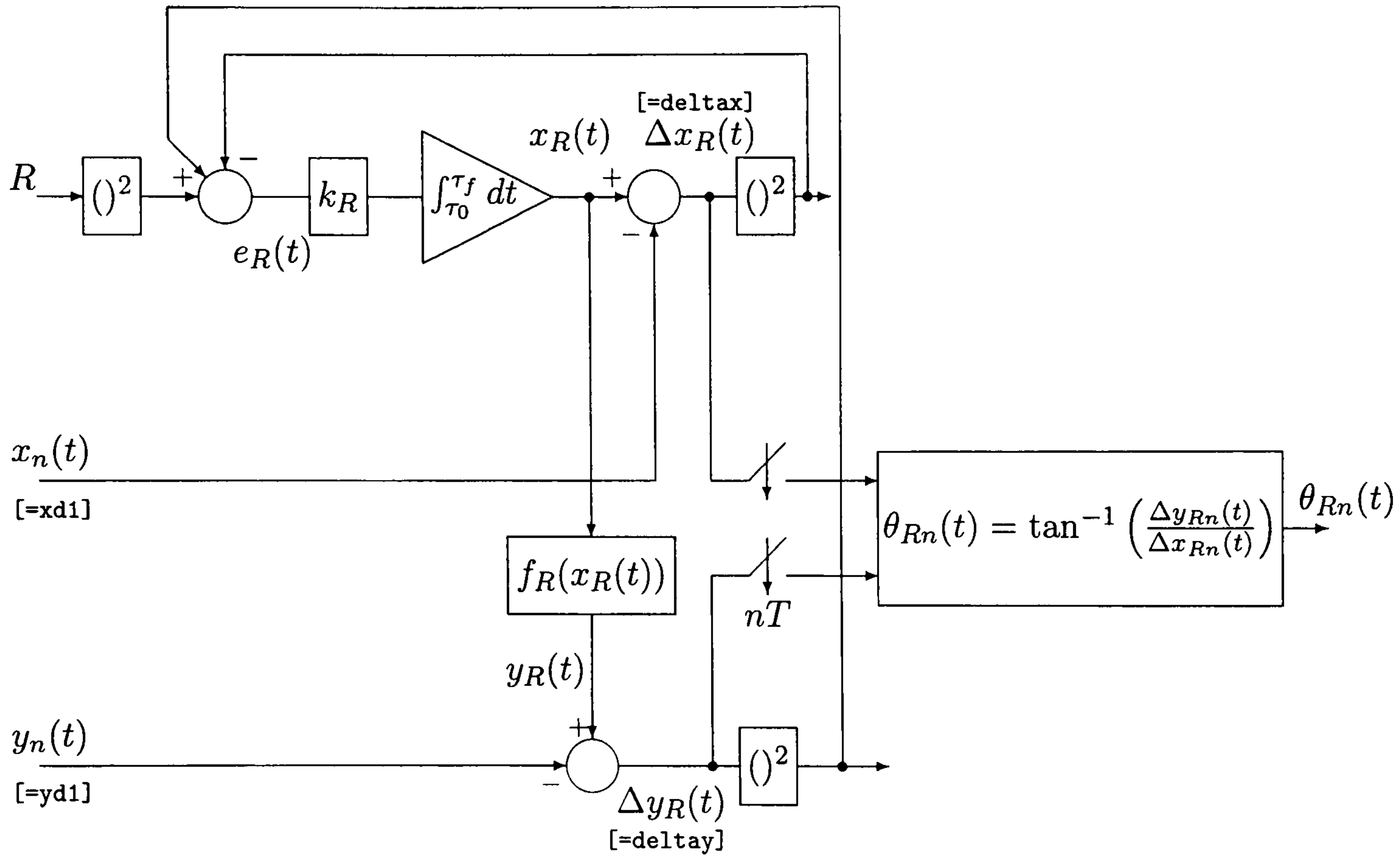


Figure 11.10: Steering algorithm: control system

(Please note, annotations such as [=xd1] *refer to the equivalent terms in the Matlab implementation.)*

task and the visual interference tasks as shown in Figure 11.13. As has already been mentioned, these lags are implemented in a manner similar to the way that working memory usage was defined by Baddeley et al. (1999); that is the lags are produced by performing calculations that make use of temporary storage. (Please see Section 4.2 for more details of the experimental tasks being modelled.)

Confusion was defined to be:

> the difference between the *perceived strategy* for control and the *perceived error* in observed performance.

The reason for using exponential lags as the model for cognition was as follows. Both of the cognitive tasks have a steep learning curve while the user concentrates fully. After a time, the user is familiar with the task and no longer has to concentrate as much to the point when the task becomes semi-automatic with little attention being paid to it (as discussed in schematic control modes in Section 2.8.2).

The decision was taken to not produce a detailed model of the cognition involved in driving under delayed visual feedback and performing interpolated letter-tracing tasks. Firstly, it was thought that there was insufficient knowledge regarding the nature of the cognition involved in driving under delayed feedback and therefore a more detailed model would require a number of assumptions to be made. In addition to this consideration, a more detailed model of the cognition involved would make the control system considerably more complex and therefore unexpected results might be seen. More complex systems have been produced, but are usually concerned with specific manual-control tasks such as finger tracking (for example Bélair and Beuter, 1995; Beuter and Bélair, 1993) rather than complex motor-control tasks such as driving. Confusion was therefore represented by the two exponential functions as previously mentioned.

As part of the proposed model the reasoning activity is shown in Figure 11.11. Here it can be seen that perceived error stimulates a strategy to produce a decision

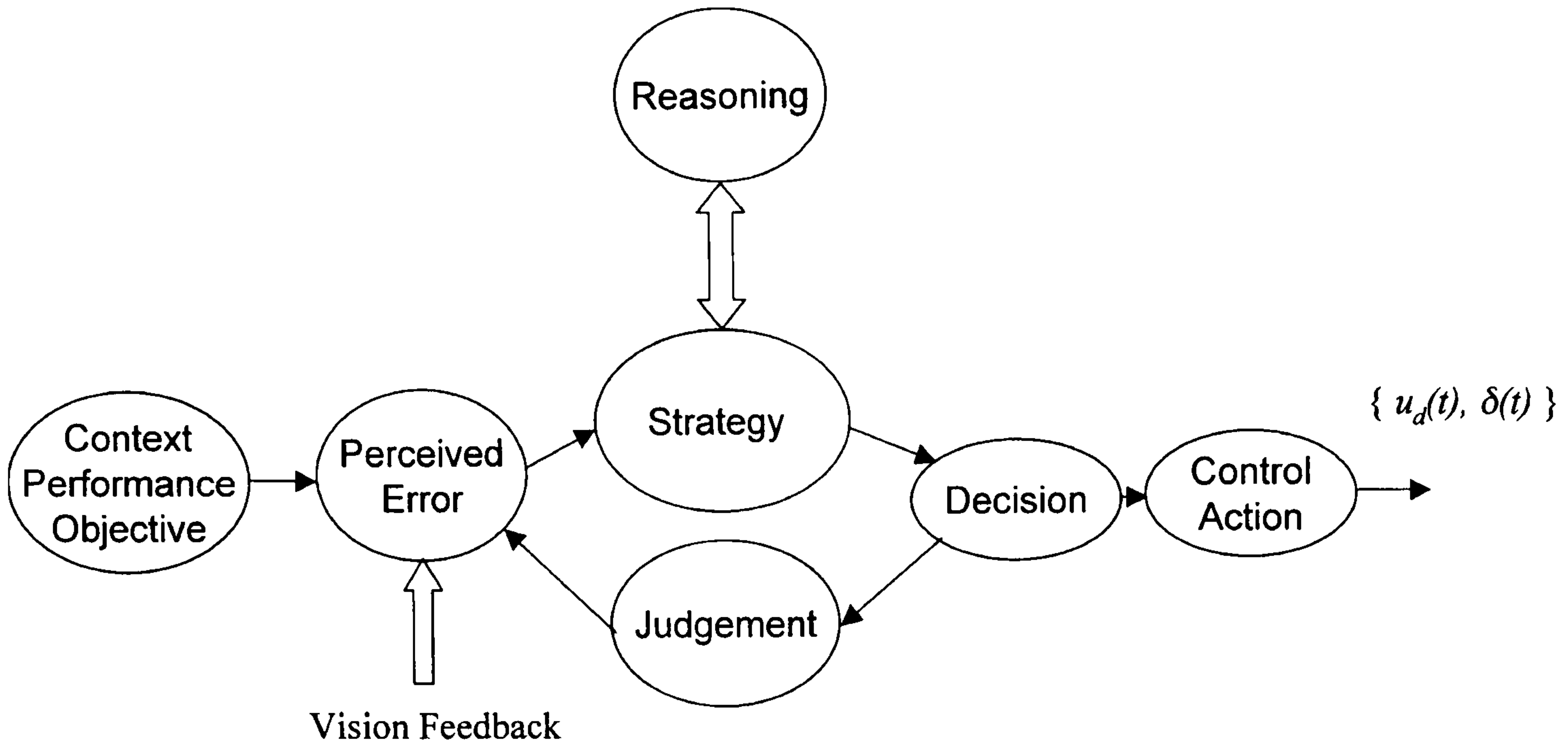


Figure 11.11: Reasoning - overview

where $u_d(t)$ *is forward speed and* $\delta(t)$ *is heading control.*

and subsequent judgement that affects perceived error. The control action which results from this reasoning means that both the speed and heading of the vehicle are used to influence the direction as illustrated in Figure 11.12.

$$C(t, \Delta\tau) = \int_{t_0}^{t_f} A(t-\Delta\tau)\left[e^{-\alpha(t-\Delta\tau)} - e^{-\beta(t-\Delta\tau)}\right] dt \tag{11.1}$$

The modelling of confusion is illustrated in Figure 11.14.

A task such as driving or letter tracing can defined as an event, $A(t-\Delta\tau)$, having an intensity (the complexity, urgency or criticality of the task) and a period (task duration).

This event triggers some activity with calculations being performed using some temporary storage. The activity can therefore be expressed as the usage of this storage. It has two phases, the first (activity) involving getting used to the task, and the second (recovery) to return to the previous state. The activity begins at time t_0 and finishes at time t_f.

This activity results in a delay, τ, the magnitude of which is proportional to the area under the activity curve, i.e. the integral of the activity (as shown in Figure

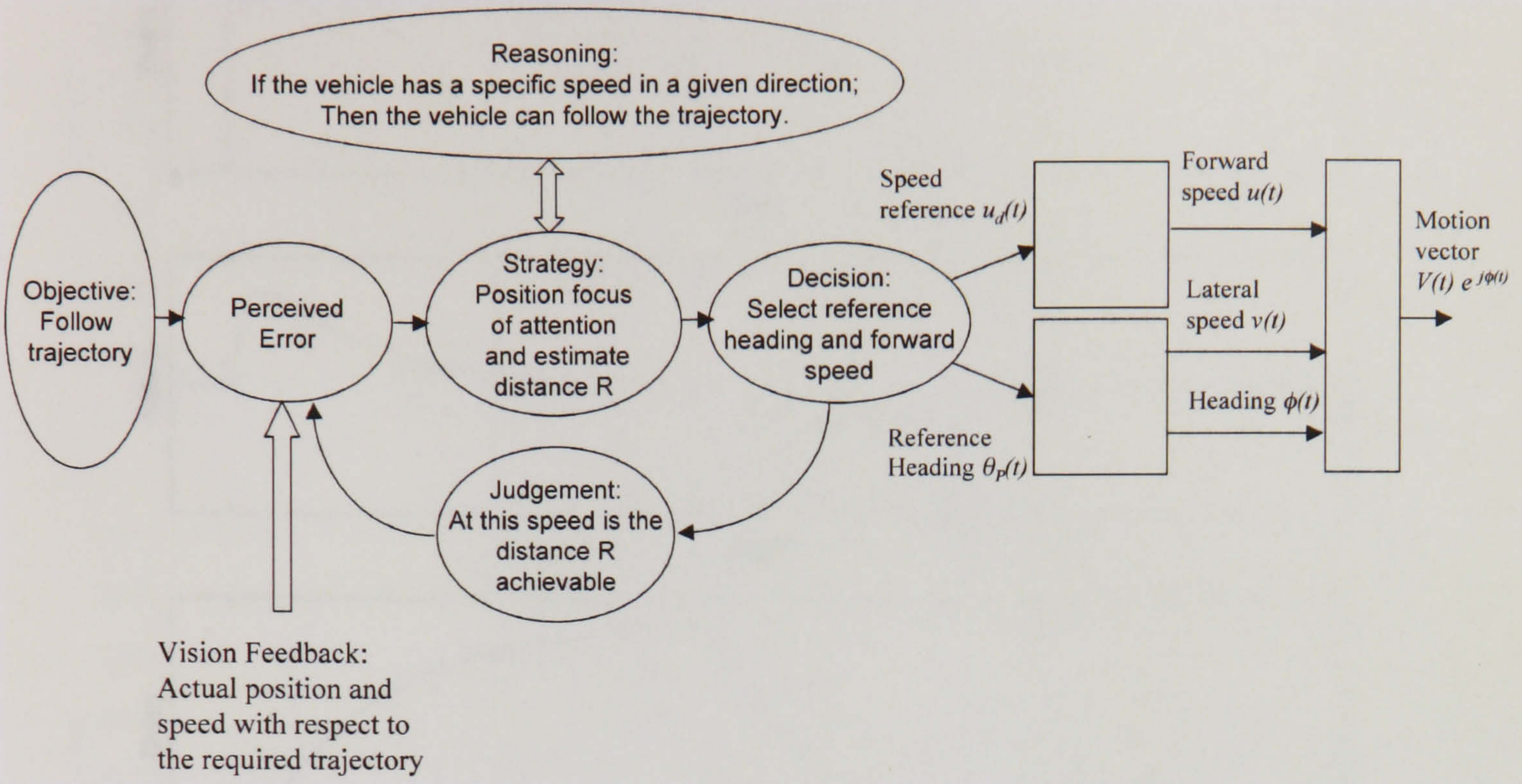


Figure 11.12: Reasoning - structure

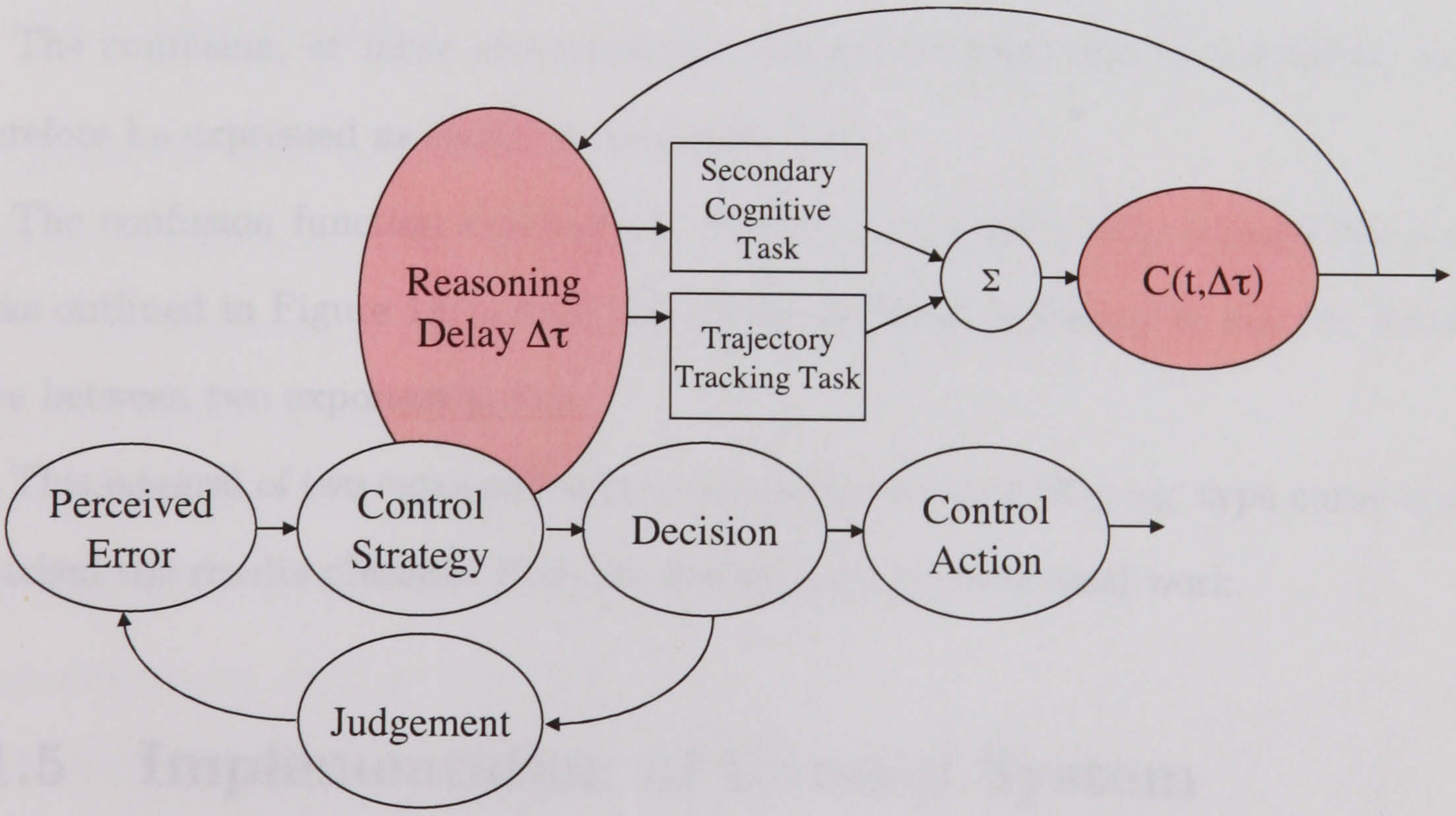


Figure 11.13: Reasoning Delay Function

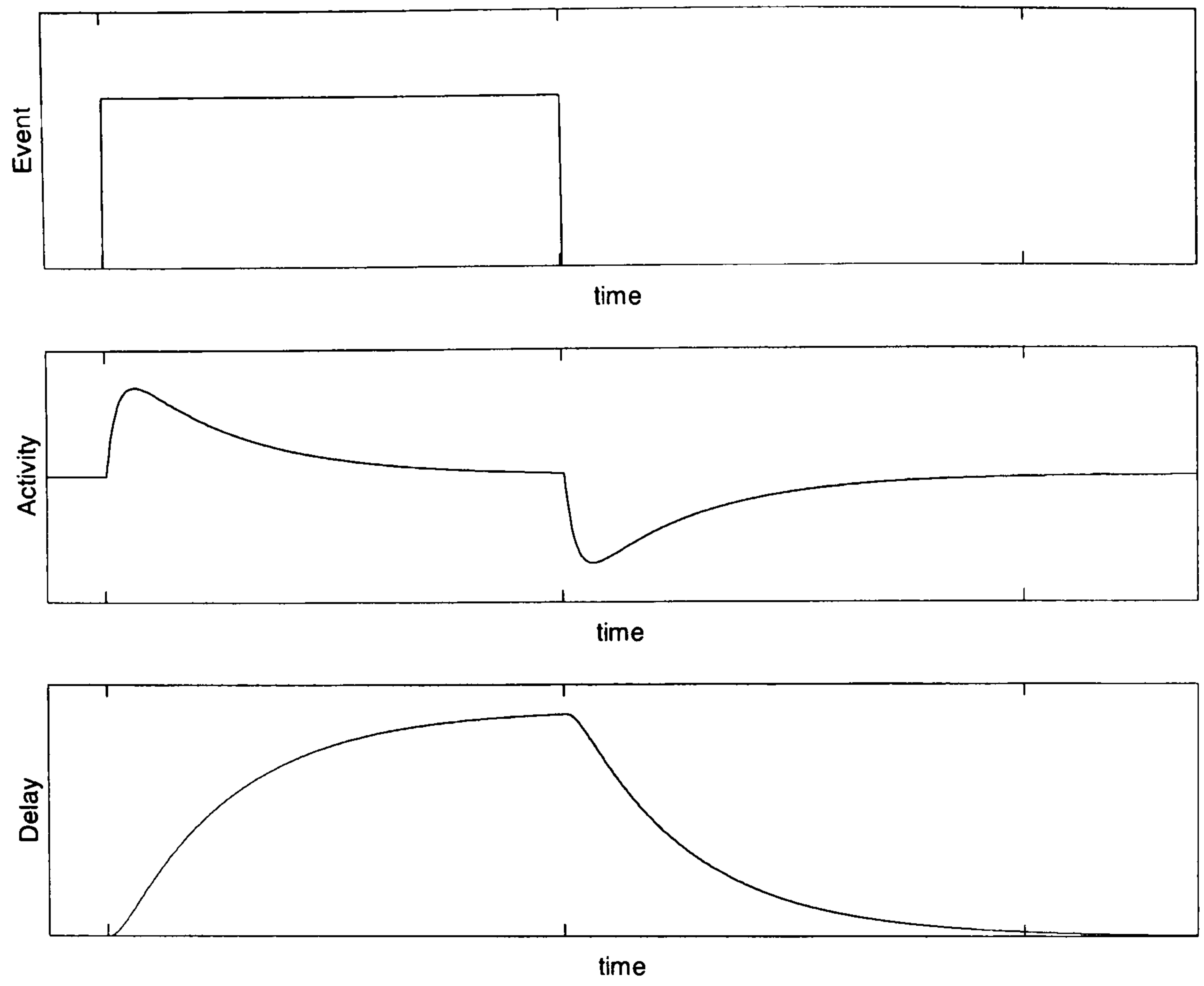


Figure 11.14: Modelling of Confusion (a detrimental effect)

11.14).

The confusion, or more accurately the amount of delay due to confusion, can therefore be expressed as shown in Equation 11.1.

The confusion function expressed in Equation 11.1 takes into account the two tasks outlined in Figure 11.13 with the confusion being expressed as the the difference between two exponential lags.

This integral of two exponential functions gives rise to a 'dog-leg' type curve that matched the results obtained from the preliminary experimental work.

11.5 Implementation of Control System

The control system was implemented in Matlab version 5. This visualisation and programming environment was chosen for its graphical output routines allowing

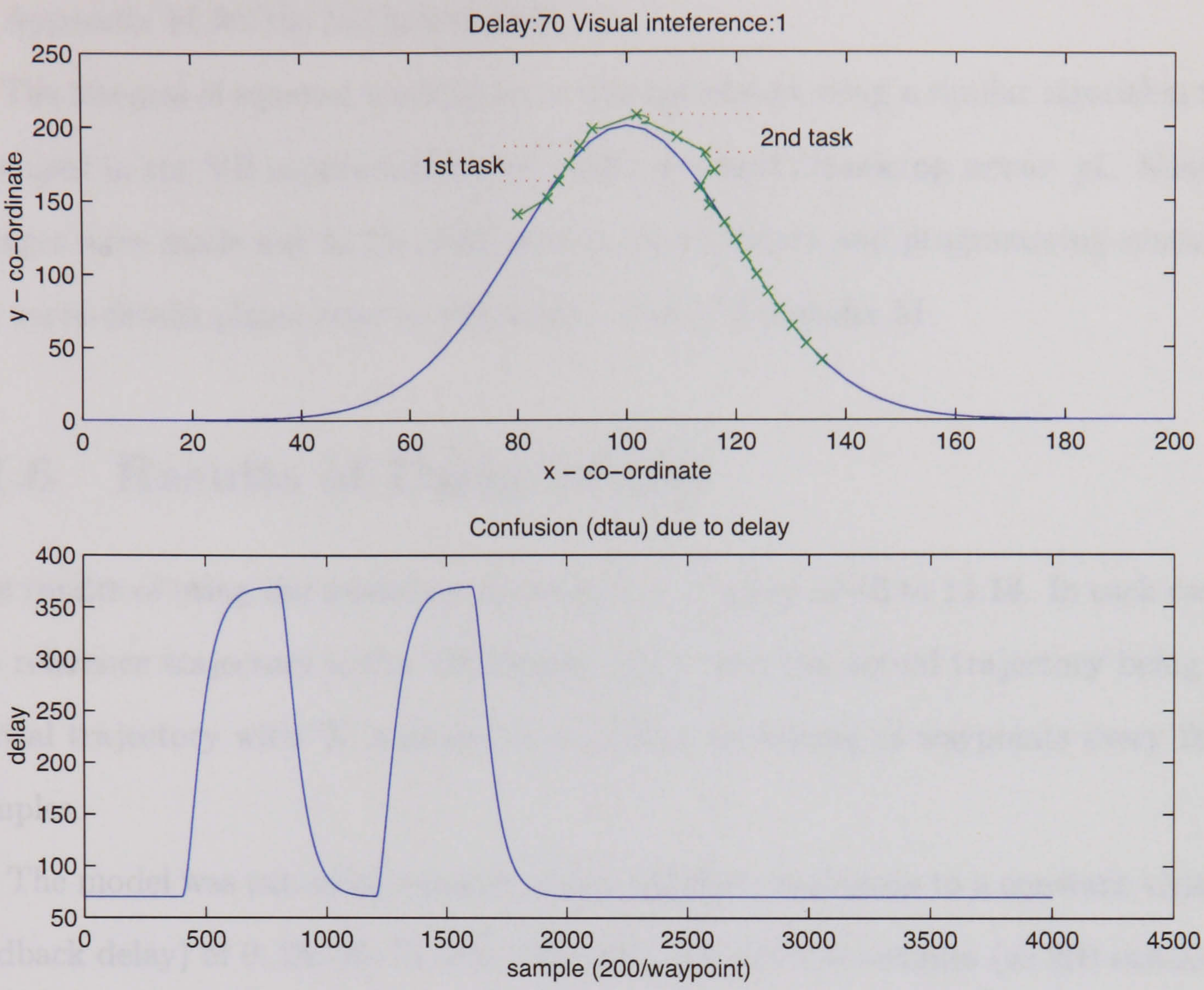


Figure 11.15: Example output of control system (delay 70, with visual interference)

mathematical functions to be plotted. However, the control system could easily have been implemented using a number of alternative programming languages.

The interpolated visual interference tasks were modelled as exponential delays and were executed just before and after the bend. This can clearly be seen on an annotated example output from the control system in Figure 11.15 showing not only the track following but also the total 'confusion' in the system, expressed as delay magnitude against sample number. This example shows a constant value of 70 (due to the feedback delay) in addition to two peaks (due to the interpolated tasks).

The implementation is summarised by means of pseudo code in Tables 11.4 and 11.5. For ease of comprehension the code is split into five main sections. The main constants used in the system are summarised in Table 11.3 (on page 201). Please see Appendix M for the full source code.

The integral of squared tracking error was calculated using a similar algorithm to that used in the VR experimental Perl script, `extract_tracking_error.pl`. Minor changes were made due to the difference in data formats and programming syntax. For more details please refer to the source code in Appendix M.

11.6 Results of Using Model

The results of using the model are illustrated in Figures 11.16 to 11.18. In each case the reference trajectory is the bell-shaped curve with the actual trajectory being a partial trajectory with 'X' markers to illustrate the setting of waypoints every 200 samples.

The model was run using constant delay settings (analogous to a constant visual feedback delay) of 0, 25, 50, 75, 100, 125, 150, 175 and 199 samples (as 200 samples exceeds constraints on matrix boundaries) and additional interpolated tasks (analogous to the visual interference tasks) in half the cases. (Sampling in this case refers to the discrete sampling that the control system performs, rather than sampling of a population of participants.)

Calculations were performed (again using Matlab) in order to obtain the integral of squared tracking error. In order to obtain accurate results the reference trajectory was resampled at 0.01 increments (as opposed to 3.33 increments as in the original definitions in the model) and measurements taken at every point on the actual trajectory to the closest point on the reference. Due to the discrete nature of this data the integral, $\int \epsilon^2 dt$ was calculated using $\sum \epsilon^2$ where ϵ is the tracking error at each point.

Errors are given in Table 11.6 and Figure 11.19.

Constant	*Implementation*	*Description*	*Value*
α	`alpha`	complexity of primary task (A)	5
a_{11}	`a11`	vehicle parameter	10
a_{12}	`a12`	vehicle parameter	0.5
a_{21}	`a21`	vehicle parameter	1
a_{22}	`a22`	vehicle parameter	10
β	`beta`	complexity of primary task (B)	4
b_1	`b1`	vehicle parameter	0.1
b_2	`b2`	vehicle parameter	1
b_3	`b3`	vehicle parameter	5
dt	`dt`	sample interval	0.1
γ	`gamma`	complexity of primary task (C)	1.5
K_p	`Kp`	vehicle parameter	50
K_s	`Ks`	vehicle parameter	1
n	`n`	number of samples	1000
p_1	`pp`	driver parameter	3
p_2		Not used as forward speed u_d is fixed	
u_d	`ud`	forward speed of vehicle	0.6
T	`T`	time period	100
z_1	`z1`	secondary task complexity factor (i)	0.8
z_2	`z2`	secondary task complexity factor (ii)	0.8

where primary task is analagous to driving with delayed feedback, and secondary task is analagous to the visuo-spatial interference task

Table 11.3: Constants Used in Control System Implementation

```
Vehicle simulation

Set vehicle parameters, waypoints and sample rate
Define reference trajectory

Human operator simulation

Set operator parameters
Set task complexities and sequences (for visual interference tasks)
Calculate confusion function over time that the vehicle moves
Determine confusion due to visual feedback delay and interference tasks
Calculate vehicle trajectory between waypoints
Calculate reference heading

Whole system

For    each time period
           Define driver reaction time model
           Define vehicle model
           Calculate total vehicle trajectory
           Set initial conditions for next period
Next
```

Table 11.4: Pseudo Code for the Control System Implementation

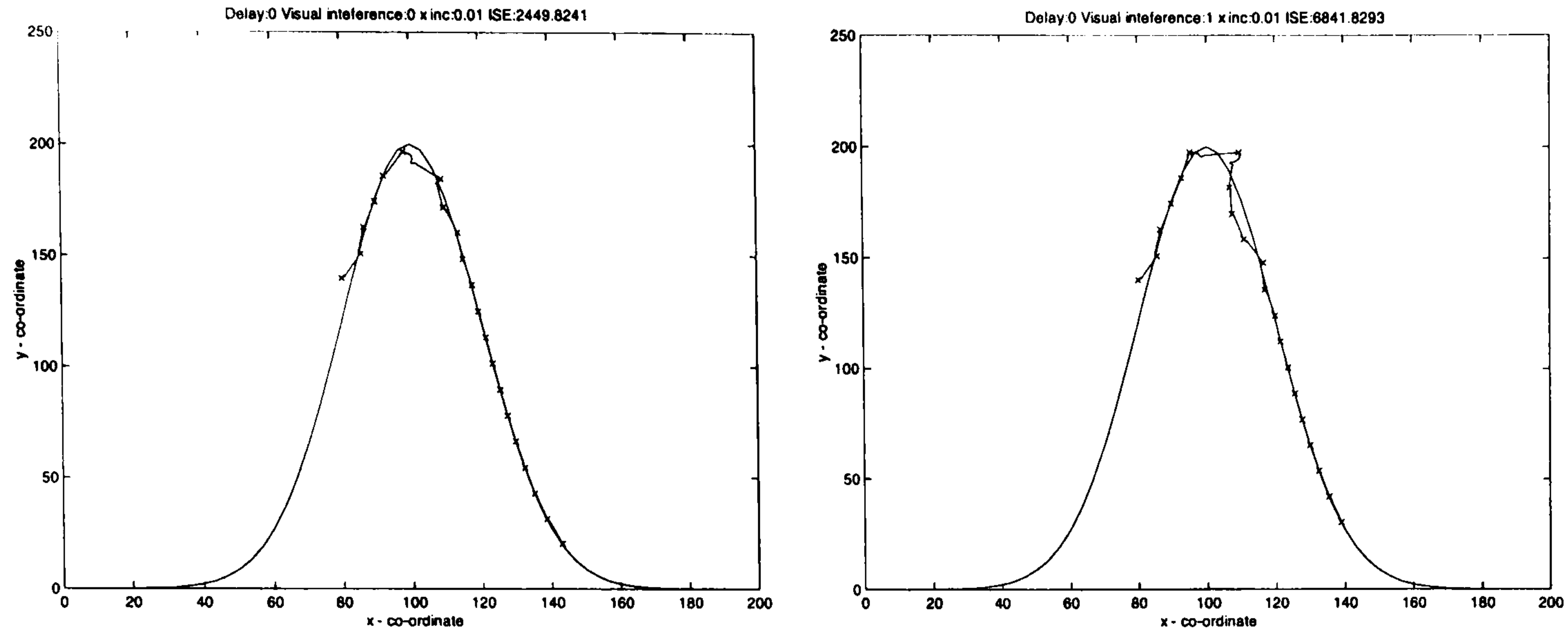
```
Analysis
Redefine reference curve between limits with small increments
For    each point on actual trajectory
           Find distance to closest point on reference trajectory
           Square distance and add to total (giving ISE)
Next

Output
Plot reference trajectory and actual trajectory
Display ISE, delay size and visual interference settings
Plot delay due to total confusion (from delays and visual interference)
```

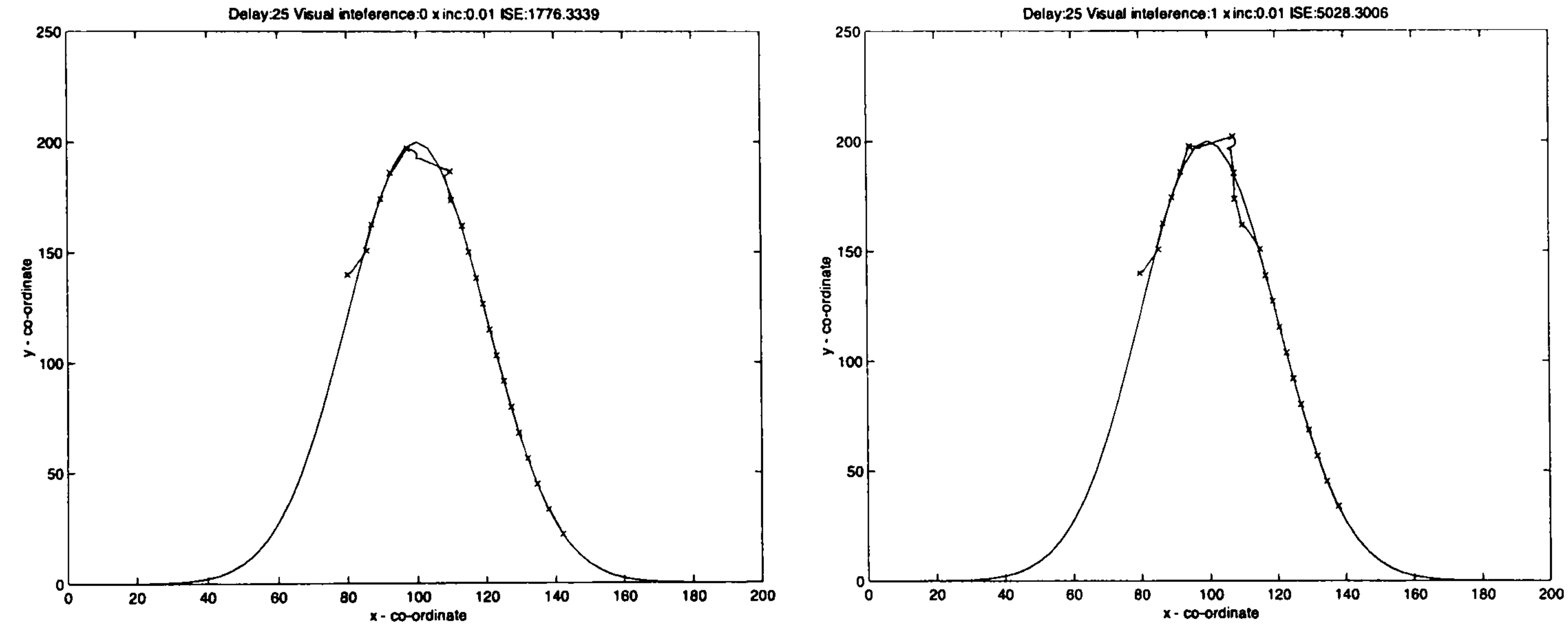
Table 11.5: Pseudo Code for the Control System (cont.)

Delay	ISE: no visual interference	ISE: visual interference
0	2449.82	6841.83
25	1776.33	5028.30
50	1822.87	5405.67
75	2909.70	18271.29
100	5449.99	41732.21
125	9560.91	71966.05
150	14740.58	108624.0
175	22554.77	149343.7
199	91547.60	203696.6

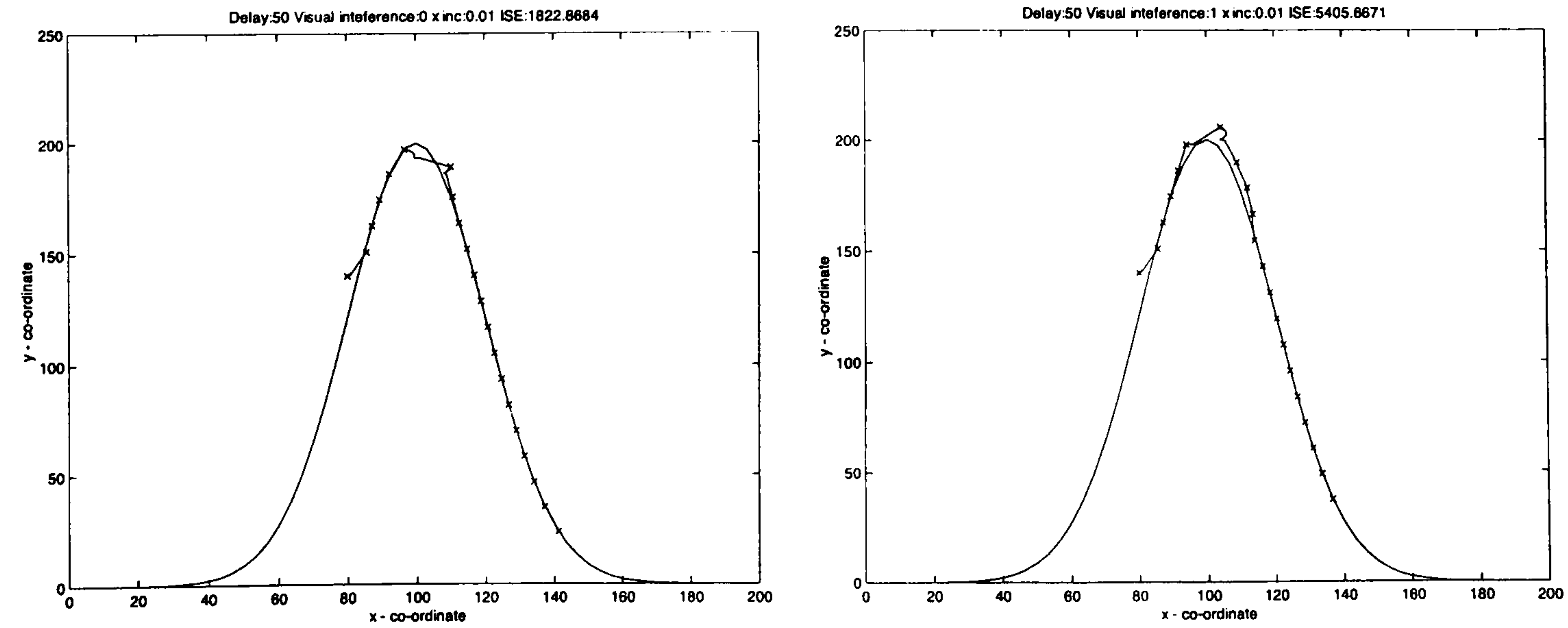
Table 11.6: Integral of Squared Tracking Error for Control Systems Model



(a) no interference, delay 0 (b) interference, delay 0

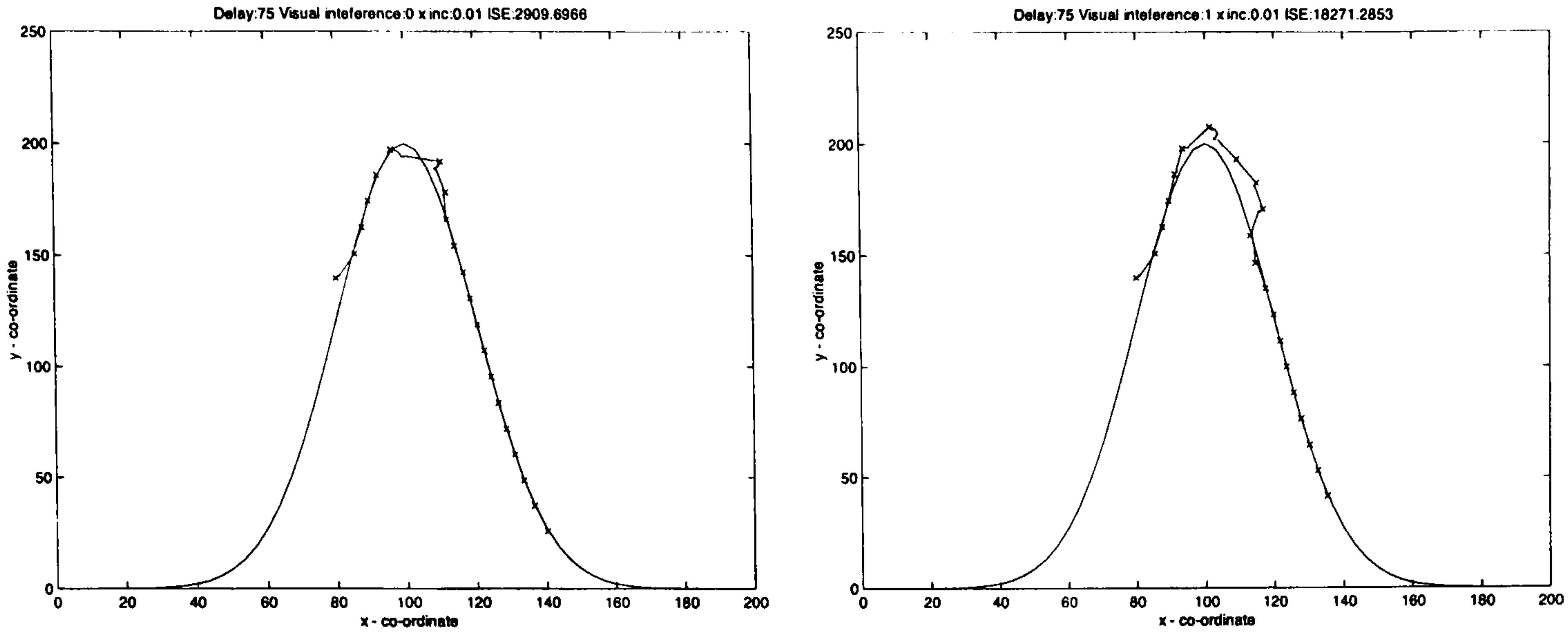


(c) no interference, delay 25 (d) interference, delay 25



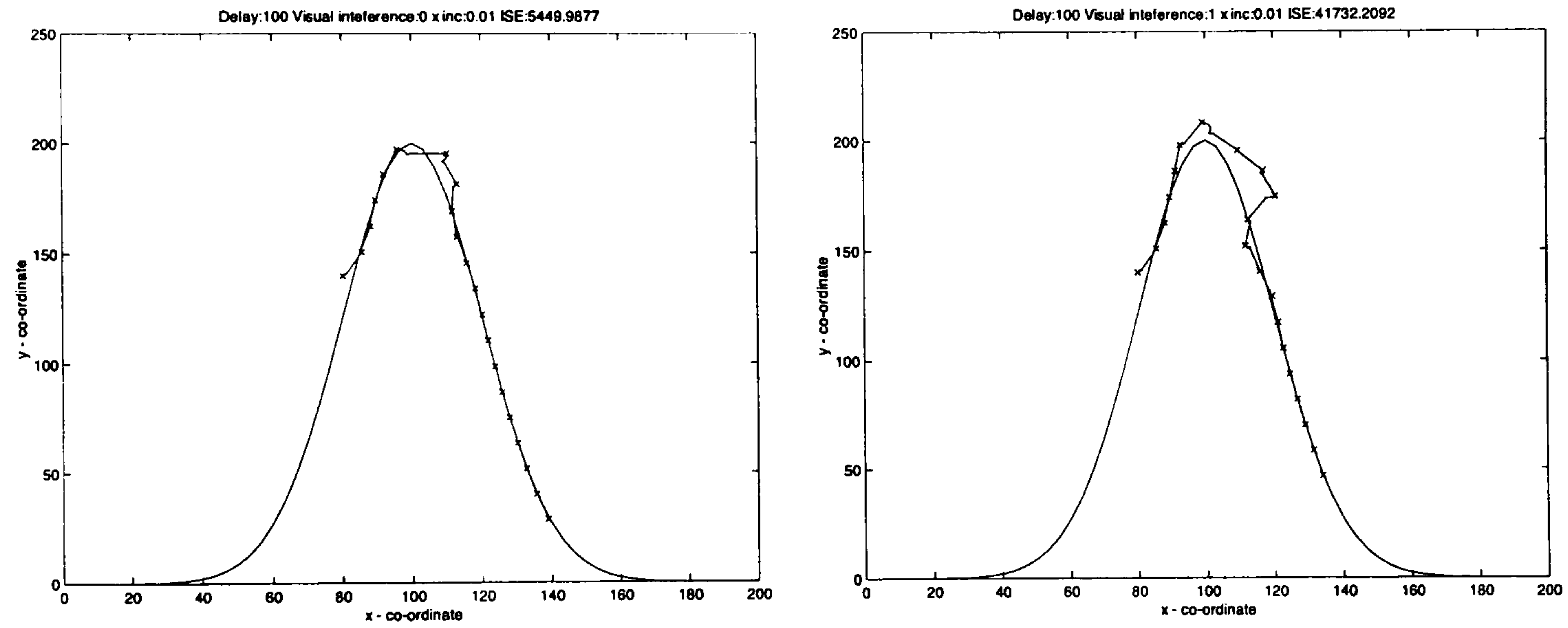
(e) no interference, delay 50 (f) interference, delay 50

Figure 11.16: Control system traces for 0 to 50 sample delays



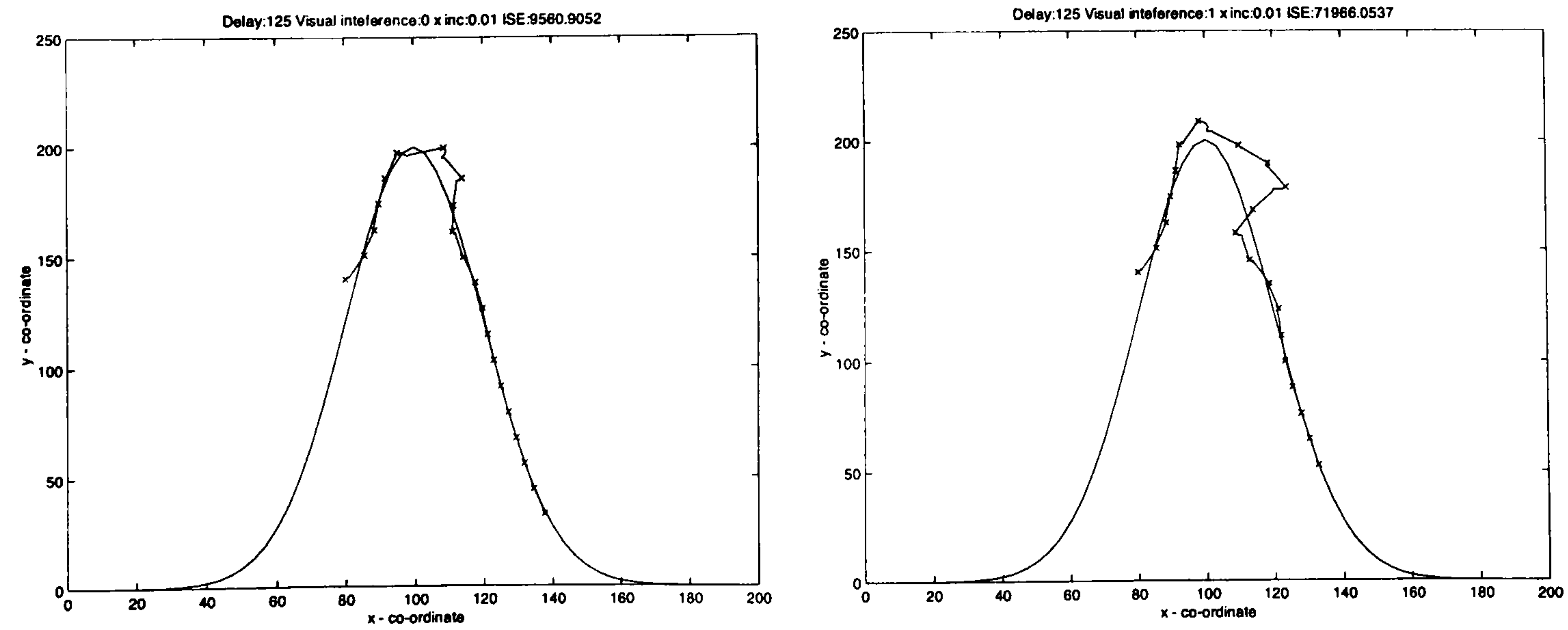
(a) no interference, delay 75

(b) interference, delay 75



(c) no interference, delay 100

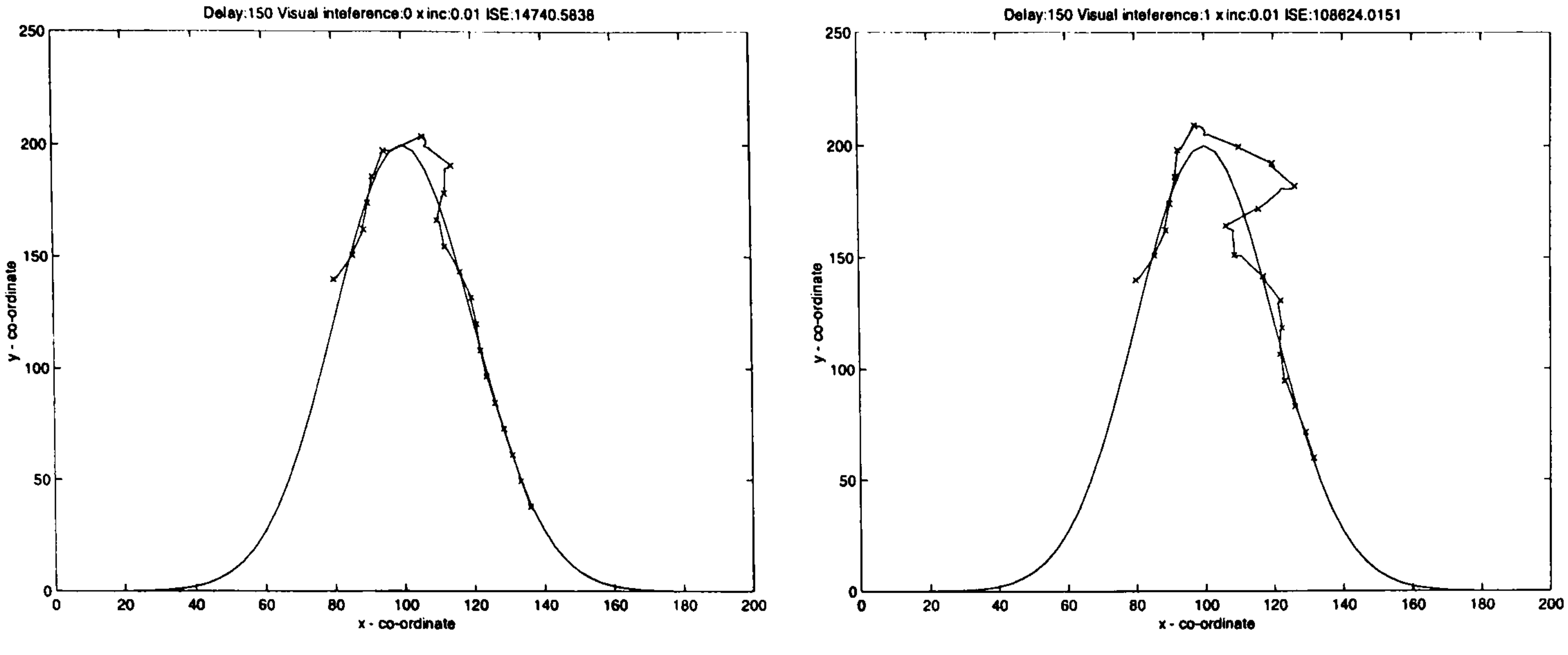
(d) interference, delay 100



(e) no interference, delay 125

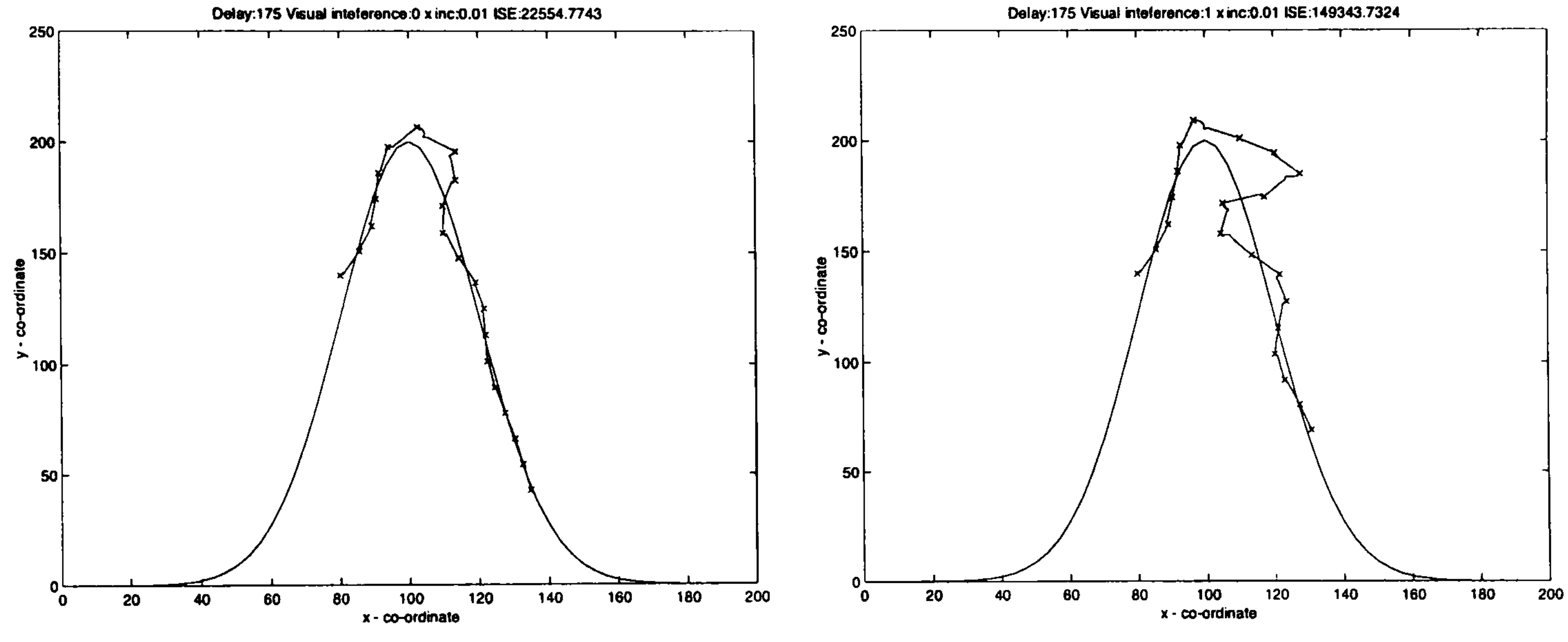
(f) interference, delay 125

Figure 11.17: Control system traces for 75 to 125 sample delays



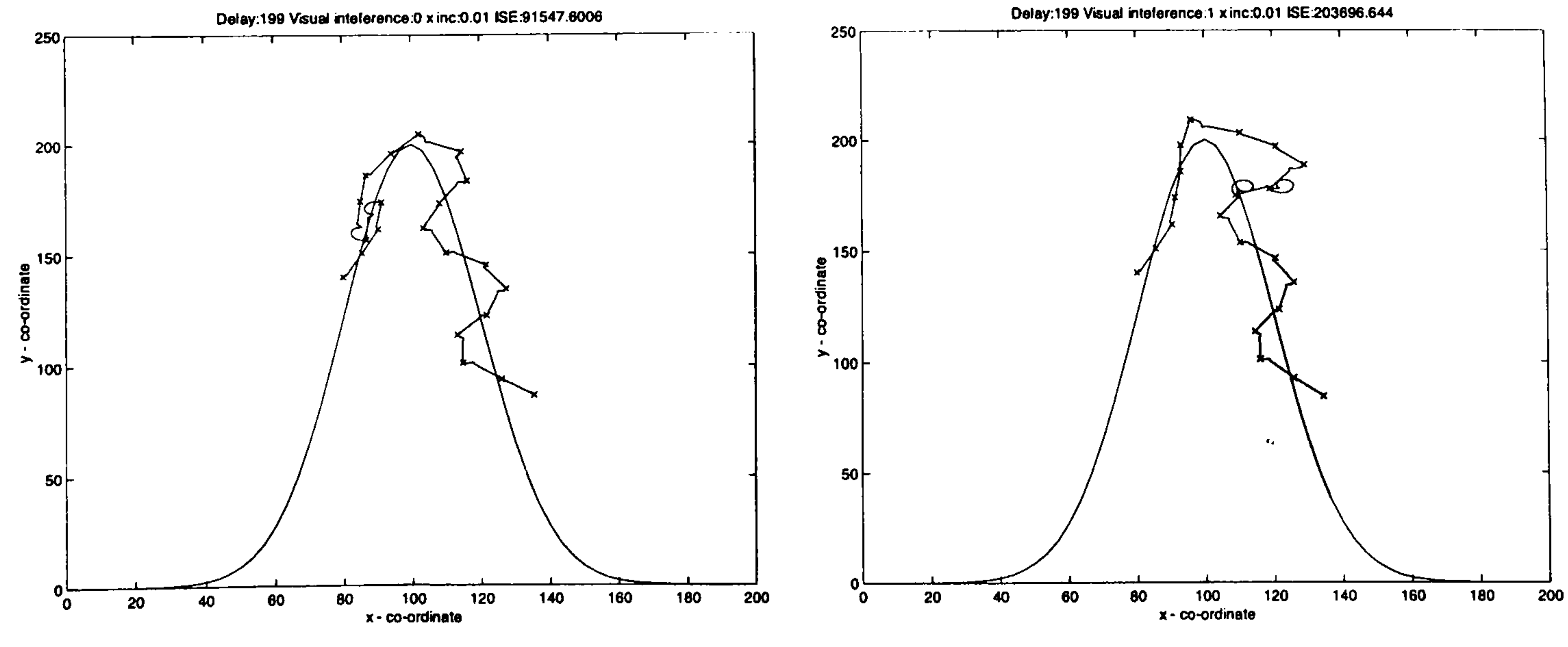
(a) no interference, delay 150

(b) interference, delay 150



(c) no interference, delay 175

(d) interference, delay 175



(e) no interference, delay 199

(f) interference, delay 199

Figure 11.18: Control system traces for 150 to 199 sample delays

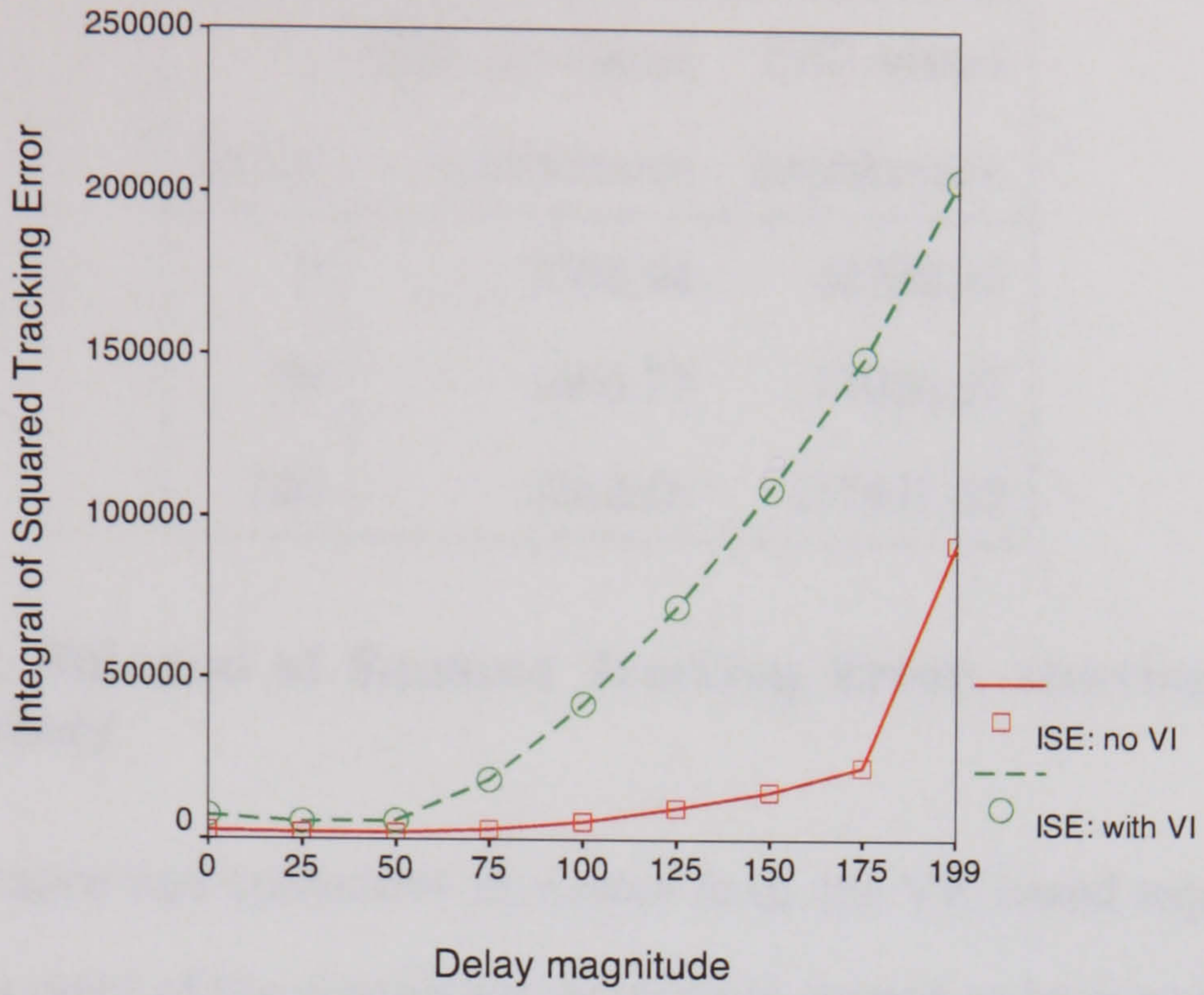


Figure 11.19: ISE for Control System Model

11.6.1 Additional analysis

Additional analysis was performed by changing the start point of the control system to begin on the reference trajectory (rather than a point off the trajectory as was previously the case).

This decision was taken in order to check that the deviations from the reference that were shown before were due to 'confusion' from the delays and interpolated tasks rather than from the start position of the system.

Similar results were seen using this new start position with straight lines being followed successfully and problems experienced at curves under delay or interpolated tasks as was previously the case. Errors are summarised in Table 11.7.

11.7 Discussion

Errors increase with delay magnitude and visual interference tasks. Visual interference appeared to have a very strong effect on performance as was the case with

Delay	ISE: no visual interference	ISE: visual interference
0	2905.94	44792.42
70	1669.77	77026.27
140	8382.66	117447.52

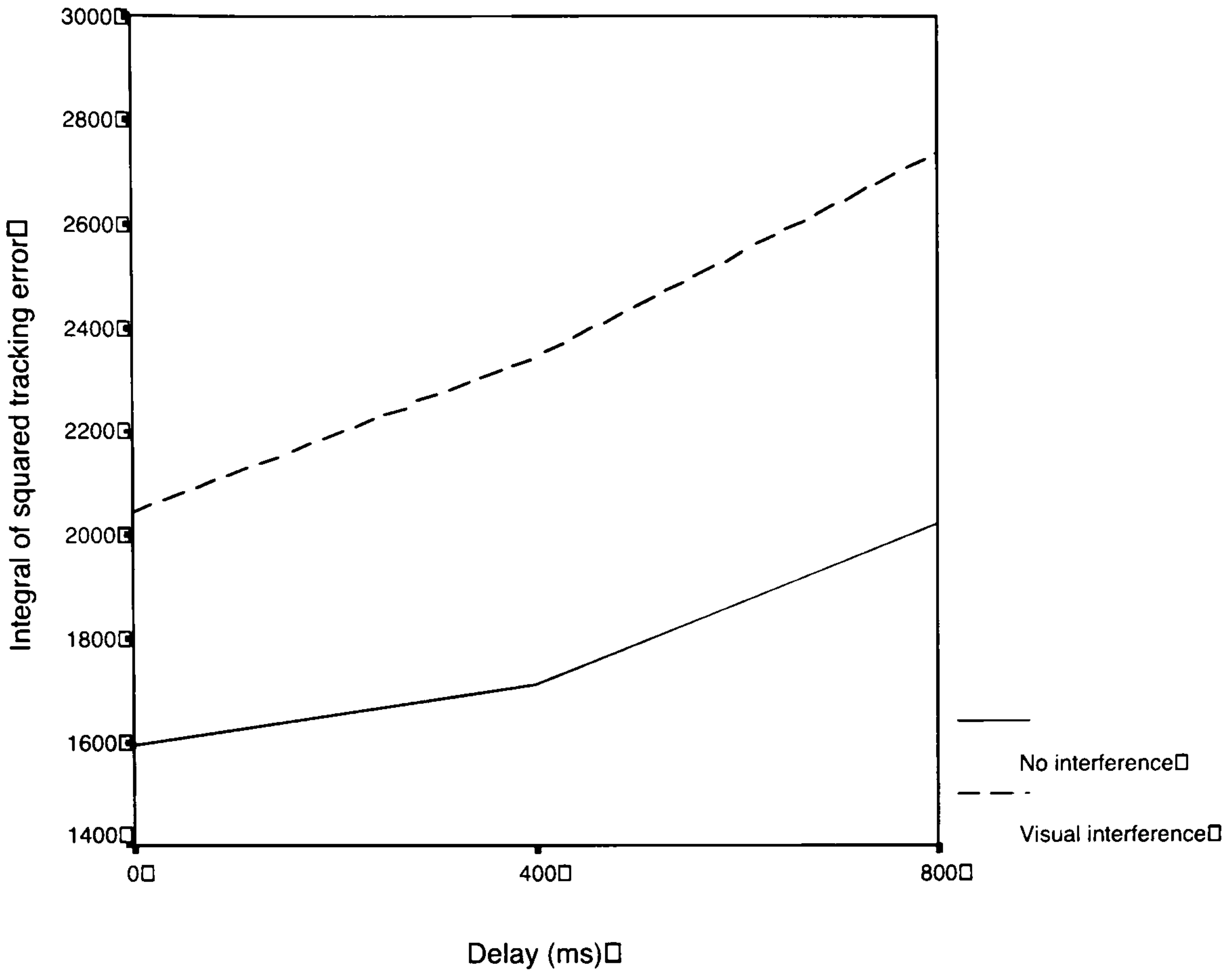
Table 11.7: Integral of Squared Tracking Error: starting on reference trajectory

human performance and subjective measures from the VR based experiments.

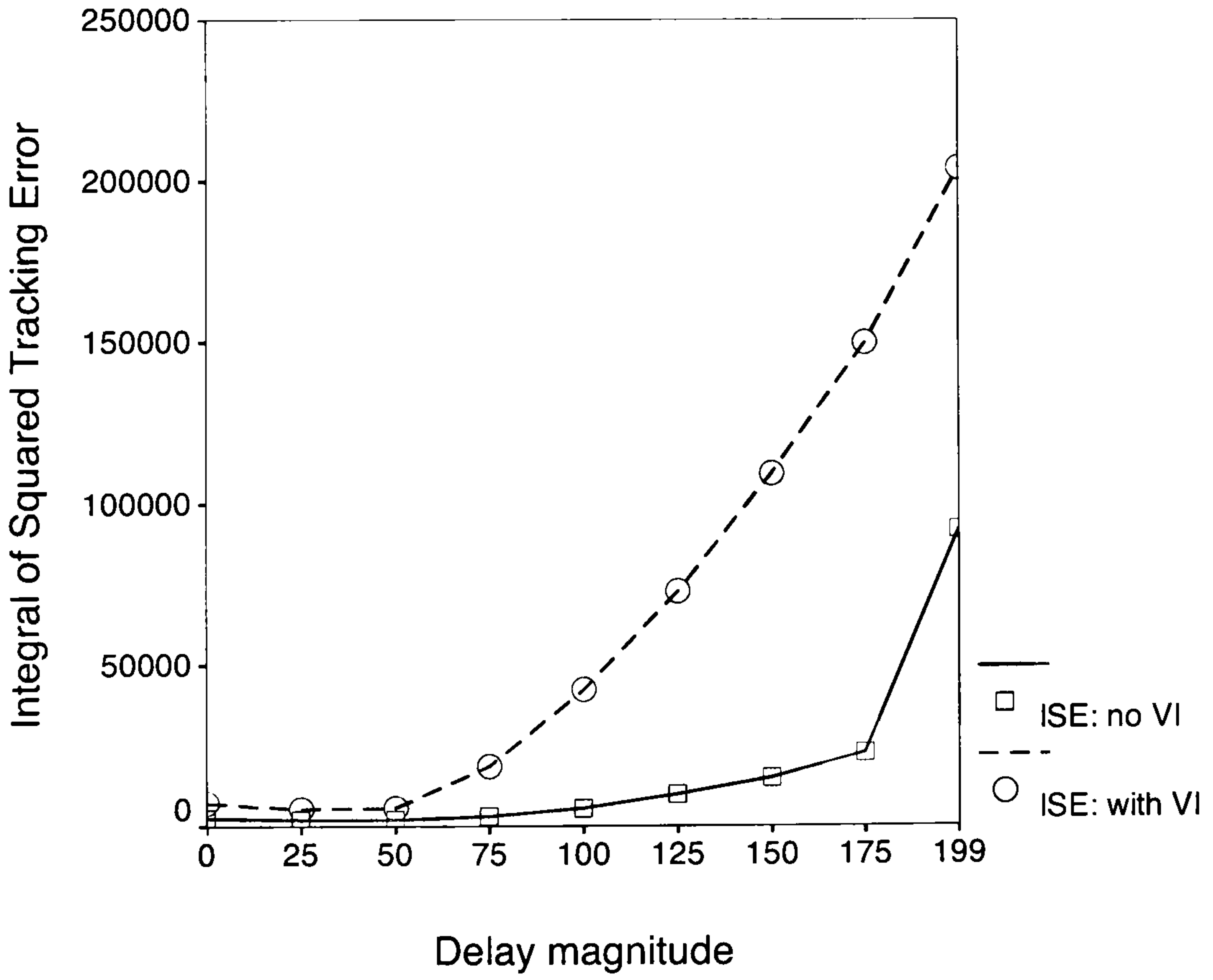
The starting point of the control system did not appear to have a significant effect on the route taken. A similar route was taken whether the system started at a point off the reference trajectory or exactly on it, with straight lines being successfully navigated, and bends causing more problems as was the case with human operators.

As can be seen in a comparison of overall driving performance (measured by the integral of squared tracking error) by the control system compared with human operators, the two give similar results, with errors increasing with delay magnitude, and visual interference tasks causing errors to increase further. It is suggested that the sharp increase in errors from 175 samples onwards demonstrates that the system has become unstable and therefore errors will increase dramatically from this point onwards. These results are summarised in Figure 11.20.

Paired samples t-tests (using SPSS v11.01) showed no significant difference between the ISE tracking errors for the VR experiments and the ISE errors obtained from the control model ($t = 1.263, df = 2, p = 0.334$ for delays without visual interference, $t = 1.319, df = 2, p = 0.318$ with visual interference). This result supports the claim that the control model performs in a similar manner to a human operator with similar performance decrements with visual delays and visual interference tasks.



(a) ISE: human operator



(b) ISE: control system

Figure 11.20: Comparison of Model Performance with Human Performance

11.7 Discussion

From the analysis and subjective comparisons already outlined it can be seen that the control system model described performs in a similar manner to a human operator driving under delayed visual feedback. It is therefore suggested that this model could be used in further work in testing ideas about compensatory methods for aiding operators and performance can be readily analysed using this model rather than running separate experiments to test each new hypothesis.

Chapter 12

Conclusions

12.1 Overview

The work outlined in this thesis has replicated past work in demonstrating a significant effect of delayed visual feedback on operator performance. In addition to simply replicating this work, a major addition to previous work has been made with an explanation of the cognitive mechanisms that are affected by delayed visual feedback. This explanation has also been shown to hold not only for experiments using human operators, but also using a control system that makes use of a system that is analagous to working memory (a temporary storage area used for spatial calculations, which is affected by spatial tasks dependant on not only the duration but also complexity of the task). It is suggested that this model is of use in future investigations in this area as it fails in a similar manner to human operators under similar conditions (with delay and visual interference having a detrimental effect on performance).

In order to summarise, the aims of this research, originally stated in Chapter 1, are restated and evaluated below.

The research aims were as follows:

- To replicate previous work in showing the detrimental effects of delayed visual feedback on operator performance.
- To investigate the cognitive nature of this effect and highlight which cognitive mechanisms appear to be failing.

- To create a virtual environment to enable investigation of complex tasks in a measurable manner and allow interpolated tasks to be incorporated in a natural way.
- To create a model that performs in a similar manner to human operators when using delayed feedback.

The first of these aims, to replicate previous work, has been met by the pilot work described in Chapter 3 and also by the main experimental work described in Chapters 4 and 9. The work outlined in these chapters clearly demonstrates the detrimental effects of delayed visual feedback on operator performance.

The second of these aims, to investigate the cognitive nature of this effect, has also been met with results demonstrating a link between working memory disruption and delayed visual feedback. These results, presented in Chapter 9, give support for the hypothesis that the effects of delayed visual feedback can be understood in terms of working memory disruption. In addition to this empirical data a simulation was constructed and tested that also adopted this hypothesis, as described in Chapter 11. The results of using this simulation also support this hypothesis, in addition to demonstrating that the model, although specific to the task of remote operation of vehicles, is of use in that it both succeeds and fails in a similar manner to human operators.

The third of these aims, namely of creating a virtual environment, has been met with an immersive environment being designed and implemented as documented in Chapters 6 and 7. This thesis has therefore demonstrated the use of virtual environments and immersive virtual reality as a tool for experimental research as was presented in Day et al. (2000)

The final aim, that of creating a model or simulation that performs in a similar manner to human operators, has also been met as described in Chapter 11. The model was derived from empirical data from the pilot studies, and then refined to encapsulate the hypotheses concerning working memory from the main experimental work. This model clearly demonstrates the link between visual interference and visual delays, and forms a useful tool for future simulation and theoretical study as it is sensitive to task complexity and duration and fails in a similar manner to human operators.

12.2 Main findings

The research outlined in this thesis provides an empiric model of the effects of delay on operator performance. It contains several major findings, all of which are original contributions to the area. These are as follows:

- The discovery that the effects of delayed visual feedback are due to visuo-spatial working memory disruption.
- Validation of this claim by empirical studies of human performance and control systems model performance.
- Further validation of this claim by demonstrating that delayed visual feedback cannot be adequately explained in terms of load to the central executive (i.e. loading general working memory resources)
- The demonstration of a link between visual interference and visual delays.
- The derivation of a cognitive model, using a control systems engineering approach, that encapsulates the human cognition involved in remotely operating vehicles under delayed visual feedback. This model not only behaves in a similar manner to human operators but also fails in a similar manner.
- The novel use of virtual reality (VR) as an experimental tool for human factors investigation.

12.3 Hypothesis testing

In order to begin the investigation into delayed visual feedback several hypotheses were formulated (as described in Chapter 4, Section 4.3). These are restated below:

Null hypotheses

H00 An increase in visual delay magnitude will have no effect on driving performance.

H01 The presence of visual interference tasks will have no significant effect on driving performance.

H02 The presence of visual interference tasks will not affect driving performance in a similar manner to visual delays.

H03 An increase in track complexity will have no significant effect on driving performance.

Alternate hypotheses

H11 Results of the experiments will show a similar performance decrement due to delays as has been found in preliminary experiments, namely that an increase in delay magnitude will cause a performance decrement.

H12 There will be threshold value of delay below which the effects of the delays will be negligible.

H13 There will be a threshold value of delay above which the performance does not decrease any more (complete failure).

H14 The spatial letter-processing task will disrupt tracking (driving) performance, i.e. Baddeley's findings will be replicated.

H15 Delays in visual feedback cause confusion due to disruptions in visuo-spatial working memory, therefore visual interference which also disrupts visuo-spatial working memory will give a similar performance decrement to visual delays.

H16 An increase in track complexity will cause a performance decrement.

The null hypotheses **H00**, **H01** and **H03** were rejected as driving performance was significantly affected by visual interference tasks, visual delays, and track complexity as reported in Chapter 9. The alternate hypotheses **H11**, **H14** and **H15** were therefore accepted. **H12** and **H13** could neither be accepted or rejected due to lack of evidence; there was no indication of exactly where these threshold values were (due to the limited number of delay values considered). It is suggested that future studies could investigate a larger number of delay settings in order to test these hypotheses.

The acceptance of these hypotheses is discussed in Sections 12.3.1 to 12.3.4 below. Please also see Section 9.5 of Chapter 9 for a more detailed discussion of the results.

12.3.1 Effects of Visual Interference on Working Memory

As has been discussed in Section 2.7 work has been carried out in designing models of human memory, in particular, a model that explains the difficulty experienced with visuo-spatial interference tasks.

This model, developed by Baddeley et al. (1975) and Baddeley and Lieberman (1980), was used as a basis for the investigations outlined in this thesis. In these investigative studies by Baddeley et al. into the nature of working memory an important fact was ascertained, namely that additional visuo-spatial tasks caused a significant reduction in tracking performance. Results of these visual pursuit rotor tracking experiments are summarised in Table 12.1.

From these results it can clearly be seen that visuo-spatial tasks (such as Brooks'

	Mean percent time on target	**Standard Deviation**
Control *(no memory task)*	90.8	5.7
Verbal memory task *(sentence classification)*	88.0	4.6
Visual memory task *(letter tracing)*	78.0	11.6

Table 12.1: Visual pursuit rotor tracking results

(1968) letter-tracing task used by Baddeley) significantly affect tracking performance.

12.3.2 Replicating Baddeley's results in VR

These tracking performance results were obtained from visual pursuit rotor tracking tasks. This task was then extended into a driving task (in a virtual environment) and the same visual interference tasks used. Baddeley's results were replicated in these modified experiments in order to ascertain whether the modified tasks and equipment had affected the results. More details of these experiments are given in Chapters 4 and 9.

In particular, results showed that visual interference tasks had significant effects on targeting errors. Completion times were not significantly affected by the visual interference tasks. This agrees with the results of Baddeley's work thus showing that the use of driving in a virtual environment is an appropriate extension to the original task of pursuit rotor tracking.

Due to these results the null hypothesis **H01** is rejected and the alternate hypothesis **H14** is accepted (i.e. the spatial letter-tracing task was found to disrupt driving).

12.3.3 Effects of Visual Delay on Working Memory

In addition to investigating the effects of visuo-spatial interference tasks the virtual reality based experiments also considered the effects of visual feedback delays. The reasoning behind this design decision was as follows.

From pilot work already carried out low frame rate visual feedback can be considered as a form of delay. Now, low frame rate feedback can in turn be considered as visual feedback with additional blank 'interference' frames, i.e. low frame rate feedback is similar to inserting interference into the visual feedback. It can therefore be suggested that visual interference may well have similar effects on performance as visual delays.

This reasoning can also be expressed in terms of working memory disruption. It is known that visual interference causes a disruption to visuo-spatial working memory (from work by Baddeley as previously discussed). As visual interference appears to share similarities with visual delays it is therefore suggested that visual delays may also cause a disruption to working memory. In order to investigate this suggestion the two factors were compared experimentally and the effect on performance was measured.

Results showed that delays, in a similar manner to visual interference tasks, were found to have highly significant effects on completion times and ISE tracking errors. Targeting errors and letter tracing tasks were not significantly affected by delays.

These results demonstrate that overall driving performance (measured by tracking errors) was affected in a highly similar manner by visual interference tasks and delays. This therefore supports the hypothesis that visual delays cause disruption of visual working memory (in a similar manner to visual interference tasks). The results also suggest that people sacrificed speed for accuracy in the presence of visual delays but did not under visual interference. This premise is supported by analysis of correlations between measures as described in Section 9.3.

In order to further support this argument that visual delays can be understood to disrupt visuo-spatial working memory, a further comparison was made between visual delays, visual interference tasks (known to disrupt visuo-spatial working memory) and central executive disruption tasks (which place a general load on working memory resources). This additional comparison is presented in Chapters 5 and 10. Results from this experiment demonstrated that visual delays have highly similar effects on performance compared with visual interference tasks, and central executive disruption tasks do not have a significant effect. From this it can be concluded that the original claim, that visual delays can be explained in terms of visuo-spatial working memory disruption, is sound.

From these results the null hypotheses **H00** and **H02** are rejected and alternate hypotheses **H11**, and **H15** are accepted. Additional analysis described in Chapter 9 also means that hypothesis **H16** is accepted.

12.3.4 Modelling work - model and results

In order to support the suggested hypothesis that the detrimental effects of delayed visual feedback can be explained in terms of working memory disruption a control system model was designed and implemented to perform a tracking task around a bend. Results from this model show that the control system yielded similar results to human operators (with performance being measured by the integral of squared tracking error). In both cases errors increased with delay magnitude, and the presence of visual interference tasks caused errors to increase further. More details are given in Chapter 11.

12.4 Discussion

The effect of delayed feedback of all forms on the operation of a system is to reduce the bounds of stability of that system. For example, delayed auditory feedback is known to produce stuttering and blocks in speech (Lee, 1951), delayed visual feedback is known to produce overcompensation in control movements in targeting exercises (McGovern, 1993) and finger oscillations in manual tracking exercises (Beuter et al., 1995). McGovern (1993) mentions this over-control of steering by novices giving rise to what he terms '*vehicle travel oscillating about the desired path*'. These findings have also been reported by Spain (1987). This behaviour has been clearly seen as a result of visual delay in experiments by Day (1998, 1999); Day et al. (1999, 2000, 2001a,b). An important point to note is that the severity of performance degredation is determined not only by the delay magnitude but also the nature of the task itself Keran et al. (1994). For this reason experiments were performed using the task of remote driving.

From the results already presented it can be seen that there is strong support for the argument that visual delays cause disruption to visuo-spatial working memory and therefore cause a marked decrease in performance of the visuo-spatial task of driving (tracking).

This support is based not only on the results yielded by using a behavioural approach (pilot experiments with human operators) but also a cognitive approach (virtual reality based experiments testing a cognitive model of working memory). In addition to this data, results from the control system model, that encapsulates the assumptions regarding visuo-spatial tasks disrupting performance in a similar manner to visual delays, also support this argument.

12.4.1 Possible Solutions

Getting to this stage of being able to support the hypothesis that delayed visual feedback causes disruptions to working memory took three years. For this reason no solutions were attempted to support the operator and reduce disruption to working memory. Possible solutions would have to reduce the load on visuo-spatial working memory, possibly by using spatial cues such as waypoints, orientation guides (compass) or overlays as used in predictive displays. Other ideas that may be worth investigating are to draw analogies from the methods employed in two-dimensional interfaces such as the desktop metaphor, using iconic representations and direct manipulation interfaces. The equivalent to a direct manipulation interface in three-dimensional driving is however somewhat difficult to define. A possible equivalent would be to use full automation of the vehicle. This however defeats the purpose of the study, namely that of human operators in the control loop. An alternative approach is therefore required. Such an alternative could be to use the ideas already employed in producing predictive displays, with some simulated environment being rendered and overlaying the actual feedback. Other similar ideas as were explored by Conner and Holden (1997) in using visual effects to provide immediate feedback for users even when delays were present also appear to be useful if analogies could be found for a 3D world. Effects used in the 2D interface were motion blur, transparency and defocusing. Further investigation would be required to see if any of these ideas could improve usability.

As has been mentioned in Section 2.6 of Chapter 2, there have been many attempts to compensate for delays. These compensatory methods have often been based on an engineering approach (design a solution that seems to help) rather than a cognitive one (understanding the problem in order to help to solve it). However, some of these methods may be utilised together with the understanding gained of delayed visual feedback being a working memory problem. Early solutions involving a *move and wait* strategy are not of use when the vehicle being controlled requires frequent control signals (for example, a submersible operating in a strong current, or a remotely piloted aircraft operating at high speeds).

The area of predictive displays does appear to be a valid solution, particularly if the predictions are based on the cognition of the user rather than contrived formulae that happens to fit the data. These predictive displays range from wireframe graphics overlaying conventional time-delayed displays (Noyes and Sheridan, 1984) to complex computer generated graphical displays (Park, 1991). Such ideas of controlling a virtual robot or vehicle (Bejczy et al., 1990; Sheridan, 1991; Jägersand, 1999) do appear to have much to offer. In particular, the idea expressed in *Smith's principle* (1958) that '*... the output from a system with delay $\mathcal{T}$ is the same as that desired from a delay-free system, only delayed by $\mathcal{T}$*' seems a useful assumption to build into a system the offers some simulated display.

The natural extension of these simulated displays is to model the actual world accurately and produce a virtual world (using VR). In such a system the operator controls a virtual world that responds to the operator with no delays, and the real world and virtual world are compared to ensure the two worlds are the same, apart from the time difference (Hendrix, 1994; James and Caird, 1995; Karron et al., 1997; Tsumaki et al., 1996).

Alternatives to the ideas of using some sort of predictive display or visual cues to show the operator how much delay is present have also been investigated. For example, Graves (1997) considered an enhancement of a bomb disposal robot using some automation on the robot. This led to the operator applying supervisory control rather than direct control thus reducing operator workload. Others have also taken this approach of automating the robot so that, in the example of the Mars Rover vehicle, it will stop moving if it detects an obstacle.

It is possible that the ideas of stochastic resonance (McNamara and Wiesenfeld,

1989) could be used in the development of compensatory measures; namely that of increasing the input noise resulting in an improvement in the output signal-to-noise ratio. The reasoning for this is that delayed visual feedback can be considered as introducing instability into the operator control loop. If one considers this instability as analogous to a high signal-to-noise ratio in the output as Vasilakos and Beuter (1993) suggest, then the idea of introducing some carefully selected input 'noise' in order to improve the stability of the system (i.e. the performance of the operator) may hold. This idea has been explored by Vasilakos and Beuter (1993) among others, by means of mathematical models of the dynamics involved and results showed that augmented noise tended to reduce oscillations therefore suggesting that this idea is worth further investigation.

Another potential source of solutions lies in the area of control engineering. Smith (1957, 1959) outlines a method of introducing a minor feedback loop in order to prevent what Smith calls oscillations due to dead time (some lag due to transportation or flow). The analogy with human behaviour appearing to show some of these oscillatory characteristics (typically of motor control resulting in oscillations of the artifact being operated) is strong, and therefore a similar feedback mechanism might be possible. In a similar manner, Celka (1995) describes using a control scheme for controlling chaotic orbits (for time-delayed feedback systems) and applies this work to optics.

12.4.2 Limitations

It should be noted that there are various limitations to the findings of this thesis.

The control systems model used was based on an assumption regarding the driving strategy. More detailed studies should be made of actual strategies employed for driving and modifications made to the model. In addition to this assumption, the dynamics of the system were defined with values chosen by Prof. George Russell based on his experience of typical values for such a system. However, these values were not fully evaluated to see if they matched the virtual reality based experiments with typical values being chosen (for example, the vehicle dynamics in the VR experiments was not accurately measured to ensure that the control system vehicle simulation shared the same dynamics).

In the interests of keeping the experiments to a reasonable length of time there were only three delay settings investigated (0, 400 and 800 ms). It would be useful to repeat these experiments with a wider range of delays, in particular to further investigate the existence of a threshold value (the point of cognitive failure of the operator) above which an increase in the delay magnitude results in no further performance deficit. This threshold was implied in the experiments with participants demonstrating partial or even complete cognitive failure under large delays with additional visual interference tasks.

As was mentioned in the discussion at the end of Chapter 9, the vehicle was controlled using head movements for heading (steering to the left or right) and mouse button presses for forward movement. It would be useful to compare this rather unusual control method with more conventional actuators; namely a joystick.

It should be noted that it took three years to get to the point of testing and supporting the hypothesis that delays in visual feedback cause a disruption in working memory. This was due to the amount of time spent in searching the literature for relevant work, designing and running pilot studies, selecting and setting up equipment along with the software design and implementation and the design and running of experiments. The VR equipment in particular took approximately one year to write software for, with approximately six months being taken to get the system working on the departmental network, with operating system upgrades and other major issues. The other six months were taken in ascertaining what the system could do, designing software and then implementing and testing the software.

12.5 Future Work

As has been mentioned in the previous section various limitations were imposed on the experimental and modelling work due to time constraints. Running the experiments again with more delay settings would yield interesting data, in particular looking at delays from 0-300 ms to check for a threshold value below which delays do not affect performance and similarly looking at larger delays (1 s and above) to investigate whether there is another threshold above which performance does not get any worse.

It would also be interesting to investigate the strategies that human operators employ to compensate for the visual interference tasks and delayed feedback. Looking at more complicated tracks may also be a useful extension.

Further extensions to the experiments would be to make the virtual environment resemble more closely a particular application of remotely operated vehicles and to modify the control mechanisms accordingly (i.e. use a joystick rather than head movements and a 3D mouse). For instance, the environment could readily be modified to resemble an underwater task with the vehicle modelling a submersible. This would then check the ecological validity of the current experiments.

Another major area of future work is to develop further the control system model. As has already been mentioned the model is based on a naive driving strategy which may need modification on closer investigation of actual strategies employed. In a similar manner the dynamics of the system could be adjusted to ensure a closer correlation with the system being modelled (both human operator and vehicle dynamics).

In addition to these extensions to the model it would also be interesting to test the model using a more complicated required trajectory rather than the single bend that was used in the testing thus far.

The model could also be extended with ideas of compensatory mechanisms and provides an efficient method of testing hypotheses regarding operator performance without the need for extensive laboratory experiments. As such this model, with suitable modifications, may well be of use for those industries that have found delayed visual feedback to be a problem in remote operation of artifacts such as vehicles or manipulators.

As has been mentioned in Section 12.4.1 various partial solutions merit further investigation to see if they can be incorporated with the findings of this thesis to produce solutions that are more closely linked to the cognition of the user.

In addition to this work to produce solutions to the problem of delayed feedback, a more detailed theoretical investigation into the exact nature and parameters of working memory may yield useful general results regarding capacity or load that may have implications for the design of solutions.

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Appendix A

Pilot Work

A.1 Materials for pilot experiment i

A.1.1 Exp i: Pre-Experiment Quesionnaire

Participant no: ☐

Please tick (√) the appropriate box for the answer. If any of the questions are unclear, please feel free to ask for clarification.

1. Age:
   < 21 ☐ 21 – 30 ☐ 31 – 40 ☐ 41 – 50 ☐ 51 – 60 ☐ > 60 ☐
2. Sex:
   Male ☐ Female ☐
3. What is your dominant hand?
   Left ☐ Right ☐
4. Do you usually wear spectacles or contact lenses?
   Yes ☐ No ☐
5. If yes, are you wearing them now?
   Yes ☐ No ☐
6. Do you have any physical problem that could interfere with controlling a vehicle *(e.g. arthritis)*
   Yes ☐ No ☐
7. Using the scale, how frequently do you use a personal computer including both recreational and work use?
   (mark a cross, X, on the line)

   Little 1 2 3 4 5 *Lots*
8. Using the scale, how would you rate your experience with video editing and production?
   (mark a cross, X, on the line)

   No experience 1 2 3 4 5 *Experienced*

9. Using the scale, how would you rate your experience with immersive graphics such as computer games or virtual reality?
   (mark a cross, X, on the line)

   No experience 1 2 3 4 5 *Experienced*

10. How much driving experience do you have (in years)?
    < 1 ☐ 1 – 5 ☐ 5 – 10 ☐ > 10 ☐

11. Have you ever had a driving accident?
    Yes ☐ No ☐

12. If yes, how long ago was this accident? ______________________

13. Using the scale, how would you describe your feelings about driving?
    (mark a cross, X, on the line)

    Hate it 1 2 3 4 5 *Love it*

14. Using the scale, how would you rate your experience with remotely controlled vehicles?
    (mark a cross, X, on the line)

    No experience 1 2 3 4 5 *Experienced*

A.1.2 Exp i: Post-Experiment Quesionnaire

Participant no: ☐

Please tick ($\surd$) the appropriate box for the answer. If any of the questions are unclear, please feel free to ask for clarification.

1. Using the scale, how much do you consider that the delays affected your *ability* to control the vehicle?
   (mark a cross, X, on the line)

   Little 1 2 3 4 5 *Lots*

2. Using the scale, how much do you consider that the delays affected your *enjoyment* when controlling the vehicle?
   (mark a cross, X, on the line)

   Little 1 2 3 4 5 *Lots*

3. Using the scale, how would you rate your enjoyment of controlling the vehicle with *small* delays?
   (mark a cross, X, on the line)

   Hated it 1 2 3 4 5 *Loved it*

4. Using the scale, how would you rate your enjoyment of controlling the vehicle with *large* delays?
   (mark a cross, X, on the line)

   Hated it 1 2 3 4 5 *Loved it*

5. Please rank the following categories according to how important you think they are in making the vehicle easier to use.
   (1=most important, 7=least important, X=not significant)

Size of display	☐
Resolution of display	☐
Frame rate of video	☐
Delay in video	☐
Monochrome video	☐
Camera angle (view angle)	☐
Difficulties in using the controller	☐

6. Would you prefer to have less delay in the display, even if that meant reducing the size or resolution of it?
   Yes ☐ No ☐

7. When did you notice the delays in the system more?
   Straight line ☐ Maneouvering ☐
8. Any other comments: ______________________________*(continue beneath if required)*

A.1.3 Exp i: Data Recording Sheet - Reaction Times and Targeting Errors

Participant no: ☐

Task	Reaction Time (min:s:ms)	Error (mm)	(L/R)	Comments
1	: :			
2	: :			
3	: :			
4	: :			
5	: :			
6	: :			
7	: :			
8	: :			
9	: :			
10	: :			
11	: :			
12	: :			

P1	: :			
P2	: :			
P3	: :			

A.2 Low frame rate video code for exp ii – v5.c

```
/* =====================================================*/
/*                                                      */
/*  Video output program: v5.c                          */
/*  Uses library ISCLLIB.LIB                            */
/*                                                      */
/*  Phil Day  17/03/99                                  */
/*  Modified by David Inglis 04/05/99                   */
/*            - Ctrl Break handler and user input       */
/*                                                      */
/*  Program sets up DT2851/2858 cards, initializes and  */
/*  acquires image on on-board frame buffer 0, copies to */
/*  buffer 1 then ouputs                                */
/*  Using grayscale colour lookup tables for input and  */
/*  output                                              */
/*                                                      */
/*                                                      */
/*                                                      */
/* =====================================================*/

#include <stdio.h>
#include <ctype.h>
#include <stdlib.h>
#include <dos.h>
#include "isdefs.c"

#define INTERNAL_SYNC 0
#define EXTERNAL_SYNC 1
#define OFF 0
#define ON 1
#define EVER ;;

int c_break(void)
{
  printf("Terminated");
  is_display(OFF);
  is_end();

  return(0);
}

void main(int argc, char *argv[])
{
  /* constant defns */
  const unsigned int ip_buffer=0;
  const unsigned int op_buffer=1;

  /* variable declarations */
  int count, loop, del;

  /* create a new ctrl-break handler */
  ctrlbrk(c_break);
```

```
  /* check command line arguments for delay */
  if (argc==1) {
    printf("Please specify delay in msecs, e.g. V5 1000\n (delay for 1 sec)\n");
    exit(0);
  }

  del=atoi(argv[1]);

  /* setup card */
  is_initialize();

  is_select_input_frame(ip_buffer);
  is_select_output_frame(op_buffer);
  is_select_sync_source(EXTERNAL_SYNC);

  is_display(ON);

  printf("Press ctrl+break to exit");

  for(EVER)
  {
    /* acquire image */
    is_acquire(ip_buffer, 1); /* frame_no, frame_count : 0..127, 1..128 */

    /* copy image to op_buffer */
    is_frame_copy(ip_buffer,op_buffer);

    delay(del);
  }
}
```

A.3 Video passthrough code for experiment ii – vid_op2.c

```
/* =====================================================*/
/*                                                      */
/*  Video output program: vid_op2.c                     */
/*  Uses library ISCLLIB.LIB                            */
/*                                                      */
/*  Phil Day  16/03/99                                  */
/*                                                      */
/*                                                      */
/*  Program sets up DT2851/2858 cards, initializes and  */
/*  sets passthrough functionality (display video       */
/*  immediately)                                        */
/*  Using grayscale colour lookup tables for input and  */
/*  output                                              */
/*                                                      */
/*                                                      */
/*                                                      */
/* =====================================================*/

#include <stdio.h>
#include <ctype.h>
#include <stdlib.h>
#include "isdefs.c"


void main()
{
  /* setup card */
  is_initialize();
  is_display(1);
  is_select_input_frame(0);
  is_select_output_frame(0);
  is_select_sync_source(1);  /* 0 = internal sync, 1 = external */
  is_select_ilut(0);        /* 256 grayscale */
  is_select_olut(0);

   /* place in passthrough */
  printf("place in passthro");
  is_passthru();

  is_end();
}
```

Appendix B

Experimental Materials

B.1 Experimental Script

Thank you for agreeing to take part in this study. Please could you fill out the following questionnaire.

[Pre-experiment questionnaire]

Thanks very much. The aim of this study is to investigate the effects that visual delays have on the tasks that people perform. The experiments will consist of driving down a virtual track towards a target with differing amounts of delay in the visual feedback. This is not a test of your ability to control the vehicle, but instead, is simply a method of investigating the effects of visual delays on performance. Any data that is collected will be strictly anonymous.

[Show user the setup]

You will be wearing the following headset, which will be used to display the simulation. Movements of the head to the left and right will result in a change in direction of the vehicle that you are driving, while movements up and down will just change the view angle. Forward movement is achieved by pressing the left most button on the top surface of the 3D mouse. Reversing is achieved by pressing the right most button.

The aim of the task is to keep the vehicle in the middle of the track (shown by the boundary markings), and to hit the target as close to the middle (marked by a vertical green line) as possible.

In addition to the delay that you will sometimes experience in the displayed simulation, there is an additional task that you will have to complete at various points during the experiment. This task will involve a block letter being displayed briefly. The letter will then disappear and you must try to hold it in your mind and trace the corners of the letter from the corner marked with an asterisk. The tracing will be verbal, with you replying 'yes' if the corner is at the extreme top or bottom of the letter, and 'no' otherwise. For example, for the following letter, F, the tracing would be ...

[trace letter F]

On completion of the experiment, you will be asked to fill out a questionnaire giving your judgement of how much the delays affected you. In addition to this, it would be useful if you could explain any problems that you have at the time, e.g. "I've stopped moving because I'm lost". If at any time you feel unwell or upset and wish to stop, please tell me and we will halt the experiment.

There will be a short pause at the beginning of each task while the system loads the track. During this time, the headset will initially display whatever was last seen, will then go black for a short time, and then the new track will be displayed. As soon as this new track appears, you may start the driving task. The task finishes when you hit the target at the end of the track. The display will then freeze. Between each task, there will be brief time to wait while the equipment is reset for the next task.

We will now perform some practice tasks in order to allow you to become more familiar with the equipment.

[track1]

Try driving forward by pressing the left most mouse button. Try turning your whole body slightly to one side to turn the vehicle, and then turn back onto the road. Now drive towards the target and hit it.

[track4]

Try driving forward as before. This time to turn, try rotating your whole body. Experiment with tilting your head forward and back to see more or less of the track. Now drive towards the target and hit it.

[track1FF]

Now try driving as before. When the letter appears, try to carry on driving, but keep the letter in your mind while you trace the corners by saying 'yes' or 'no'. Now drive towards the target and hit it.

Do you have any questions or difficulties with the equipment? Then we will begin the experiment.

[Experiment]

The experiment is now finished. Please could you complete this final questionnaire.

[Post-experiment questionnaire]

Thank you very much for your participation. Are there any more questions that you would like to ask? Thanks for your help and time. Goodbye!

B.2 Pre-experiment Questionnaire

Participant no: ☐

Please tick (√) the appropriate box for the answer. If any of the questions are unclear, feel free to ask for clarification.

1. Age: <21 ☐ 21-30 ☐ 31-40 ☐ 41-50 ☐ 51-60 ☐ >60 ☐
2. Sex: Male ☐ Female ☐
3. Which is your dominant hand? Left ☐ Right ☐
4. Do you normally wear spectacles or contact lenses (for some tasks, or all the time)? No ☐ Yes ☐
5. If you normally wear spectacles or contact lenses, are you wearing them now?
   No ☐ Yes ☐ n/a ☐
6. Do you suffer from epilepsy or any other complaints that can be triggered by using low resolution screens? No ☐ Yes ☐
7. Do you have any physical problems that could interfere with controlling a vehicle (please give details)?
   No ☐ Yes ☐ Details: ______________________________
8. Using the scale, how frequently do use a personal computer including both work and recreational use? *(Mark a cross, X, on the line.)*

   Little 1 2 3 4 5 *Lots*
9. Using the scale, how would you rate your experience with video editing and production? *(Mark a cross, X, on the line.)*

   No experience 1 2 3 4 5 *Very experienced*
10. Using the scale, how would you rate your experience with immersive graphics such as computer games or virtual reality?

    No experience 1 2 3 4 5 *Very experienced*
11. How much driving experience do you have (in years)?
    <1 ☐ 1-5 ☐ 6-10 ☐ >10 ☐
12. Have you ever had a driving accident? No ☐ Yes ☐
13. If so, how long ago was this accident (in years)?
    <1 ☐ 1-5 ☐ 6-10 ☐ >10 ☐

14. Using the scale, how would you describe your feelings about driving?

    Hate it 1 2 3 4 5 *Love it*

15. Using the scale, how would you rate your experience with remotely controlled vehicles or computer based driving simulations?

    No experience 1 2 3 4 5 *Very experienced*

B.3 Post-experiment Questionnaire

Participant no: ☐

Please tick (√) or number the appropriate box for the answer. If any of the questions are unclear, feel free to ask for clarification.

1. Using the scale, how much do you consider that the delays affected your *ability* to control the vehicle? *(Mark a cross, X, on the line.)*

   Little 1 2 3 4 5 *Lots*

2. Using the scale, how much do you consider that the delays affected your *enjoyment* when controlling the vehicle?

   Little 1 2 3 4 5 *Lots*

3. Using the scale, how easy did you find the vehicle to control with the 3D mouse?

   Very difficult 1 2 3 4 5 *Very easy*

4. Using the scale, how easy did you find the vehicle to control with the VR headset?

   Very difficult 1 2 3 4 5 *Very easy*

5. Using the following scales, what were your impressions of the overall system with *no* delays?
   - (a) *Frustrating* 1 2 3 4 5 *Satisfying*
   - (b) *Confusing* 1 2 3 4 5 *Not confusing*
   - (c) *Tiring* 1 2 3 4 5 *Not tiring*
   - (d) *Difficult* 1 2 3 4 5 *Easy*

6. Using the following scales, what were your impressions of the overall system with *large* delays?
   - (a) *Frustrating* 1 2 3 4 5 *Satisfying*
   - (b) *Confusing* 1 2 3 4 5 *Not confusing*
   - (c) *Tiring* 1 2 3 4 5 *Not tiring*
   - (d) *Difficult* 1 2 3 4 5 *Easy*

7. Using the following scales, what were your impressions of the overall system with *no* letter tracing tasks?

(a)	*Frustrating*	1	2	3	4	5	*Satisfying*
(b)	*Confusing*	1	2	3	4	5	*Not confusing*
(c)	*Tiring*	1	2	3	4	5	*Not tiring*
(d)	*Difficult*	1	2	3	4	5	*Easy*

8. Using the following scales, what were your impressions of the overall system *with* letter tracing tasks?

(a)	*Frustrating*	1	2	3	4	5	*Satisfying*
(b)	*Confusing*	1	2	3	4	5	*Not confusing*
(c)	*Tiring*	1	2	3	4	5	*Not tiring*
(d)	*Difficult*	1	2	3	4	5	*Easy*

9. Please rank the following categories according to how important you think they are in making the vehicle easier to control. *(1=very important, 9=less important, X=not significant)*

Size of display ☐
Resolution of display ☐
Colour of objects in simulation ☐
Realism of simulation ☐
Frame rate of display ☐
Delay in display ☐
Letter tracing tasks ☐
Angle of view ☐
Difficulties in using the VR equipment ☐

10. Would you prefer to have less delay in the display, even if that meant reducing the size, resolution or complexity of it? No ☐ Yes ☐

11. When did you notice the delays in the system more?
Straight line ☐ Maneouvering ☐

12. Any other comments: ____________________
(continue beneath if required)

B.4 Data Recording Sheet

Participant no: ☐

	letter 1	letter 2	Comments
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			

Appendix C

Main Experimental Perl Script - experiments.pl

```
#!/usr/local/bin/perl

# This is a script to run the VR based experiments
# into cognitive effects of delayed visual feedback
#
# It goes through the following process
#
#   Gets participant number, looks up order of experimental conditions
#   and letter orders if nec (in exp_order and letter_order)
#   then calls vcrun for relevant VDI file piping output to
#   file (name of form pNcMtX where N=participant number, M condition
#   no, X=trial number
#
# Looks for files 'last_participant', 'exp_order' and 'letter_order' in
#  /home/division/experiments/
#
#
# Expected file format of last_participant:
#  N where N = number of last participant to do experiment
#
# Expected file format of exp_order:
#  30+ lines each of form 'N X .. X ' (30 codes)
#    where N = participant number
#    (ensure that line ends with space before line-feed)
#
# Expected file format of letter_order:
#  30+ lines each of form 'N: L .. L ' (30 letters)
#    where N = participant number
#    (ensure that line ends with space before line-feed)
#
# Modified - delay settings changed to just 3 settings (0, 400, 800 ms)
#   so only have 30 tasks to do.
#
#  Phil Day
#
#  21/08/2000

# Dummy flag = if set=1 then don't run vcrun commands but just print
#  what would be used to execute command
#  (useful for checking program!)
```

C Main Experimental Perl Script - experiments.pl

```
#$dummy=1;   # dummy run - just echo commands
$dummy=0;    # execute commands

# Preamble
print "___________________________________________________________\n";
print " Delayed visual feedback experiment script: experiments.pl\n";
print "                 Phil Day 21/08/2000 \n";
print "___________________________________________________________\n\n";

if ($dummy)
{
  print "** Dummy run - don't execute vcrun just print ";
  print "command syntax **\n\n";
}

print "Generating new participant number...\n";

# look up last participant to do experiment
open(LAST_PARTICIPANT, '+</home/division/experiments/last_participant');
# read last participant number
$last_participant = <LAST_PARTICIPANT>;
#increment
$last_participant++;
# move to start of file
seek(LAST_PARTICIPANT,0,0);
print { LAST_PARTICIPANT } "$last_participant";
close(LAST_PARTICIPANT);

$p_no = $last_participant;

# get participant number
print "Participant Number:$p_no\n\n";

# look up order of exp conditions (in file exp_order)
# <filename means open for input (read)
open(EXP_ORDER, '</home/division/experiments/exp_order');
# read conditions  (@conditions denotes array)
@conditions = <EXP_ORDER>;
close(EXP_ORDER);

# look up order of letters (in file letter_order)
# <filename means open for input (read)
open(LETTER_ORDER, '</home/division/experiments/letter_order');
# read letters
@letters = <LETTER_ORDER>;
close(LETTER_ORDER);

# get required line of experimental order file
#  (works as each participant details are on 1 line)
$exp_line = @conditions[$p_no-1];
# $p_no - 1 as array start at 0, but participant numbering starts at 1
# print "$exp_line\n";

# split line into conditions
```

```
@req_conditions = split / /,$exp_line;

#get required line of letters
$letter_line = @letters[$p_no-1];
# split line into letters
@req_letters = split / /,$letter_line;


# repeat for 30 trials calling relevant vdi files and piping output to
# individual files

# set variables
$letter_count = 1;
# start at 1 as @req_letters[0] contains participant number
$current_letters = "";


# start at 1 as 0 is 'participant number:'
for ($trial_no=1; $trial_no<31; $trial_no++)
{
  print "\nParticipant:$p_no Trial:$trial_no ";
  print "Condition:@req_conditions[$trial_no]\n";

  if (@req_conditions[$trial_no] > 14)
  {
    $current_letters = @req_letters[$letter_count];
    $letter_count++;
    $current_letters .= @req_letters[$letter_count];
    $letter_count++;
  }
  else
  {
    $current_letters = "";
  }

  $op_string = "p";
  $command_string = "vcrun -D PV10=enabled dvise vdifiles/track";

  SWITCH:
  {
    if (@req_conditions[$trial_no]==0)
      {
        $track_no = 1;
        $delay = 0;
      }
    if (@req_conditions[$trial_no]==1)
      {
        $track_no = 2;
        $delay = 0;
      }
    if (@req_conditions[$trial_no]==2)
      {
        $track_no = 3;
        $delay = 0;
```

```
   }
 if (@req_conditions[$trial_no]==3)
   {
     $track_no = 4;
     $delay = 0;
   }
 if (@req_conditions[$trial_no]==4)
   {
     $track_no = 5;
     $delay = 0;
   }
 if (@req_conditions[$trial_no]==5)
   {
     $track_no = 1;
     $delay = 400;
   }
 if (@req_conditions[$trial_no]==6)
   {
     $track_no = 2;
     $delay = 400;
   }
 if (@req_conditions[$trial_no]==7)
   {
     $track_no = 3;
     $delay = 400;
   }
 if (@req_conditions[$trial_no]==8)
   {
     $track_no = 4;
     $delay = 400;
   }
 if (@req_conditions[$trial_no]==9)
   {
     $track_no = 5;
     $delay = 400;
   }
 if (@req_conditions[$trial_no]==10)
   {
     $track_no = 1;
     $delay = 800;
   }
 if (@req_conditions[$trial_no]==11)
   {
     $track_no = 2;
     $delay = 800;
   }
 if (@req_conditions[$trial_no]==12)
   {
     $track_no = 3;
     $delay = 800;
   }
 if (@req_conditions[$trial_no]==13)
   {
     $track_no = 4;
```

```
    $delay = 800;
   }
 if (@req_conditions[$trial_no]==14)
   {
    $track_no = 5;
    $delay = 800;
   }
 if (@req_conditions[$trial_no]==15)
   {
    $track_no = 1;
    $delay = 0;
   }
 if (@req_conditions[$trial_no]==16)
   {
    $track_no = 2;
    $delay = 0;
   }
 if (@req_conditions[$trial_no]==17)
   {
    $track_no = 3;
    $delay = 0;
   }
 if (@req_conditions[$trial_no]==18)
   {
    $track_no = 4;
    $delay = 0;
   }
 if (@req_conditions[$trial_no]==19)
   {
    $track_no = 5;
    $delay = 0;
   }
 if (@req_conditions[$trial_no]==20)
   {
    $track_no = 1;
    $delay = 400;
   }
 if (@req_conditions[$trial_no]==21)
   {
    $track_no = 2;
    $delay = 400;
   }
 if (@req_conditions[$trial_no]==22)
   {
    $track_no = 3;
    $delay = 400;
   }
 if (@req_conditions[$trial_no]==23)
   {
    $track_no = 4;
    $delay = 400;
   }
 if (@req_conditions[$trial_no]==24)
   {
```

```
      $track_no = 5;
      $delay = 400;
    }
  if (@req_conditions[$trial_no]==25)
    {
      $track_no = 1;
      $delay = 800;
    }
  if (@req_conditions[$trial_no]==26)
    {
      $track_no = 2;
      $delay = 800;
    }
  if (@req_conditions[$trial_no]==27)
    {
      $track_no = 3;
      $delay = 800;
    }
  if (@req_conditions[$trial_no]==28)
    {
      $track_no = 4;
      $delay = 800;
    }
  if (@req_conditions[$trial_no]==29)
    {
      $track_no = 5;
      $delay = 800;
    }
}


# generate output filename of form pXcMtN_trackY_dD
#  where X = participant no, M = condition no, N = trial no, Y = track
#    no, D  = delay
#  (track no can also include 2 letters if visual interference)
$op_string .= $p_no;
# . is string concatenation, and X .= Y represents X = X.Y
$op_string .= "c";
if (@req_conditions[$trial_no] < 10) { $op_string .= "0"; }
$op_string .= @req_conditions[$trial_no];
$op_string .= "t";
$op_string .= $trial_no;
# condition
$op_string .= "_track";
$op_string .= $track_no;
$op_string .= $current_letters;
$op_string .= "_d";
$op_string .= $delay;

# pipe output to file
$command_string .= $track_no;
$command_string .= $current_letters;
$command_string .= ".vdi -notoolbox > /home/division/experiments/data/";
$command_string .= $op_string;
```

```
  # kill queues (just in case previous trial didn't end cleanly)
  if ($dummy)
  {
    print "/home/division/bin/killq\n";
  }
  else
  {
    system ("/home/division/bin/killq");
  }

  print "  (P$p_no T$trial_no VI:$current_letters Delay:$delay ms ";
  print "Track:$track_no)\n";
  # wait for keypress before rendering simulation (so can change delays!)
  print "-- Set delay, RESET delay h/w, <ENTER> to continue ";
  print "(B=back N=skip to next) --\n";
  $test = ( <STDIN> );
  if ( ($test =~ /B/) || ($test =~ /b/) ) {
    if ($trial_no > 1) {
      print "** Back to previous trial..\n";
      # reset letter_count if looked up letters in previous trial
      if (@req_conditions[$trial_no] > 14) {
        # this trial looked up 2 letters so set letter_count back 2
        $letter_count = $letter_count -2;
      }
      if (@req_conditions[$trial_no-1] > 14) {
        # previous trial used 2 letters so set letter_count back 2
        $letter_count = $letter_count -2;
      }
      $trial_no=$trial_no-2;  # -2 as gets incremented at end of loop anyway
    }
  }
  elsif ( ($test =~ /N/) || ($test =~ /n/) ) {
    print "** Skipping to next trial..\n";
  }
  else {
    if ($dummy) {
      # render relevant VDI file
      print "$command_string\n";
    }
    else
    {
      system ($command_string);
    }
  }
}

print "\n-- End of experiment for participant $p_no --\n";
```

Appendix D

Example Geometry File - track1.vgf

```
DIV-VIZ2
HEADER
(
  VERSION=1:00;
  DATE=14:08:00;
  TIME=09:05
)
{
}

/*
 *  road17
 * geom file track1.vgf
 *
 * defines track 1 (SSSS) in 1 file to ensure sections line up!
 * with single white lines on edge
 *
 * All objects defined using tristrips.
 *
 * 14/8/2000
 *
 */

OBJECT
(
  NAME=road_object; PLANE=NORMAL; DRAWMODE=FILLED;
)
{
  GEOGROUP (
    NAME=road;
    F_MATERIAL="material/road_materials:GREY1";
    B_MATERIAL=F_MATERIAL;
    VERTEX=NONE;
  )
  {
    // road 20 units wide.  100 long (z)
    TRISTRIP {
{ -10 , -16.99 , 0 }
{ 10 , -16.99 , 0 }
{ -10 , -16.99 , -100 }
{ 10 , -16.99 , -100 }
{ -10 , -16.99 , -200 }
```

```
{ 10 , -16.99 , -200 }
{ -10 , -16.99 , -300 }
{ 10 , -16.99 , -300 }
{ -10 , -16.99 , -400 }
{ 10 , -16.99 , -400 }
    }
  }

  GEOGROUP (
    NAME=edge_lines;
    F_MATERIAL="material/road_materials:WHITE";
    B_MATERIAL=F_MATERIAL;
    VERTEX=NONE;
  )
  {
    // single white lines on sides of road
    // LHS line 1
    TRISTRIP
    {
{ -10 , -16.98 , 0 }
{ -9 , -16.98 , 0 }
{ -10 , -16.98 , -100 }
{ -9 , -16.98 , -100 }
{ -10 , -16.98 , -200 }
{ -9 , -16.98 , -200 }
{ -10 , -16.98 , -300 }
{ -9 , -16.98 , -300 }
{ -10 , -16.98 , -400 }
{ -9 , -16.98 , -400 }
    }

    // LHS line 2
    TRISTRIP
    {
    }


    // RHS line 1
    TRISTRIP
    {
    }

    // RHS line 2
    TRISTRIP
    {
{ 9 , -16.98 , 0 }
{ 10 , -16.98 , 0 }
{ 9 , -16.98 , -100 }
{ 10 , -16.98 , -100 }
{ 9 , -16.98 , -200 }
{ 10 , -16.98 , -200 }
{ 9 , -16.98 , -300 }
{ 10 , -16.98 , -300 }
{ 9 , -16.98 , -400 }
```

```
{ 10 , -16.98 , -400 }
    }
  }

  GEOGROUP (
    NAME=end_target_background;
    F_MATERIAL="material/road_materials:GREY3";
    B_MATERIAL=F_MATERIAL;
    VERTEX=NONE;
  )
  {
    TRISTRIP{
{ -10 , -16.99 , -400 }
{ 10 , -16.99 , -400 }
{ -10 , 0 , -400 }
{ 10 , 0 , -400 }
    }
  }

  GEOGROUP (
    NAME=end_target_foreground;
    F_MATERIAL="material/road_materials:GREEN";
    B_MATERIAL=F_MATERIAL;
    VERTEX=NONE;
  )
  {  /* z at -399.99 so foregd in front of background */
    TRISTRIP{
{ -0.25 , -16.99 , -399.99 }
{ -0.25 , 0 , -399.99 }
{ 0.25 , -16.99 , -399.99 }
{ 0.25 , 0 , -399.99 }
    }
  }
}
```

Appendix E

Example Material File - road_materials.vmf

```
DIV-VIZ2
HEADER
(
  VERSION=2:08;
  DATE=21:5:94;
  TIME=9:13;
  FILETYPE=MATERIAL
)
{
}

MATERIAL(NAME="RED")
{
  AMBIENT {0.5, 0, 0}
  DIFFUSE {0.5, 0, 0}
  EMISSIVE {0.5, 0, 0}
  OPACITY {0.5, 0.5, 0.5}
}

MATERIAL(NAME="DARKRED")
{
  AMBIENT {0.1, 0, 0}
  DIFFUSE {0.1, 0, 0}
  EMISSIVE {0.1, 0, 0}
//  OPACITY {0.5, 0.5, 0.5}
}

MATERIAL(NAME="GREEN")
{
  AMBIENT {0, 1, 0}
  DIFFUSE {0, 1, 0}
  EMISSIVE {0, 1, 0}
}

MATERIAL(NAME="BLUE")
{
  AMBIENT {0, 0, 1}
  DIFFUSE {0, 0, 1}
  EMISSIVE {0, 0, 1}
}
```

E Example Material File - road_materials.vmf

```
MATERIAL(NAME="WHITE")
{
  EMISSIVE {1, 1, 1}
}


MATERIAL(NAME="GREY3")
{
  AMBIENT {0.3, 0.3, 0.3 }
  DIFFUSE {0.3, 0.3, 0.3 }
  EMISSIVE {0.25, 0.25, 0.25 }
}


MATERIAL(NAME="GREY2")
{
  AMBIENT {0.2, 0.2, 0.2 }
  DIFFUSE {0.2, 0.2, 0.2 }
  EMISSIVE {0.2, 0.2, 0.2 }
}


MATERIAL(NAME="GREY1")
{
  AMBIENT {0.1, 0.1, 0.1 }
  DIFFUSE {0.1, 0.1, 0.1 }
  EMISSIVE {0.1, 0.1, 0.1 }
}

MATERIAL(NAME="BLACK")
{
  AMBIENT {0, 0, 0}
  DIFFUSE {0, 0, 0}
  OPACITY {0.5, 0.5, 0.5}
}
```

Appendix F

Example VDI File - track4FG.vdi

```
DIV-VDI1
Header (Version=2:1; Date=6:7:100; Time=16:34; Unit=M ){}

UseLibrary (File="road_materials.bmf"; Type=MaterialsFile ){
}

/* track4.vdi
 *
 * SLRS
 *
 * 2 bends - LR
 * 1 straight, then 1 left, 1 right bend, then 1 straight
 *
 * 11/7/2000
 *
 */


Zone (Name=vdiZone){
  TickRate {50}
  Event  {
    BodyCreate  {
      dvBodyStartupPosition(0, -0.3, 0.8);
      dvBodyLevelFlying(On);
    }
    BodyPartCreate (Limb=hand) { }
    BodyPartCreate (Limb=head)
    {
      dvBodyPartAttach(crosshair1, head, 0, 0.1, -0.19, 0, 0, 0, Off);
      dvBodyPartAttach(letterF, head, 0, 0.09, -0.7, 0, 0, 0, Off);
      dvBodyPartAttach(letterG, head, 0, 0.09, -0.7, 0, 0, 0, Off);
      dvBodyPartAttach(letterM, head, 0, 0.09, -0.7, 0, 0, 0, Off);
      dvBodyPartAttach(letterN, head, 0, 0.09, -0.7, 0, 0, 0, Off);
      dvBodyPartAttach(letterW, head, 0, 0.09, -0.7, 0, 0, 0, Off);
      dvBodyPartAttach(letterZ, head, 0, 0.09, -0.7, 0, 0, 0, Off);
    }
    ZoneEnable {
dvPrint("* Experiment begun at %d\nKey:\tP = current Position\n\tO = current
Orientation\n\tT = current Time (s)\n\n\n");}
 }
 Object (Name=ambientLight) {
   Light  {
```

```
      Type {Ambient }
      State {On }
      Colour {0.35, 0.35, 0.35}
    }
  }
  Object (Name=directLight) {
    Orientation {-45, 0, 0}
    Light  {
      Type {Directional }
      State {On }
      Colour {0.9, 0.9, 0.9}
    }
  }
  Object (Name=startline) {
    Visual  {
      State {Off }
      Geometry {"geometry/startline"}
    }
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {On }
    }
  }
  Object (Name=finishline) {
    Visual  {
      State {Off }
      Geometry {"geometry/finishline"}
    }
    Position {-4.575,0,-9.652}
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {On }
    }
  }
  Object (Name=root) {
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
```

```
      LockPitch
      LockYaw
    }
    Object (Name=ground1) {
      Visual  {
        Geometry {"geometry/ground1"}
      }
      Collision  {
        State {Off }
      }
      Constraints  {
        LockX
        LockY
        LockZ
        LockRoll
        LockPitch
        LockYaw
      }
    }

    Object (Name=road) {
      Visual  {
        State {On }
        Geometry {"geometry/track4"}
      }
      Constraints  {
        LockX
        LockY
        LockZ
        LockRoll
        LockPitch
        LockYaw
      }
    }
  }
  Object (Name=crosshair1) {
    Visual  {
      State {Off }
      Geometry {"geometry/crosshair1"}
    }
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {On }
    }
    Event  {
      Collide (Object=visual_task1)
      {
```

```
        dvPrint("* Interference task visual_task1 started at
  P:%op O:%oo T:%t D:%d\n");

// switch off Collisions on visual_task so can't make letter appear again
dvObjectCollision(visual_task1,NULL,Off,NULL);

        // make letter appear
        dvObjectVisual(letterF, NULL, On, NULL, NULL, NULL);

        // make ground, road and lines disappear
        // (so don't cover parts of the letter)
        dvObjectVisualTree(root,Off,NULL,NULL);

        // trigger an event which switches off letter after 1 secs
        dvObjectDelayedEvent(letterF, User1, 1);
      }
      Collide (Object=visual_task2)
      {
        dvPrint("* Interference task visual_task2 started at
  P:%op O:%oo T:%t D:%d\n");

// switch off Collisions on visual_task so
   // can't make letter appear again
dvObjectCollision(visual_task2,NULL,Off,NULL);

        // make letter appear
        dvObjectVisual(letterG, NULL, On, NULL, NULL, NULL);

        // make ground, road and lines disappear
        // (so don't cover parts of the letter)
        dvObjectVisualTree(root,Off,NULL,NULL);

        // trigger an event which switches off letter
        dvObjectDelayedEvent(letterG, User1, 1);
      }
      Tick  { dvPrint("P:%op O:%oo T:%t D:%d\n"); }

      Collide (Object=startline) {
        dvPrint("* Crossed start line at P:%op O:%op T:%t D:%d\n");
      }
      Collide (Object=finishline) {
        dvPrint("* Crossed finish line at P:%op O:%op T:%t D:%d\n");
        // trigger event which kills visual system thus killing dvise
        dvObjectDelayedEvent(crosshair1, User2, 2);
      }
      User2 {
        // dvPrint("User2 event\n");
        dvExec("/home/division/bin/die","vcrun");
      }
    }
  }

  Object (Name=visual_task1)
  {
```

```
    Visual  {
      State {Off}
      Geometry {"geometry/visual_task1"}
    }
    Position { 0, 0, -2.5}
    // i.e. at 0,0,-100 in geometry, i.e. at end of first straight section
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {On }
    }
  }

  Object (Name=visual_task2)
  {
    Visual  {
      State {Off}
      Geometry {"geometry/visual_task1"}
    }
    Position { -4.75, 0, -7.5}
    // i.e. at (-190, 0, -300) in geometry
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {On }
    }
  }
  Object (Name=letterF) {
    Visual  {
      State {Off }
      Geometry {"geometry/letterF"}
    }
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {Off }
```

```
    }
    Event {
      ObjectCreate (*) {
        // stretch letter in x slightly to make wider
        dvObjectScale (*, 1.1, 1.0, 1.0);
      }
      User1 {
        dvPrint("* %on disappeared at P:%op O:%oo T:%t D:%d\n");

        // make ground, road and lines reappear
        dvObjectVisualTree(root,On,NULL,NULL);

        // make letter disappear
        dvObjectVisual(*, NULL, Off, NULL, NULL, NULL);
      }
    }
  }

  Object (Name=letterG) {
    Visual  {
      State {Off }
      Geometry {"geometry/letterG"}
    }
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {Off }
    }
    Event {
      ObjectCreate (*) {
        // stretch letter in x slightly to make wider
        dvObjectScale (*, 1.1, 1.0, 1.0);
      }
      User1 {
        dvPrint("* %on disappeared at P:%op O:%oo T:%t D:%d\n");

        // make ground, road and lines reappear
        dvObjectVisualTree(root,On,NULL,NULL);

        // make letter disappear
        dvObjectVisual(*, NULL, Off, NULL, NULL, NULL);
      }
    }
  }

  Object (Name=letterM) {
    Visual  {
      State {Off }
```

```
      Geometry {"geometry/letterM"}
    }
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {Off }
    }
    Event {
      ObjectCreate (*) {
        // stretch letter in x slightly to make wider
        dvObjectScale (*, 1.1, 1.0, 1.0);
      }
      User1 {
        dvPrint("* %on disappeared at P:%op O:%oo T:%t D:%d\n");

        // make ground, road and lines reappear
        dvObjectVisualTree(root,On,NULL,NULL);

        // make letter disappear
        dvObjectVisual(*, NULL, Off, NULL, NULL, NULL);
      }
    }
  }

  Object (Name=letterN) {
    Visual  {
      State {Off }
      Geometry {"geometry/letterN"}
    }
    Constraints  {
      LockX
      LockY
      LockZ
      LockRoll
      LockPitch
      LockYaw
    }
    Collision  {
      State {Off }
    }
    Event {
      ObjectCreate (*) {
        // stretch letter in x slightly to make wider
        dvObjectScale (*, 1.1, 1.0, 1.0);
      }
      User1 {
        dvPrint("* %on disappeared at P:%op O:%oo T:%t D:%d\n");
```

```
      // make ground, road and lines reappear
      dvObjectVisualTree(root,On,NULL,NULL);

      // make letter disappear
      dvObjectVisual(*, NULL, Off, NULL, NULL, NULL);
    }
  }
}

Object (Name=letterW) {
  Visual  {
    State {Off }
    Geometry {"geometry/letterW"}
  }
  Constraints  {
    LockX
    LockY
    LockZ
    LockRoll
    LockPitch
    LockYaw
  }
  Collision  {
    State {Off }
  }
  Event {
    ObjectCreate (*) {
      // stretch letter in x slightly to make wider
      dvObjectScale (*, 1.1, 1.0, 1.0);
    }
    User1 {
      dvPrint("* %on disappeared at P:%op O:%oo T:%t D:%d\n");

      // make ground, road and lines reappear
      dvObjectVisualTree(root,On,NULL,NULL);

      // make letter disappear
      dvObjectVisual(*, NULL, Off, NULL, NULL, NULL);
    }
  }
}

Object (Name=letterZ) {
  Visual  {
    State {Off }
    Geometry {"geometry/letterZ"}
  }
  Constraints  {
    LockX
    LockY
    LockZ
    LockRoll
    LockPitch
    LockYaw
```

```
    }
    Collision  {
      State {Off }
    }
    Event {
      ObjectCreate (*) {
        // stretch letter in x slightly to make wider
        dvObjectScale (*, 1.1, 1.0, 1.0);
      }
      User1 {
        dvPrint("* %on disappeared at P:%op O:%oo T:%t D:%d\n");

        // make ground, road and lines reappear
        dvObjectVisualTree(root,On,NULL,NULL);

        // make letter disappear
        dvObjectVisual(*, NULL, Off, NULL, NULL, NULL);
      }
    }
  }
}
```

Appendix G

Experimental Analysis Scripts

G.1 extract_completion_times.pl

```
#!/usr/bin/perl

# This is a script to extract completion times from results of VR based
#   PhD experiments from data files in specified dir
#
# Change made - outputs completion times in order of conditions (0-29)
#   rather than just in order of trial for ease of analysis.
#
#
# Files are searched for 2 strings, $start_line and $finish_line
#  and results are written for each participant in $results_file
#
#  Phil Day
#
#  14/11/2000
#
#
#  works fine except that data files don't seem to always have start
# line entry
# instead, to start line entry, have to search for first line in file
# where z < 0.00
#
# If can't find finish line, completion time is negative.  Thus need
# to manually search for first line in file where z > N and X > M
# (different for each track).


##################################
#
#  Define variables
#
##################################

# size variables
$number_of_subjects = 40;
$number_of_trials = 30;

# search strings
$req_start_line = '\* Crossed start';
$req_finish_line = '\* Crossed finish';
```

G.1 extract_completion_times.pl

```
$results_file = "completion_times";



#######################################
#
#  For each participant N loop around
#  and extract completion times from
#  filenames pNtM... where
#  0<M<41   (trial no)
#
#######################################

print "Extracting completion times from data files.\n";

# get list of files in current directory
@files = glob("p*");  # all filenames matching p*

open(RESULTS_FILE,">> $results_file"); # open file for appending
# write descriptions of each field to results file
$description = "Participant";
for ($i=0; $i<30; $i++) {
  $description .= "\tC$i";
}
print { RESULTS_FILE } "$description";

# for each participant
for ($p_no=1; $p_no<($number_of_subjects+1); $p_no++) {
# for ($p_no=2; $p_no<3; $p_no++) {

  # discard results for participants 1, 22, 28, 34
  # (results discarded as exp not run properly for p1, p22 had 1 eye,
  # p28 had letter N stuck on for 4 trials and so learnt it,
  # p34 noise in lab)
  if ( ($p_no==1) || ($p_no==22) || ($p_no==28) || ($p_no==34)) { next; }

  print "Extracting participant $p_no results.\n";

  # write participant no to results file
  print {RESULTS_FILE} "\n$p_no";

  # for each condition
  for ($condition_no=0;$condition_no<($number_of_trials);$condition_no++) {

    # print "C$condition_no ";

    # read data file for this trial

    # set filename
    # filename starts pPcNN where P = $p_no NN = $condition_no
    #     letter tracing task

    if ( $condition_no < 10 ) {
```

```
      $data_file = "p" . $p_no . "c0" . $condition_no;
    }
    else {
      $data_file = "p" . $p_no . "c" . $condition_no;
    }

    # print "D:$data_file \n";

    # reset variables (so if times not found don't use previous value)
    $start_time = 0;
    $finish_time = 0;
    $start_line = "";
    $finish_line = "";


    # search for filename containing $p_no $condition_no
    foreach $file (@files) {
      #if ($file =~ m?$data_file?) {
# can't use m?blah? in DOS version.  use m/blah/
if ($file =~ m/$data_file/) {
        # m?blah? match blah once only
        #print "P$p_no C$condition_no $file match\n";
        # match if expression matched by regexp is contained in @files
        $data_file = $file;

        $not_found_start=1;

        # get input from file  (open file for reading)
        # if file not exist then don't do anything

        if ( open(DATA_FILE, "< $data_file") )
        {
          @current_data_file = <DATA_FILE>;
        }
  else { print "$data_file not found\n"; }
        close(DATA_FILE);

        foreach $line (@current_data_file) {

          # find start and finish lines

          # only look at lines starting P:(
          if ($line =~ /P:\(/ )
          {
            # get X and Z values from line

            # split line on spaces
            @line_words = split " ", $line;
            # x_posn is @line_words[0] with 'P:(' on front and ',' on end
            # z_posn is @line_words[2] with ')' on end
              #print "X:@line_words[0] Z:@line_words[2]\n";
            $x_posn = substr @line_words[0], 3, -1;
              # chop off first 3 chars and last char
            $z_posn = substr @line_words[2], 0, -1;
```

```
     if ($not_found_start)
     {
      # search for first Z position less than 0

      if ($z_posn < 0) {
       $start_line = $line;
       $not_found_start=0;
      }
     }
     else {
      # search for X and Z to match finish line depending on track_no

      # now $data_file contains trackN so match track_no
      if ($data_file =~ "track1") {
       # Z < -10, X within -0.25 to 0.25 inclusive
       if ( ($z_posn < -10) && (($x_posn <= 0.25) &&
($x_posn >= -0.25)) ) {
        $finish_line = $line ;
        last;
        # stop searching lines as found finish line
       }
      }
      elsif ($data_file =~ "track2") {
       # X < -7.25, Z within -4.5 to -5.0 inclusive
       if ( ($x_posn < -7.25) && (($z_posn <= -4.5) &&
($z_posn >= -5.0)) ) {
        $finish_line = $line ;
        last;
        # stop searching lines as found finish line
       }
      }
      elsif ($data_file =~ "track3") {
       # X > 7.25, Z within -4.5 to -5.0 inclusive
       if ( ($x_posn > 7.25) && (($z_posn <= -4.5) &&
($z_posn >= -5.0)) ) {
        $finish_line = $line ;
        last;
        # stop searching lines as found finish line
       }
      }
      elsif ($data_file =~ "track4") {
       # Z < -9.5, X within -4.25 to -4.75 inclusive
       if ( ($z_posn < -9.5) && (($x_posn <= -4.25) &&
($x_posn >= -4.75)) ) {
        $finish_line = $line ;
        last;
        # stop searching lines as found finish line
       }
      }
      elsif ($data_file =~ "track5") {
       # Z < -9.5, X within 4.25 to 4.75 inclusive
       if ( ($z_posn < -9.5) && (($x_posn <= 4.75) &&
($x_posn >= 4.25)) ) {
```

```
                $finish_line = $line ;
                last;
                # stop searching lines as found finish line
              }
            }
          }
        }
      }

        # extract times from start and finish lines
        # start line of form
          # P:(-0.0224422, -0.172081, -0.053854)
#  O:(-1.38743, -2.87466, -0.636941)
#  T:5.86986 D:Mon Nov 27 10:38:35 2000
        # finish line of form
          # P:(-0.0224422, -0.172081, -0.053854)
#  O:(-1.38743, -2.87466, -0.636941)
#  T:5.86986 D:Mon Nov 27 10:38:35 2000

        #print "Condition $condition_no.Start: $start_line\n";
        #print "Finish: $finish_line \n";

        # split lines on spaces
        @start_line_words = split " ", $start_line;
        @finish_line_words = split " ", $finish_line;
        $start_time = @start_line_words[6];
        $finish_time = @finish_line_words[6];

        # remove T: from front of both numbers
        $start_time = substr $start_time, 2;
        $finish_time = substr $finish_time, 2;

        # print "Start:  $start_time  Finish:  $finish_time\n";
        $completion_time = $finish_time - $start_time;
        # print "Completion time therefore:$completion_time\n\n";

        # write completion time to results file
        print { RESULTS_FILE } "\t$completion_time";
      }
    }
  }
}

close (RESULTS_FILE);
```

G.2 extract_targeting_errors.pl

```
#!/usr/bin/perl

# This is a script to extract targeting errors from results of VR based
#   PhD experiments from data files in specified dir
#
#
#  Phil Day
#
#  13/02/2001
#
#



#################################
#
#  Define variables
#
#################################

# size variables
$number_of_subjects = 40;
$number_of_trials = 30;

$results_file = "targeting_errors";



#######################################
#
#  For each participant N loop around
#  and extract targeting errors from
#  filenames pNtM... where
#  0<M<41   (trial no)
#
#######################################

print "Extracting targeting errors from data files.\n";

# get list of files in current directory
@files = glob("p*");  # all filenames matching p*

open(RESULTS_FILE,">> $results_file");  # open file for appending
# write descriptions of each field to results file
$description = "Participant";
for ($i=0; $i<30; $i++) {
  $description .= "\tC$i";
}
print { RESULTS_FILE } "$description";

# for each participant
for ($p_no=1; $p_no<($number_of_subjects+1); $p_no++) {
#for ($p_no=2; $p_no<3; $p_no++) {
```

```
  # discard results for participants 1, 22, 28, 34
  # (results discarded as exp not run properly for p1, p22 had 1 eye,
  # p28 had letter N stuck on for 4 trials and so learnt it, p34 noise in lab)
  if ( ($p_no==1) || ($p_no==22) || ($p_no==28) || ($p_no==34)) { next; }

  print "Extracting participant $p_no results.\n";

  # write participant no to results file
  print {RESULTS_FILE} "\n$p_no";

  # for each condition
  for ($condition_no=0;$condition_no<($number_of_trials);$condition_no++) {
  #for ($condition_no=0;$condition_no<(2);$condition_no++) {
    # print "C$condition_no ";

    # read data file for this trial

    # set filename
    # filename starts pPcNN where P = $p_no NN = $condition_no
    #     letter tracing task

    if ( $condition_no < 10 ) {
      $data_file = "p" . $p_no . "c0" . $condition_no;
    }
    else {
      $data_file = "p" . $p_no . "c" . $condition_no;
    }

    # print "D:$data_file \n";

    # reset variables (so if times not found don't use previous value)
    $start_time = 0;
    $finish_time = 0;
    $start_line = "";
    $finish_line = "";

    # search for filename containing $p_no $condition_no
    foreach $file (@files) {
      #if ($file =~ m?$data_file?) {
# can't use m?blah? in DOS version.  use m/blah/
if ($file =~ m/$data_file/) {
        # m?blah? match blah once only
        #print "P$p_no C$condition_no $file match\n";
        # match if expression matched by regexp is contained in @files
        $data_file = $file;

        # get input from file  (open file for reading)
        # if file not exist then don't do anything

        if ( open(DATA_FILE, "< $data_file") )
        {
          @current_data_file = <DATA_FILE>;
        }
```

```
  else { print "$data_file not found\n"; }
        close(DATA_FILE);

        foreach $line (@current_data_file) {

          # find finish lines

          # only look at lines starting P:(
          if ($line =~ /P:\(/ )
          {
            # get X and Z values from line

            # split line on spaces
            @line_words = split " ", $line;
            # x_posn is @line_words[0] with 'P:(' on front and ',' on end
            # z_posn is @line_words[2] with ')' on end
              #print "X:@line_words[0] Z:@line_words[2]\n";
            $x_posn = substr @line_words[0], 3, -1;
              # chop off first 3 chars and last char
            $z_posn = substr @line_words[2], 0, -1;

            # search for X and Z to match finish line depending on track_no

            # now $data_file contains trackN so match track_no
            if ($data_file =~ "track1") {
              # Z < -10, X within -0.25 to 0.25 inclusive
              if ( ($z_posn < -10) && (($x_posn <= 0.25) &&
($x_posn >= -0.25)) ) {
                $finish_line = $line ;
                last;
                # stop searching lines as found finish line
              }
            }
            elsif ($data_file =~ "track2") {
              # X < -7.25, Z within -4.5 to -5.0 inclusive
              if ( ($x_posn < -7.25) && (($z_posn <= -4.5) &&
($z_posn >= -5.0)) ) {
                $finish_line = $line ;
                last;
                # stop searching lines as found finish line
              }
            }
            elsif ($data_file =~ "track3") {
              # X > 7.25, Z within -4.5 to -5.0 inclusive
              if ( ($x_posn > 7.25) && (($z_posn <= -4.5) &&
($z_posn >= -5.0)) ) {
                $finish_line = $line ;
                last;
                # stop searching lines as found finish line
              }
            }
            elsif ($data_file =~ "track4") {
              # Z < -9.5, X within -4.25 to -4.75 inclusive
              if ( ($z_posn < -9.5) && (($x_posn <= -4.25) &&
```

```
($x_posn >= -4.75)) ) {
                $finish_line = $line ;
                last;
                # stop searching lines as found finish line
              }
            }
            elsif ($data_file =~ "track5") {
              # Z < -9.5, X within 4.25 to 4.75 inclusive
              if ( ($z_posn < -9.5) && (($x_posn <= 4.75) &&
($x_posn >= 4.25)) ) {
                $finish_line = $line ;
                last;
                # stop searching lines as found finish line
              }
            }
          }
        }

        # extract position from finish lines
        # finish line of form
          # P:(-0.0224422, -0.172081, -0.053854)
 #  0:(-1.38743, -2.87466, -0.636941)
 #  T:5.86986 D:Mon Nov 27 10:38:35 2000

        #print "Condition $condition_no.Finish: $finish_line \n";

        # split lines on spaces
        @finish_line_words = split " ", $finish_line;

        $final_x_posn = substr @finish_line_words[0], 3, -1;
        # chop off first 3 chars and last char
        $final_z_posn = substr @finish_line_words[2], 0, -1;

   # error = sqrt((ideal x - actual x)^2 + (ideal z - actual z)^2)
   # need function that takes 2 2D coordinates and returns error
   # int get_error(actual_x, actual_z, ideal_x, ideal_z);

   # print "Posn: ($final_x_posn,$final_z_posn)\n";
        if ($data_file =~ "track1") {
          # Z < -10, X within -0.25 to 0.25 inclusive
 $ideal_x =  0.0;
 $ideal_z = -10.0;
        }
        elsif ($data_file =~ "track2") {
          # X < -7.25, Z within -4.5 to -5.0 inclusive
 $ideal_x = -7.25;
 $ideal_z = -4.75;
        }
        elsif ($data_file =~ "track3") {
          # X > 7.25, Z within -4.5 to -5.0 inclusive
 $ideal_x =  7.25;
 $ideal_z = -4.75;
        }
        elsif ($data_file =~ "track4") {
```

```
     # Z < -9.5, X within -4.25 to -4.75 inclusive
$ideal_x = -4.50;
$ideal_z = -9.50;
    }
    elsif ($data_file =~ "track5") {
     # Z < -9.5, X within 4.25 to 4.75 inclusive
$ideal_x =  4.50;
$ideal_z = -9.50;
    }

 $final_error = get_error($final_x_posn, $final_z_posn,
$ideal_x, $ideal_z);

    # write completion time to results file
    print { RESULTS_FILE } "\t$final_error";
   }
  }
 }
}

close (RESULTS_FILE);

sub get_error {
 # error = sqrt((ideal x - actual x)^2 + (ideal z - actual z)^2)
 # need function that takes 2 2D coordinates and returns error
 # int get_error(actual_x, actual_z, ideal_x, ideal_z);
 my ($actual_x, $actual_y, $ideal_x, $ideal_y) = @_;

 #print "Actual:($actual_x,$actual_y) Ideal:($ideal_x,$ideal_y) : ";

 $i = $ideal_x - $actual_x;
 $j = $ideal_y - $actual_y;
 # $tmp = sqrt(($i*$i) + ($j*$j));
 $tmp = sqrt((($ideal_x - $actual_x)*($ideal_x - $actual_x)) +
(($ideal_y - $actual_y)*($ideal_y - $actual_y)));

 $result = sqrt((($ideal_x - $actual_x)*($ideal_x - $actual_x)) +
(($ideal_y - $actual_y)*($ideal_y - $actual_y)));

 #print "$result \n";

 return $result;
}
```

G.3 extract_trace_positions.pl

```
#!/usr/bin/perl

# This is a script to extract X & Z positions from results of VR based
#   PhD experiments from data files in specified dir
#
# Positions are written to files for use in Matlab to plot traces of
#   user position against track boundaries
#
# 120 files written: of form pNcM where N = 1..5, M = 0..29
#   files written in subdirectory of current called results/
#
#  Phil Day
#
#  22/12/2000
#
#

#################################
#
#  Define variables
#
#################################

# size variables
$number_of_subjects = 40;
$number_of_conditions = 30;

print "Extracting positions from data files.";

# get list of files in current directory
@files = glob("p*");  # all filenames matching p*

# for each participant 1..40
for ($p_no=1; $p_no<($number_of_subjects+1); $p_no++) {

  # discard results for participants 1, 22, 28, 34
  # (results discarded as exp not run properly for p1, p22 had 1 eye,
  #  p28 had letter N stuck on for 4 trials and so learnt it,
  #  p34 noise in lab)
  if ( ($p_no==1) || ($p_no==22) || ($p_no==28) || ($p_no==34)) { next; }


  print "\nExtracting results for participant $p_no";

  # for each condition 0..29
  for ($cond=0; $cond<$number_of_conditions; $cond++) {

    # read file that matches pNcM
    if ($cond < 10) {
      $req_file = "p" . $p_no . "c0" . $cond;
    }
    else {
```

```
      $req_file = "p" . $p_no . "c" . $cond;
    }

    foreach $file (@files) {
      if ($file =~ m/$req_file/) {
        # m?blah? match blah once only (Only in Unix version)

  # print "$file $req_file\n";

        # setup files for results
        $results_filex = "results/p" . $p_no . "c" . $cond . "x.m";
        $results_filez = "results/p" . $p_no . "c" . $cond . "z.m";

        open(RESULTS_X,">> $results_filex");  # open file for appending
        open(RESULTS_Z,">> $results_filez");  # open file for appending
        print {RESULTS_X} "p" . $p_no . "c" . $cond . "x = [";
        print {RESULTS_Z} "p" . $p_no . "c" . $cond . "z = [";

        # read file
        # get input from file  (open file for reading)
        # if file not exist then don't do anything
        if ( open(DATA_FILE, "< $file") )
        {
          @current_data_file = <DATA_FILE>;
        }
        close(DATA_FILE);

        foreach $line (@current_data_file) {
          # only look at lines starting P:(
          if ($line =~ /^P:\(/ )
          {
            # reset variables
            $x_posn ="";
            $z_posn ="";

            # get X and Z values from line

            # split line on spaces
            @line_words = split " ", $line;
            # x_posn is @line_words[0] with 'P:(' on front and ',' on end
            # z_posn is @line_words[2] with ')' on end
              #print "$line\n";
            $x_posn = substr @line_words[0], 3, -1;
            # chop off first 3 chars and last char
            $z_posn = substr @line_words[2], 0, -1;
              #print "X:$x_posn Z:$z_posn before\n";

            # convert numbers into VDI scale (*40)
            $x_posn = $x_posn * 40.0;
            $z_posn = $z_posn * 40.0;
              #print " X:$x_posn Z:$z_posn after\n";

            # write to x and z results files
            print {RESULTS_X} "$x_posn\n";
```

```
            print {RESULTS_Z} "$z_posn\n";
          }
        } # end foreach line

      }
      #else { print "$file not match $req_file \n"; }
    } # end foreach $file (@files)

  print {RESULTS_X} "]";
  print {RESULTS_Z} "]";
  close (RESULTS_X);
  close (RESULTS_Z);
  }
}
```

G.4 extract_tracking_errors.pl

```
#!/usr/bin/perl

# This is a script to extract tracking errors from results of VR based
#   PhD experiments from data files in specified dir
#
#  Phil Day
#
#  23/02/2001
#
#



##################################
#
#  Define variables
#
##################################

# size variables
$number_of_subjects = 40;
$number_of_trials = 30;


########################################
#
#  For each participant N loop around
#  and extract targeting errors from
#  filenames pNtM...
#
########################################

print "Extracting tracking errors from data files.\n";

# get list of files in current directory
@files = glob("p*");  # all filenames matching p*

# for each participant
#for ($p_no=1; $p_no<($number_of_subjects+1); $p_no++) {
for ($p_no=17; $p_no<($number_of_subjects+1); $p_no++) {
# temp hack to resume calcs

  # discard results for participants 1, 22, 28, 34
  # (results discarded as exp not run properly for p1, p22 had 1 eye,
  # p28 had letter N stuck on for 4 trials and so learnt it, p34 noise in lab)
  if ( ($p_no==1) || ($p_no==22) || ($p_no==28) || ($p_no==34)) { next; }

  print "\nExtracting participant $p_no results.  ";

  # for each condition
    #$number_of_trials=2; # temp hack
  for ($condition_no=0;$condition_no<($number_of_trials);$condition_no++) {
      # read file
```

```
# temp hack to only calculate for straight track
# if ( ($condition_no==0) || ($condition_no==5) || ($condition_no==10) ||
#($condition_no==15) || ($condition_no==20) || ($condition_no==25) )
{
    # set filename
    # filename starts pPcNN where P = $p_no NN = $condition_no
    #    letter tracing task

    if ( $condition_no < 10 ) {
      $data_file = "p" . $p_no . "c0" . $condition_no;
    }
    else {
      $data_file = "p" . $p_no . "c" . $condition_no;
    }

 # create results file
 $results_file = "errors\\" . $data_file;
 # open(RESULTS_FILE,">> $results_file");  # open file for appending
 if ( open(RESULTS_FILE,">> $results_file") ) {
 }
 else {
   print "$results_file not opened\n";
    }

 print "c$condition_no ";
 print { RESULTS_FILE } "P:$p_no C:$condition_no tracking errors\n";

    # search for filename containing $p_no $condition_no
    foreach $file (@files) {
# can't use m?blah? in DOS version.  use m/blah/
if ($file =~ m/$data_file/) {
        # match if expression matched by regexp is contained in @files
        $data_file = $file;

        # get input from file  (open file for reading)
        # if file not exist then don't do anything

        if ( open(DATA_FILE, "< $data_file") )
        {
          @current_data_file = <DATA_FILE>;
        }
  else { print "$data_file not found\n"; }
        close(DATA_FILE);

        # set flags
        $not_found_start=1;
        $not_found_finish=1;

        foreach $line (@current_data_file) {

          # only look at lines starting P:(
          if ( ($line =~ /P:\(/ ) && $not_found_finish )
          {
```

```
            # get X and Z values from line

            # split line on spaces
            @line_words = split " ", $line;
            # x_posn is @line_words[0] with 'P:(' on front and ',' on end
            # z_posn is @line_words[2] with ')' on end
              #print "X:@line_words[0] Z:@line_words[2]\n";
            $x_posn = substr @line_words[0], 3, -1;
              # chop off first 3 chars and last char
            $z_posn = substr @line_words[2], 0, -1;

            ################################
# check for start line
################################

# skip all lines before start line crossed
            if ($not_found_start)
            {
              # search for first Z position less than 0
              if ($z_posn < 0) {
                $start_line = $line;
                $not_found_start=0;
              }
            }
else {

################################
# check for finish line
################################

  # if finish line then don't look at following lines
              # i.e. $not_found_finish = 0; last;

  if ($data_file =~ "track1") {
                # Z < -10, X within -0.25 to 0.25 inclusive
                if ( ($z_posn < -10) && (($x_posn <= 0.25) &&
($x_posn >= -0.25)) ) {
                  $not_found_finish = 0;
                  last;
                  # stop searching lines as found finish line
                }
              }
              elsif ($data_file =~ "track2") {
                # X < -7.25, Z within -4.5 to -5.0 inclusive
                if ( ($x_posn < -7.25) && (($z_posn <= -4.5) &&
($z_posn >= -5.0)) ) {
                  $not_found_finish = 0;
                  last;
                  # stop searching lines as found finish line
                }
              }
              elsif ($data_file =~ "track3") {
                # X > 7.25, Z within -4.5 to -5.0 inclusive
                if ( ($x_posn > 7.25) && (($z_posn <= -4.5) &&
```

```
($z_posn >= -5.0)) ) {
         $not_found_finish = 0;
         last;
         # stop seaching lines as found finish line
        }
       }
       elsif ($data_file =~ "track4") {
        # Z < -9.5, X within -4.25 to -4.75 inclusive
        if ( ($z_posn < -9.5) && (($x_posn <= -4.25) &&
($x_posn >= -4.75)) ) {
         $not_found_finish = 0;
         last;
         # stop searching lines as found finish line
        }
       }
       elsif ($data_file =~ "track5") {
        # Z < -9.5, X within 4.25 to 4.75 inclusive
        if ( ($z_posn < -9.5) && (($x_posn <= 4.75) &&
($x_posn >= 4.25)) ) {
         $not_found_finish = 0;
         last;
         # stop searching lines as found finish line
        }
       }

 ############################
 # calculate error
 ############################

 # get track_no
  # calculate distance from closest point on midline each time

 # read midline into memory
 # each line of file of form X<tab>Z
 if ($data_file =~ "track1") {
if ( open(MIDLINE_FILE, "< t1_midline") ) {
  @midline = <MIDLINE_FILE>;
}
else { print "t1_midline file not found \n"; }
close (MIDLINE_FILE);
 }
 elsif ($data_file =~ "track2") {
if ( open(MIDLINE_FILE, "< t2_midline") ) {
  @midline = <MIDLINE_FILE>;
}
else { print "t2_midline file not found \n"; }
close (MIDLINE_FILE);
 }
 elsif ($data_file =~ "track3"){
if ( open(MIDLINE_FILE, "< t3_midline") ) {
  @midline = <MIDLINE_FILE>;
}
else { print "t3_midline file not found \n"; }
close (MIDLINE_FILE);
```

```
 }
 elsif ($data_file =~ "track4"){
if ( open(MIDLINE_FILE, "< t4_midline") ) {
  @midline = <MIDLINE_FILE>;
}
else { print "t4_midline file not found \n"; }
close (MIDLINE_FILE);
 }
 elsif ($data_file =~ "track5"){
if ( open(MIDLINE_FILE, "< t5_midline") ) {
  @midline = <MIDLINE_FILE>;
}
else { print "t5_midline file not found \n"; }
close (MIDLINE_FILE);
 }

 # initialise variable
 $min_distance = 9999;

 # for each line in file
    # get position
    # find closest point on midline (i.e. distance is smallest)
 foreach $posn (@midline) {
   # get values from line
@midline_nos = split "\t", $posn;
$midx = @midline_nos[0];
$midz = @midline_nos[1];
   $distance = get_distance($x_posn, $z_posn, $midx, $midz);

# store if minimal value so far
if ( $distance < $min_distance ) {
  $min_distance = $distance;
}
 }

    # calculate tracking error
 $error = $min_distance;

  # write error to file
  print { RESULTS_FILE } "$error\n";
} # end else (check for finish line)
 } # end if line starts P:(
  } # end foreach line in file
  } # end if file matches data_file
} # end for each file in directory

    close(RESULTS_FILE);
} # end if condition 0, 5, 10, 15, 20 or 25
  }
  # end of for all conditions loop
}
# end of for all participants loop

sub get_distance {
```

```
  # distance between 2 points using Pythagorus' theorum

  # give params meaningful names
  my ($x1, $y1, $x2, $y2) = @_;

  $result = sqrt( (($x1-$x2)*($x1-$x2)) + (($y1-$y2)*($y1-$y2)) );

  # print "Result: $result \n";

  return $result;
}
```

G.5 summarise_tracking_errors.pl

```
#!/usr/bin/perl

# This is a script to summarise tracking errors generated by
#  extract_tracking_errors.pl
#
#  Phil Day
#
#  12/03/2001
#  modified 08/08/2001 to give sum of squared rather than mean and total
#


#################################
#
#  Define variables
#
#################################

# size variables
$number_of_subjects = 40;
$number_of_trials = 30;
$results_file = "IS_tracking_errors";

#######################################
#
#  For each participant N loop around
#  and summarise targeting errors from
#  filenames pNcM
#
#######################################

print "Summarising tracking errors.\n";

# get list of files in current directory
@files = glob("p*");  # all filenames matching p*

#  create results files
if ( open(RESULTS_FILE,">> $results_file") ) {
}
else {
  print "$results_file not opened\n";
}

# write column headings to results files
print { RESULTS_FILE } "P_NO";
for ($condition_no=0;$condition_no<($number_of_trials);$condition_no++) {
    print { RESULTS_FILE } "\tC$condition_no";
}
print { RESULTS_FILE } "\n";

# for each participant
  #$number_of_subjects = 2; # temp hack
```

```
for ($p_no=1; $p_no<($number_of_subjects+1); $p_no++) {

  # discard results for participants 1, 22, 28, 34
  # (results discarded as exp not run properly for p1, p22 had 1 eye,
  # p28 had letter N stuck on for 4 trials and so learnt it, p34 noise in lab)
  if ( ($p_no==1) || ($p_no==22) || ($p_no==28) || ($p_no==34)) { next; }

  print "\nExtracting participant $p_no results.  ";
  print { RESULTS_FILE } "$p_no";

  # for each condition
    #$number_of_trials=2; # temp hack
  for ($condition_no=0;$condition_no<($number_of_trials);$condition_no++) {
    # set filename
    # filename starts pPcNN where P = $p_no NN = $condition_no
    #     letter tracing task

    if ( $condition_no < 10 ) {
      $data_file = "p" . $p_no . "c0" . $condition_no;
    }
    else {
      $data_file = "p" . $p_no . "c" . $condition_no;
    }



    # search for filename containing $p_no $condition_no
    foreach $file (@files) {
# can't use m?blah? in DOS version.  use m/blah/
if ($file =~ m/$data_file/) {
        # match if expression matched by regexp is contained in @files
        $data_file = $file;

        # get input from file  (open file for reading)
        # if file not exist then don't do anything

        if ( open(DATA_FILE, "< $data_file") )
        {
          @current_data_file = <DATA_FILE>;
        }
  else { print "$data_file not found\n"; }
        close(DATA_FILE);

        # reset vars
  $count = 0; $total=0; $square=0;

        foreach $line (@current_data_file) {
    if ($count>0) { # discard 1st line
   # square targeting error
$square = $line * $line;
   $total += $square;
 }
 $count++;
  } # end foreach line in file
```

```
  print "P$p_no C$condition_no Tot squared err:$total\n";
  } # end if file matches data_file
} # end for each file in directory

# write results to files
   print { RESULTS_FILE } "\t$total";
  }
  # end of for all conditions loop
  print { RESULTS_FILE } "\n";
}
# end of for all participants loop

close(RESULTS_FILE);
```

Appendix H

Random Order Generation Program

```
#include "stdio.h"
#include "stdlib.h"

int main()
{
  /*
   * true = non zero, false = 0
   * array of flags each set true if got the number
   */

  int got_num[30];
  int tmp = 0;
  int store[30];
  int participants=40;
  int no_conditions=30;
  int count,loop,i=0;
  char blah;

  for (count=0; count<participants; count++)
  {
    /* reset flags to false */
    for (i=0; i<no_conditions; i++)
      got_num[i] = 0;

    /* seed random no gen */
    srand(count);

    for (loop=0; loop<=(no_conditions-1); loop++)
    {
      /* get random number */
      tmp = randint(no_conditions);

      if (!got_num[tmp])
      {
        /* if have not already got that number then store it */
        store[loop] = tmp;
        /* set flag so don't get again */
        got_num[tmp]=1;
      }
      else
      {
        /* else if have already got it don't store and try another random num */
```

```
        loop--;
      }
    }

    /* output results */
    printf( "%d: ", count+1 );
    for (i=0; i<no_conditions; i++)
      printf("%d ", store[i] );
    printf("\n");
  }
}

int randint(int u)  /* 0..1-u */
{
  int r = rand();
  if  (r<0) r
  =-r;
  return r%u;
}
```

Appendix I

Delay Hardware Documentation

I.1 Delay Hardware Circuit

The layout of the delay circuit is shown in Figure I.1.

I.2 Systems settings - ipu.inp

```
############################################################################
#
# IPU Unit device
#
############################################################################

%include  "defaults.cfg"

#
# Define the configuration for the Fastrak
#

Fastrak {
    Port        "$(FASTRAK_PORT)"
    BaudRate     $(FASTRAK_BAUD)
    UpdateRate  10
#   FastrakFormat euler

    #
    # Sensor for hand.
    #
    Sensor 1 {
        Name    "hand"
        preOrientation (0, -90, 90)
    }

    #
    # Sensor for head.
    #
    Sensor 2 {
       Name    "head"
    }
}

#
```

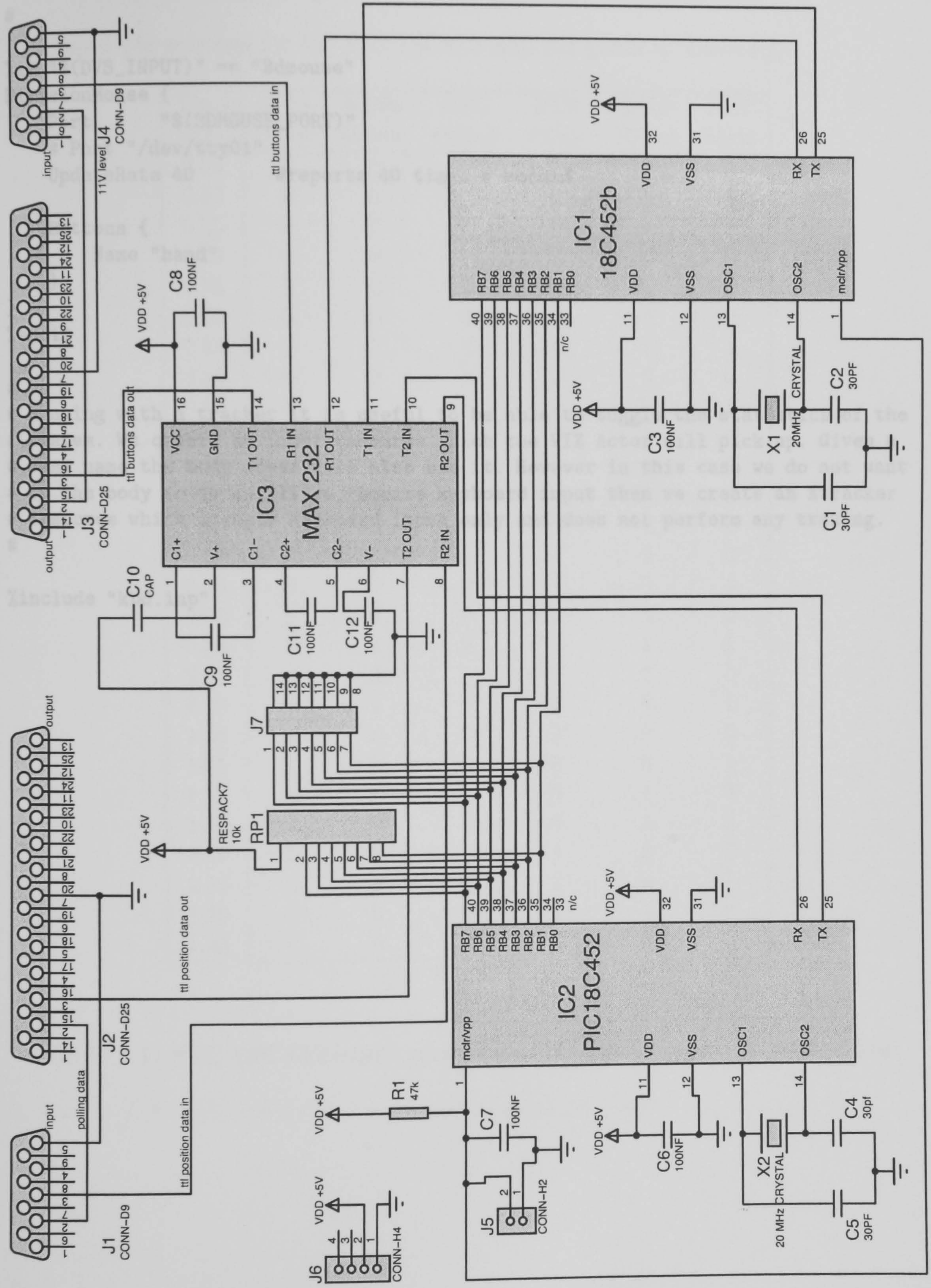

Figure I.1: Delay hardware circuit diagram

```
# Set up the mouse for the hand. Only set up if this is the default
#

%if "$(DVS_INPUT)" == "3dmouse"
DivisionMouse {
    Port      "$(3DMOUSE_PORT)"
    # Port "/dev/tty01"
    UpdateRate 40       #reports 40 times a second

    Buttons {
        Name "hand"
    }
}
%endif

#
# Running with a tracker it is useful to be able to toggle the statistics of the
# system. We create an input resource which the VIZ Actor will pick up. Given a
# sane name the body actor will also use it. However in this case we do not want
# to the body to do so. If we require keyboard input then we create an Xtracker
# resource which accepts keyboard input only and does not perform any traking.
#

%include "kbd.inp"
```

I.3 Input pin settings - 50ms resolution

The input pin settings for the PIC 18C452 chip are given in Table I.1.

Time (us)	RB7a 1 sec	RB6a 500ms	RB5 400ms	RB4 200ms	RB3 100ms	RB2 50ms
0.05	0	0	0	0	0	1
0.10	0	0	0	0	1	0
0.15	0	0	0	0	1	1
0.20	0	0	0	1	0	0
0.25	0	0	0	1	0	1
0.30	0	0	0	1	1	0
0.35	0	0	0	1	1	1
0.40	0	0	1	0	0	0
0.45	0	0	1	0	0	1
0.50	0	1	0	0	0	0
0.55	0	1	0	0	0	1
0.60	0	1	0	1	1	0
0.65	0	1	0	1	1	1
0.70	0	1	0	1	0	0
0.75	0	1	0	1	0	1
0.80	0	1	0	0	1	0
0.85	0	1	0	0	1	1
0.90	0	1	1	0	0	0
0.95	0	1	1	0	0	1
1.00	1	0	0	0	0	0
1.05	1	0	0	0	0	1
1.10	1	0	0	0	1	0
1.15	1	0	0	0	1	1
1.20	1	0	0	1	0	0
1.25	1	0	0	1	0	1
1.30	1	0	0	1	1	0
1.35	1	0	0	1	1	1

1 = 0V

Table I.1: PIC 18C452 input pins selection guide for 50ms resolution

I.4 Input pin settings - 100ms resolution

The input pin settings for the PIC 18C452 chip are given in Table I.2.

Time (us)	RB7	RB6	RB5	RB4	RB3	RB2
0.1	0	0	0	0	0	1
0.2	0	0	0	0	1	0
0.3	0	0	0	0	1	1
0.4	0	0	0	1	0	0
0.5	0	0	0	1	0	1
0.6	0	0	0	1	1	0
0.7	0	0	0	1	1	1
0.8	0	0	1	0	0	0
0.9	0	0	1	0	0	1
1.0	0	1	0	0	0	0
1.1	0	1	0	0	0	1
1.2	0	1	0	0	1	0
1.3	0	1	0	0	1	1
1.4	0	1	0	1	0	0
1.5	0	1	0	1	0	1
1.6	0	1	0	1	1	0
1.7	0	1	0	1	1	1
1.8	0	1	1	0	0	0
1.9	0	1	1	0	0	1
2.0	1	0	0	0	0	0
2.1	1	0	0	0	0	1
2.2	1	0	0	0	1	0
2.3	1	0	0	0	1	1
2.4	1	0	0	1	0	0
2.5	1	0	0	1	0	1
2.6	1	0	0	1	1	0
2.7	1	0	0	1	1	1
2.8	1	0	1	0	0	0
2.9	1	0	1	0	0	1

1 = 0V

Table I.2: PIC 18C452 input pins selection guide for 100ms resolution

I.5 PIC 18C452 data memory locations used for delay settings

The data memory locations used for the positional delay are shown in Table I.3 and the locations for button-press delay are in Table I.4.

50 ms resolution			**100 ms resolution**		
Delay time	Start address	End address	Delay time	Start address	End address
1 sec.	0100	03F7	2 sec.	0100	03F7
500 ms	014C	02C7	1 sec.	027C	03F7
400 ms	03AC	04D5	800 ms	03F8	0527
200 ms	04D6	0573	400 ms	04D6	0573
100 ms	0574	05BF	200 ms	0574	05BF
50 ms	05C0	05E5	100 ms	05C0	05E5

Table I.3: Position data memory locations

Delay time	Start address	End address
2 sec.	0100	0267
1 sec.	0268	031B
800 ms	031C	03AB
500 ms	031C	0375
400 ms	03AC	03F3
200 ms	03F4	0417
100 ms	0418	0429
50 ms	042A	0432

Table I.4: Buttons data memory locations

I.6 Program to delay headset signals: hset.asm

```
; 18C452 position @ 50ms&100ms steps program nov. 2000/A. Wilson
; constant declarations :- none
;variables:-
counter1 equ  h'80'
counter2  equ  h'81'
org h'00';initial system vectors
goto  start
org  h'20'; system subroutines
list p=18C452
include <p18C452.inc>
;=============================================================
init  movlw  h'ff'
movwf  TRISB ;set portb to inputs
bsf  TXSTA,BRGH ;baud rate hi
movlw  d'10'
movwf  SPBRG ;value 115.2 kb
bcf  TXSTA,SYNC ;async
bsf  PIE1,RCIE ;enable
bsf  PIE1,TXIE ;enable
bsf  TXSTA,TXEN ;enable
bsf  RCSTA,SPEN ;serial
bsf  RCSTA,CREN ;cont
movlw  d'165';set for 165
movwf  counter1 ;load counter1
return
;=====================================================
;sub routines
byte_chk btfss  PIR1,RCIF  ;byte rx
goto  byte_chk
movf  RCREG,w ;clr flag
return
;-----------------------------------------------------
save_byte movwf  POSTINC0  ;inc fsr0
return
;-----------------------------------------------------
send_byte movwf  TXREG ;clr txif,start tx
tx_out btfss  PIR1,TXIF  ;if txreg mt, return
goto  tx_out
return
;-----------------------------------------------------
byte_in btfss PIR1,RCIF   ;check for byte
goto byte_in
return
;-------------------------------------------------------
recall_byte movf  INDF0,w   ;recall data
return
;-------------------------------------------------------
save_new movf  RCREG,w ;clr int flag & restart
movwf  POSTINC0 ;inc fsr0
return
;=======================================================
next call  byte_chk ;send & save
```

```
call  send_byte ;registers
call  save_byte
decfsz  counter2
goto  next
return
;-------------------------------------------------------
next1 call  byte_in ;recall, send&save
call  recall_byte ;registers
call  send_byte
call  save_new
decfsz  counter2
goto  next1
return
;========================================================
count5 movlw  d'05';
movwf  counter1
return
;--------------------------------------------------------
count4 movlw  d'04';
movwf  counter1
return
;--------------------------------------------------------
count2 movlw  d'02';
movwf  counter1
return
;--------------------------------------------------------
fsr_152 movlw  d'152';
movwf  counter2
return
;--------------------------------------------------------
fsr_76 movlw  d'76';
movwf  counter2
return
;--------------------------------------------------------
fsr_38 movlw  d'38';
movwf  counter2
return
;=========================================================


;SAVE & SEND routines
del7 LFSR 0,0100 ;2.0s @100 memory address
call  count5 ;set counter1=5
loop7 call  fsr_152 ;set counter2=152
call  next ;152 saved
decfsz counter1,f ;152x5=760
goto loop7
return


del6 LFSR 0,027C ;1.0s @100 memory address
call  count5 ;set counter1=4
loop6 call  fsr_76 ;set counter2=152
call  next
```

```
decfsz counter1,f ;152x4=608
goto loop6
return

del5 LFSR 0,03F8 ;0.8s @100  memory address
call  count2 ;set counter1=2
loop5 call  fsr_152 ;set counter2=152
call  next
decfsz counter1,f ;152x2=308
goto loop5
return

del4 LFSR 0,04D6
call  fsr_152 ;0.4s memory address or 0.2s @50ms
call  next ;set 152
return

del3 LFSR 0,0574
call  fsr_76 ;0.2s memory address or 0.1s @ 50ms
call  next ;set 76
return

del2 LFSR 0,05C0
call  fsr_38 ;0.1s memory address or 0.05s @ 50ms
call  next ;set 38
return
;----------------------------------------------------------------------
del7a LFSR 0,0100 ;1.0s @50 memory address
call  count5 ;set counter1=5
loop7a call  fsr_152 ;set counter2=152
call  next ;152 saved
decfsz counter1,f ;152x5=760
goto loop7a
return

del6a LFSR 0,014C ;0.5s @50 memory address
call  count5 ;set counter1=5
loop6a call  fsr_76 ;set counter2=76
call  next
decfsz counter1,f ;76x5=500MS
goto loop6a
return

del5a LFSR 0,03AC ;0.4s @50  memory address
call  count2 ;set counter1=2
loop5a call  fsr_152 ;set counter2=152
call  next
decfsz counter1,f ;152x2=308
goto loop5a
return
;======================================================================
;recall,send&save routines
del_7 LFSR 0,0100 ;2.0s @100 memory address
call  count5 ;set counter1=5
```

```
loop_7 call  fsr_152 ;set counter2=152
call  next1 ;recall&save
decfsz counter1,f ;152x5=760
goto loop_7
return

del_6 LFSR 0,027C ;1.0s @100 memory address
call  count5 ;set counter1=4
loop_6 call  fsr_76 ;set counter2=152
call  next1 ;recall&save
decfsz counter1,f ;152x4=608
goto loop_6
return

del_5 LFSR 0,03F8 ;0.8 @100s memory address
call  count2 ;set counter1=2
loop_5 call  fsr_152 ;set counter2=152
call  next1 ;recall&save
decfsz counter1,f ;152x2=304
goto loop_5
return

del_4 LFSR 0,04D6 ;0.4ms address or 0.2s @50ms
call  fsr_152 ;set counter2=152
call next1 ;recall send&save
return

del_3 LFSR 0,0574 ;0.2ms address or 0.1s @50ms
call  fsr_76 ;set counter2=76
call next1 ;recall send&save
return

del_2 LFSR 0,05C0 ;0.1ms address or 0.05s @50ms
call  fsr_38 ;set counter2=38
call next1 ;recall send&save
return
;--------------------------------------------------------------------------
del_7a LFSR 0,0100 ;1.0s @50 memory address
call  count5 ;set counter1=5
loop_7a call  fsr_152 ;set counter2=152
call  next1 ;recall&save
decfsz counter1,f ;152x5=760
goto loop_7a
return

del_6a LFSR 0,014C ;0.5s @50 memory address
call  count5 ;set counter1=2
loop_6a call  fsr_76 ;set counter2=76
call  next1 ;recall&save
decfsz counter1,f ;76X2=500MS
goto loop_6a
return

del_5a LFSR 0,03AC ;0.4s @50 memory address
```

```
call  count2 ;set counter1=2
loop_5a call  fsr_152 ;set counter2=152
call  next1 ;recall&save
decfsz counter1,f ;152x2=304
goto loop_5a
return



;==========================================================================
start call  init ;MAIN PROGRAM

start1 btfss  PORTB,7 ;check for any portb bits clear
goto start2
btfss  PORTB,6
goto start2
btfss  PORTB,5
goto start2
btfss  PORTB,4
goto start2
btfss  PORTB,3
goto start2
btfss  PORTB,2
goto start2 ;if not goto loop (data in & out)

loop call  byte_chk ;move rcreg to w reg
call  send_byte ;move w reg to tx reg
goto  loop ;repeat

start2 call  byte_chk
call  send_byte ;move data through
decfsz  counter1 ;check 165 (header lines)
goto  start2

btfss PORTB,0 ;check for 50ms/100ms
goto start3 ;if 50ms, goto start3
;else continue

btfss  PORTB,7 ;100ms SEND & SAVE ROUTINES
call  del7 ;2.0s @ rb7
btfss  PORTB,6
call  del6 ;1.0s @rb6
btfss  PORTB,5
call  del5 ;800ms @rb5
btfss  PORTB,4
call  del4 ;400ms @rb4
btfss  PORTB,3
call  del3 ;200ms @rb3
btfss  PORTB,2
call  del2 ;100ms @rb2

recall_100 btfss  PORTB,7 ;100ms RECALL,SEND & SAVE ROUTINES
call  del_7 ;2.0s @rb7
btfss  PORTB,6
```

```
call  del_6 ;1.0s 2rb6
btfss  PORTB,5
call  del_5 ;800ms @rb5
btfss  PORTB,4
call  del_4 ;400ms @rb4
btfss  PORTB,3
call  del_3 ;200ms @rb3
btfss  PORTB,2
call  del_2 ;100ms @rb2
goto  recall_100


start3 btfss  PORTB,7 ;50ms SEND & SAVE ROUTINES
call  del7a ;1.0s @rb7
btfss  PORTB,6
call  del6a ;500ms @rb6
btfss  PORTB,5
call  del5a ;400ms @rb5
btfss  PORTB,4
call  del4 ;200ms @rb4
btfss  PORTB,3
call  del3 ;100ms @rb3
btfss  PORTB,2
call  del2 ;50ms @rb2

recall_50 btfss  PORTB,7 ;50ms RECALL,SEND & SAVE ROUTINES
call  del_7a ;1.0s @rb7
btfss  PORTB,6
call  del_6a ;500ms @rb6
btfss  PORTB,5
call  del_5a ;400ms @rb5
btfss  PORTB,4
call  del_4 ;200ms @rb4
btfss  PORTB,3
call  del_3 ;100ms @rb3
btfss  PORTB,2
call  del_2 ;50ms @rb2
goto  recall _50

finish
goto  finish

end ; program complete
```

I.7 Program to delay button presses: bttns.asm

```
; 18C452 buttons 50ms & 100 ms program nov. 2000/A. Wilson
; constant declarations :- none
;variables:-
counter1 equ  h'080'
counter2  equ  h'081'
delcnt1  equ  h'082'
delcnt2  equ  h'083'

org h'00'; initial system vectors
goto  start
org  h'20'; system subroutines
list p=18C452
include <p18C452.inc>
;==============================================================
;subroutines
init  movlw  b'11111111'
movwf  TRISB ;set portb to inputs
bcf  TXSTA,BRGH ;baud rate lo
movlw  d'32'
movwf  SPBRG ;value 9.6K baud
bcf  TXSTA,SYNC ;async
bsf  PIE1,RCIE ;enable
bsf  PIE1,TXIE ;enable
bsf  TXSTA,TXEN ;enable
bsf  RCSTA,SPEN ;serial
bsf  RCSTA,CREN ;cont
movlw  d'165';set for 165
movwf  counter1 ;load counter1
return
;-------------------------------------------------------
byte_chk btfss  PIR1,RCIF  ;byte rx
goto  byte_chk
movf  RCREG,w ;clr flag
return
;-------------------------------------------------------
save_byte movwf  POSTINC0  ;inc fsr0
return
;-------------------------------------------------------
send_byte movwf  TXREG ;clr txif,start tx
tx_out btfss  PIR1,TXIF  ;if txreg mt, return
goto  tx_out
return
;-------------------------------------------------------
byte_in btfss PIR1,RCIF   ;check for byte
goto byte_in
return
;-------------------------------------------------------
recall_byte movf  INDF0,w   ;recall data
return
;-------------------------------------------------------
save_new movf  RCREG,w ;clr int flag & restart
movwf  POSTINC0 ;inc fsr0
```

```
return
;----------------------------------------------------------
delay movlw  d'255'
movwf  delcnt1
delay1 nop
nop
decfsz  delcnt1,f
goto  delay1
return
;----------------------------------------------------
pad3ms movlw  d'12'
movwf  delcnt2
delay2 call  delay
decfsz  delcnt2,f
goto  delay2
return
;========================================================
next call  byte_chk ;send & save
call  send_byte ;routine
call  save_byte
decfsz  counter2 ;count2=
goto  next ;9,18,36 etc.
call  pad3ms
return
;--------------------------------------------------------
next1 call  byte_in ;recall, send & save
call  recall_byte ;countdown routine
call  send_byte ;for registers
call  save_new
decfsz  counter2 ;check for count =0
goto  next1
call  pad3ms
return
;========================================================
del7a_fsr movlw  d'360';no of registers used
movwf  counter2 ;
LFSR 0,0100 ;2.0s delay
return
;---------------------------------------------------------
del7_fsr movlw  d'180';no of registers used
movwf  counter2 ;
LFSR 0,0268 ;1.0s delay
return
;---------------------------------------------------------
del6a_fsr movlw  d'90';no of registers used
movwf  counter2
LFSR 0,031C ;500ms delay
return
;-------------------------------------------------------------
del6_fsr movlw  d'144';no of registers used
movwf  counter2
LFSR 0,031C ;800ms delay
return
;---------------------------------------------------------
```

```
del5_fsr movlw  d'72';no of registers used
movwf  counter2
LFSR 0,03AC ;400ms delay
return
;--------------------------------------------------------
del4_fsr movlw  d'36';no of registers used
movwf  counter2
LFSR 0,03F4 ;200ms delay
return
;-------------------------------------------------------
del3_fsr movlw  d'18';no of registers used
movwf  counter2
LFSR 0,0418 ;100ms delay
return
;-----------------------------------------------------------
del2_fsr movlw  d'9';no of registers used
movwf  counter2
LFSR 0,042A ;50ms delay
return
;-----------------------------------------------------------
;SAVE & SEND routines
del7a call  del7a_fsr ;set 360
call  next ;360 saved?
return

del7 call  del7_fsr ;set 180
call  next ;180 saved?
return

del6a call  del6a_fsr ;set 90
call  next
return

del6 call  del6_fsr ;set 144
call  next
return

del5 call  del5_fsr ;set 72
call  next
return

del4 call  del4_fsr ;set 36
call  next
return

del3 call  del3_fsr ;set 18
call  next
return

del2 call  del2_fsr ;set 9
call  next
return
;====================================================================
del_7a call  del7a_fsr ;RECALL,SEND & SAVE ROUTINES
```

```
call  next1 ;360 regs
return

del_7 call  del7_fsr ;180regs
call  next1
return

del_6a call  del6a_fsr ;90 regs
call  next1
return

del_6 call  del6_fsr ;144 regs
call  next1
return

del_5 call  del5_fsr ;72 regs
call  next1
return

del_4 call  del4_fsr ;36 regs
call next1
return

del_3 call  del3_fsr ;18 regs
call next1
return

del_2 call  del2_fsr ;9 regs
call next1
return
;======================================================================
;MAIN PROGRAM
start call  init

start1 btfss  PORTB,7 ;check for any portb bits clear
goto start2 ;if not loop (data in & out)
btfss  PORTB,6 ;
goto start2 ;
btfss  PORTB,5
goto start2
btfss  PORTB,4
goto start2
btfss  PORTB,3
goto start2
btfss  PORTB,2
goto start2

loop call  byte_chk ;move rcreg to w reg
call  send_byte ;move w reg to tx reg
goto  loop ;repeat

start2 call  byte_chk ;move rcreg to w reg
call  send_byte ;move w reg to tx reg
decfsz  counter1 ;cycle 165 bytes (status info)
```

I.7 Program to delay button presses: bttns.asm

```
goto  start2

btfss PORTB,1 ;check for 50ms or 100ms
goto start3 ;if pin 0=0V goto 50ms steps


btfss  PORTB,7 ;100ms SEND & SAVE ROUTINES
call  del7a ;2.0s
btfss  PORTB,6
call del7 ;1s
btfss  PORTB,5
call  del6 ;800ms
btfss  PORTB,4
call  del5 ;400ms
btfss  PORTB,3
call  del4 ;200ms
btfss  PORTB,2
call  del3 ;100ms


recall_100 btfss  PORTB,7 ;100ms RECALL,SEND & SAVE ROUTINES
call  del_7a ;2 secs
btfss  PORTB,6
call  del_7 ;1 sec
btfss  PORTB,5
call  del_6 ;800ms
btfss  PORTB,4
call  del_5 ;400ms
btfss  PORTB,3
call  del_4 ;200ms
btfss  PORTB,2
call  del_3 ;100ms
goto recall_100


start3 btfss  PORTB,7 ;50ms SEND & SAVE ROUTINES
call  del7 ;save & send 1.0s
btfss  PORTB,6
call del6a ;save & send 500ms
btfss  PORTB,5
call  del5 ;save & send 400ms
btfss  PORTB,4
call  del4 ;save & send 200ms
btfss  PORTB,3
call  del3 ;save & send 100ms
btfss  PORTB,2
call  del2 ;save & send 50ms

recall_50 btfss  PORTB,7 ;50ms RECALL,SEND & SAVE ROUTINES
call  del_7 ;recall, save & send 1.0s
btfss  PORTB,6
call  del_6a ;recall, save & send 500ms
btfss  PORTB,5
call  del_5 ;recall, save & send 400ms
```

```
btfss  PORTB,4
call  del_4 ;recall, save & send 200ms
btfss  PORTB,3
call  del_3 ;recall, save & send 100ms
btfss  PORTB,2
call  del_2 ;recall, save & send 50ms
goto recall_50




finish
goto  finish

end ; program complete
```

Appendix J

Analysis of Variance Results for Visual Interference Experiments

The analysis of variance was calculated using the General Linear Model (GLM) for Repeated Measures in SPSS.

Output Created		14-AUG-2001 22:15:57
Comments		
Input	Data	E:\Exp_Analysis\all_data6.sav
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	35
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the model.
Syntax		GLM time_c0 time_c1 time_c2 time_c3 time_c4 time_c5 time_c6 time_c7 time_c8 time_c9 time_c10 time_c11 time_c12 time_c13 time_c14 time_c15 time_c16 time_c17 time_c18 time_c19 time_c20 time_c21 time_c22 time_c23 time_c24 time_c25 time_c26 time_c27 time_c28 time_c29 targ_c0 targ_c1 targ_c2 targ_c3 targ_c4 targ_c5 targ_c6 targ_c7 targ_c8 targ_c9 targ_c10 targ_c11 targ_c12 targ_c13 targ_c14 targ_c15 targ_c16 targ_c17 targ_c18 targ_c19 targ_c20 targ_c21 targ_c22 targ_c23 targ_c24 targ_c25 targ_c26 targ_c27 targ_c28 targ_c29 isec0 isec1 isec2 isec3 isec4 isec5 isec6 isec7 isec8 isec9 isec10 isec11 isec12 isec13 isec14 isec15 isec16 isec17 isec18 isec19 isec20 isec21 isec22 isec23 isec24 isec25 isec26 isec27 isec28 isec29 /WSFACTOR = vis_int 2 Polynomial delays 3 Polynomial tracks 5 Polynomial /MEASURE = time targ ise /METHOD = SSTYPE(3) /CRITERIA = ALPHA(.05) /WSDESIGN = vis_int delays tracks vis_int*delays vis_int*tracks delays *tracks vis_int*delays*tracks.
Resources	Elapsed Time	0:00:02.97

Table J.1: GLM Notes

Measure	VIS_INT	DELAYS	TRACKS	Dependent Variable
TIME	1	1	1	TIME_C0
			2	TIME_C1
			3	TIME_C2
			4	TIME_C3
			5	TIME_C4
		2	1	TIME_C5
			2	TIME_C6
			3	TIME_C7
			4	TIME_C8
			5	TIME_C9
		3	1	TIME_C10
			2	TIME_C11
			3	TIME_C12
			4	TIME_C13
			5	TIME_C14
	2	1	1	TIME_C15
			2	TIME_C16
			3	TIME_C17
			4	TIME_C18
			5	TIME_C19
		2	1	TIME_C20
			2	TIME_C21
			3	TIME_C22
			4	TIME_C23
			5	TIME_C24
		3	1	TIME_C25
			2	TIME_C26
			3	TIME_C27
			4	TIME_C28
			5	TIME_C29
TARG	1	1	1	TARG_C0
			2	TARG_C1
			3	TARG_C2
			4	TARG_C3
			5	TARG_C4
		2	1	TARG_C5
			2	TARG_C6
			3	TARG_C7
			4	TARG_C8
			5	TARG_C9
		3	1	TARG_C10
			2	TARG_C11
			3	TARG_C12
			4	TARG_C13
			5	TARG_C14

Table J.2: GLM Within Subjects Factors

Measure	VIS_INT	DELAYS	TRACKS	Dependent Variable
TARG	2	1	1	TARG_C15
			2	TARG_C16
			3	TARG_C17
			4	TARG_C18
			5	TARG_C19
		2	1	TARG_C20
			2	TARG_C21
			3	TARG_C22
			4	TARG_C23
			5	TARG_C24
		3	1	TARG_C25
			2	TARG_C26
			3	TARG_C27
			4	TARG_C28
			5	TARG_C29
ISE	1	1	1	ISEC0
			2	ISEC1
			3	ISEC2
			4	ISEC3
			5	ISEC4
		2	1	ISEC5
			2	ISEC6
			3	ISEC7
			4	ISEC8
			5	ISEC9
		3	1	ISEC10
			2	ISEC11
			3	ISEC12
			4	ISEC13
			5	ISEC14
	2	1	1	ISEC15
			2	ISEC16
			3	ISEC17
			4	ISEC18
			5	ISEC19
		2	1	ISEC20
			2	ISEC21
			3	ISEC22
			4	ISEC23
			5	ISEC24
		3	1	ISEC25
			2	ISEC26
			3	ISEC27
			4	ISEC28
			5	ISEC29

Table J.3: GLM Within Subjects Factors (continued)

Effect			*Value*	*F*	*Hypothesis df*	*Error df*	*Sig.*
Between Subjects	Intercept	Pillai's Trace	.965	295.041(a)	3.000	32.000	.000
		Wilks' Lambda	.035	295.041(a)	3.000	32.000	.000
		Hotelling's Trace	27.660	295.041(a)	3.000	32.000	.000
		Roy's Largest Root	27.660	295.041(a)	3.000	32.000	.000
Within Subjects	VIS_INT	Pillai's Trace	.422	7.777(a)	3.000	32.000	.000
		Wilks' Lambda	.578	7.777(a)	3.000	32.000	.000
		Hotelling's Trace	.729	7.777(a)	3.000	32.000	.000
		Roy's Largest Root	.729	7.777(a)	3.000	32.000	.000
	DELAYS	Pillai's Trace	.614	7.700(a)	6.000	29.000	.000
		Wilks' Lambda	.386	7.700(a)	6.000	29.000	.000
		Hotelling's Trace	1.593	7.700(a)	6.000	29.000	.000
		Roy's Largest Root	1.593	7.700(a)	6.000	29.000	.000
	TRACKS	Pillai's Trace	.980	96.232(a)	12.000	23.000	.000
		Wilks' Lambda	.020	96.232(a)	12.000	23.000	.000
		Hotelling's Trace	50.208	96.232(a)	12.000	23.000	.000
		Roy's Largest Root	50.208	96.232(a)	12.000	23.000	.000
	VIS_INT * DELAYS	Pillai's Trace	.292	1.992(a)	6.000	29.000	.099
		Wilks' Lambda	.708	1.992(a)	6.000	29.000	.099
		Hotelling's Trace	.412	1.992(a)	6.000	29.000	.099
		Roy's Largest Root	.412	1.992(a)	6.000	29.000	.099

a Exact statistic

b Design: Intercept
Within Subjects Design: VIS_INT + DELAYS + TRACKS + VIS_INT*DELAYS + VIS_INT*TRACKS + DELAYS*TRACKS + VIS_INT*DELAYS*TRACKS

Table J.4: GLM Multivariate Tests (b)

Effect			*Value*	*F*	*Hypothesis df*	*Error df*	*Sig.*
Within subjects	VIS_INT * TRACKS	Pillai's Trace	.610	3.001(a)	12.000	23.000	.011
		Wilks' Lambda	.390	3.001(a)	12.000	23.000	.011
		Hotelling's Trace	1.566	3.001(a)	12.000	23.000	.011
		Roy's Largest Root	1.566	3.001(a)	12.000	23.000	.011
	DELAYS * TRACKS	Pillai's Trace	.760	1.452(a)	24.000	11.000	.264
		Wilks' Lambda	.240	1.452(a)	24.000	11.000	.264
		Hotelling's Trace	3.167	1.452(a)	24.000	11.000	.264
		Roy's Largest Root	3.167	1.452(a)	24.000	11.000	.264
	VIS_INT * DELAYS * TRACKS	Pillai's Trace	.760	1.453(a)	24.000	11.000	.264
		Wilks' Lambda	.240	1.453(a)	24.000	11.000	.264
		Hotelling's Trace	3.170	1.453(a)	24.000	11.000	.264
		Roy's Largest Root	3.170	1.453(a)	24.000	11.000	.264

a Exact statistic

b Design: Intercept
Within Subjects Design: VIS_INT + DELAYS + TRACKS + VIS_INT*DELAYS + VIS_INT*TRACKS + DELAYS*TRACKS + VIS_INT*DELAYS*TRACKS

Table J.5: GLM Multivariate Tests continued (b)

						Epsilon(a)		
Within Subjects Effect	*Measure*	*Mauchly's W*	*Approx. Chi-Square*	*df*	*Sig.*	*Greenhouse-Geisser*	*Huynh-Feldt*	*Lower-bound*
VIS_INT	TIME	1.000	.000	0	.	1.000	1.000	1.000
	TARG	1.000	.000	0	.	1.000	1.000	1.000
	ISE	1.000	.000	0	.	1.000	1.000	1.000
DELAYS	TIME	.534	20.698	2	.000	.682	.701	.500
	TARG	.784	8.048	2	.017	.822	.858	.500
	ISE	.944	1.900	2	.384	.947	1.000	.500
TRACKS	TIME	.507	22.048	9	.009	.767	.852	.250
	TARG	.772	8.392	9	.496	.891	1.000	.250
	ISE	.048	98.755	9	.000	.420	.440	.250
VIS_INT * DELAYS	TIME	.851	5.341	2	.068	.870	.913	.500
	TARG	.845	5.573	2	.061	.866	.908	.500
	ISE	.726	10.589	2	.005	.785	.816	.500
VIS_INT * TRACKS	TIME	.524	20.968	9	.013	.737	.814	.250
	TARG	.752	9.221	9	.418	.876	.989	.250
	ISE	.027	116.730	9	.000	.384	.399	.250
DELAYS * TRACKS	TIME	.028	110.982	35	.000	.635	.759	.125
	TARG	.039	100.642	35	.000	.638	.764	.125
	ISE	.000	325.677	35	.000	.297	.321	.125
VIS_INT * DELAYS * TRACKS	TIME	.029	109.988	35	.000	.587	.692	.125
	TARG	.036	103.150	35	.000	.643	.771	.125
	ISE	.000	350.382	35	.000	.278	.299	.125

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b Design: Intercept Within Subjects Design: VIS_INT + DELAYS + TRACKS + VIS_INT*DELAYS + VIS_INT*TRACKS + DELAYS*TRACKS + VIS_INT*DELAYS*TRACKS

Table J.6: GLM Mauchly's Test of Sphericity (b)

J.1 Tests of Within-Subjects Effects

Within Subjects Effect		*Value*	*F*	*Hypothesis df*	*Error df*	*Sig.*
VIS_INT	Pillai's Trace	.422	7.777(a)	3.000	32.000	.000
	Wilks' Lambda	.578	7.777(a)	3.000	32.000	.000
	Hotelling's Trace	.729	7.777(a)	3.000	32.000	.000
	Roy's Largest Root	.729	7.777(a)	3.000	32.000	.000
DELAYS	Pillai's Trace	.553	8.536	6.000	134.000	.000
	Wilks' Lambda	.459	10.482(a)	6.000	132.000	.000
	Hotelling's Trace	1.154	12.504	6.000	130.000	.000
	Roy's Largest Root	1.132	25.271(b)	3.000	67.000	.000
TRACKS	Pillai's Trace	1.112	20.036	12.000	408.000	.000
	Wilks' Lambda	.182	26.752	12.000	354.822	.000
	Hotelling's Trace	2.888	31.926	12.000	398.000	.000
	Roy's Largest Root	2.137	72.657(b)	4.000	136.000	.000
VIS_INT * DELAYS	Pillai's Trace	.087	1.017	6.000	134.000	.417
	Wilks' Lambda	.913	1.019(a)	6.000	132.000	.416
	Hotelling's Trace	.094	1.020	6.000	130.000	.415
	Roy's Largest Root	.088	1.955(b)	3.000	67.000	.129
VIS_INT * TRACKS	Pillai's Trace	.194	2.351	12.000	408.000	.006
	Wilks' Lambda	.813	2.412	12.000	354.822	.005
	Hotelling's Trace	.223	2.460	12.000	398.000	.004
	Roy's Largest Root	.180	6.114(b)	4.000	136.000	.000
DELAYS * TRACKS	Pillai's Trace	.179	2.158	24.000	816.000	.001
	Wilks' Lambda	.830	2.173	24.000	783.683	.001
	Hotelling's Trace	.195	2.185	24.000	806.000	.001
	Roy's Largest Root	.119	4.056(b)	8.000	272.000	.000
VIS_INT * DELAYS * TRACKS	Pillai's Trace	.108	1.270	24.000	816.000	.174
	Wilks' Lambda	.895	1.269	24.000	783.683	.175
	Hotelling's Trace	.113	1.268	24.000	806.000	.176
	Roy's Largest Root	.064	2.176(b)	8.000	272.000	.030

a Exact statistic

b The statistic is an upper bound on F that yields a lower bound on the significance level.

c Design: Intercept. Within Subjects Design: VIS_INT + DELAYS + TRACKS + VIS_INT*DELAYS + VIS_INT*TRACKS + DELAYS*TRACKS + VIS_INT*DELAYS*TRACKS

d Tests are based on averaged variables.

Table J.7: GLM Multivariate(c,d)

Source	*Measure*		*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
VIS_INT	TIME	Sphericity Assumed	700.353	1	700.353	3.762	.061
		Greenhouse-Geisser	700.353	1.000	700.353	3.762	.061
		Huynh-Feldt	700.353	1.000	700.353	3.762	.061
		Lower-bound	700.353	1.000	700.353	3.762	.061
	TARG	Sphericity Assumed	38.465	1	38.465	11.850	.002
		Greenhouse-Geisser	38.465	1.000	38.465	11.850	.002
		Huynh-Feldt	38.465	1.000	38.465	11.850	.002
		Lower-bound	38.465	1.000	38.465	11.850	.002
	ISE	Sphericity Assumed	94240900.789	1	94240900.789	10.963	.002
		Greenhouse-Geisser	94240900.789	1.000	94240900.789	10.963	.002
		Huynh-Feldt	94240900.789	1.000	94240900.789	10.963	.002
		Lower-bound	94240900.789	1.000	94240900.789	10.963	.002
Error (VIS_INT)	TIME	Sphericity Assumed	6330.258	34	186.184		
		Greenhouse-Geisser	6330.258	34.000	186.184		
		Huynh-Feldt	6330.258	34.000	186.184		
		Lower-bound	6330.258	34.000	186.184		
	TARG	Sphericity Assumed	110.359	34	3.246		
		Greenhouse-Geisser	110.359	34.000	3.246		
		Huynh-Feldt	110.359	34.000	3.246		
		Lower-bound	110.359	34.000	3.246		
	ISE	Sphericity Assumed	292281732.095	34	8596521.532		
		Greenhouse-Geisser	292281732.095	34.000	8596521.532		
		Huynh-Feldt	292281732.095	34.000	8596521.532		
		Lower-bound	292281732.095	34.000	8596521.532		

Table J.8: GLM Univariate Tests - part 1

Source	*Measure*		*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
DELAYS	TIME	Sphericity Assumed	2159.911	2	1079.955	13.032	.000
		Greenhouse-Geisser	2159.911	1.364	1583.134	13.032	.000
		Huynh-Feldt	2159.911	1.402	1540.721	13.032	.000
		Lower-bound	2159.911	1.000	2159.911	13.032	.001
	TARG	Sphericity Assumed	10.308	2	5.154	2.761	.070
		Greenhouse-Geisser	10.308	1.644	6.270	2.761	.082
		Huynh-Feldt	10.308	1.717	6.005	2.761	.079
		Lower-bound	10.308	1.000	10.308	2.761	.106
	ISE	Sphericity Assumed	56437145.137	2	28218572.568	10.253	.000
		Greenhouse-Geisser	56437145.137	1.894	29797443.610	10.253	.000
		Huynh-Feldt	56437145.137	2.000	28218572.568	10.253	.000
		Lower-bound	56437145.137	1.000	56437145.137	10.253	.003
Error (DELAYS)	TIME	Sphericity Assumed	5635.181	68	82.870		
		Greenhouse-Geisser	5635.181	46.387	121.482		
		Huynh-Feldt	5635.181	47.664	118.227		
		Lower-bound	5635.181	34.000	165.741		
	TARG	Sphericity Assumed	126.942	68	1.867		
		Greenhouse-Geisser	126.942	55.902	2.271		
		Huynh-Feldt	126.942	58.369	2.175		
		Lower-bound	126.942	34.000	3.734		
	ISE	Sphericity Assumed	187145960.706	68	2752146.481		
		Greenhouse-Geisser	187145960.706	64.397	2906133.164		
		Huynh-Feldt	187145960.706	68.000	2752146.481		
		Lower-bound	187145960.706	34.000	5504292.962		

Table J.9: GLM Univariate Tests - part 2

Source	*Measure*		*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
TRACKS	TIME	Sphericity Assumed	7089.053	4	1772.263	26.672	.000
		Greenhouse-Geisser	7089.053	3.069	2309.774	26.672	.000
		Huynh-Feldt	7089.053	3.408	2079.961	26.672	.000
		Lower-bound	7089.053	1.000	7089.053	26.672	.000
	TARG	Sphericity Assumed	10.234	4	2.558	1.570	.186
		Greenhouse-Geisser	10.234	3.566	2.870	1.570	.193
		Huynh-Feldt	10.234	4.000	2.558	1.570	.186
		Lower-bound	10.234	1.000	10.234	1.570	.219
	ISE	Sphericity Assumed	1239676599.805	4	309919149.951	71.425	.000
		Greenhouse-Geisser	1239676599.805	1.682	737157927.886	71.425	.000
		Huynh-Feldt	1239676599.805	1.759	704619396.528	71.425	.000
		Lower-bound	1239676599.805	1.000	1239676599.805	71.425	.000
Error (TRACKS)	TIME	Sphericity Assumed	9036.580	136	66.445		
		Greenhouse-Geisser	9036.580	104.351	86.598		
		Huynh-Feldt	9036.580	115.881	77.982		
		Lower-bound	9036.580	34.000	265.782		
	TARG	Sphericity Assumed	221.636	136	1.630		
		Greenhouse-Geisser	221.636	121.242	1.828		
		Huynh-Feldt	221.636	136.000	1.630		
		Lower-bound	221.636	34.000	6.519		
	ISE	Sphericity Assumed	590113550.866	136	4339070.227		
		Greenhouse-Geisser	590113550.866	57.178	10320691.761		
		Huynh-Feldt	590113550.866	59.818	9865131.100		
		Lower-bound	590113550.866	34.000	17356280.908		

Table J.10: GLM Univariate Tests - part 3

Source	*Measure*		*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
VIS_INT * DELAYS	TIME	Sphericity Assumed	204.750	2	102.375	2.419	.097
		Greenhouse-Geisser	204.750	1.740	117.673	2.419	.105
		Huynh-Feldt	204.750	1.826	112.144	2.419	.102
		Lower-bound	204.750	1.000	204.750	2.419	.129
	TARG	Sphericity Assumed	5.689	2	2.844	1.447	.242
		Greenhouse-Geisser	5.689	1.731	3.286	1.447	.243
		Huynh-Feldt	5.689	1.816	3.133	1.447	.243
		Lower-bound	5.689	1.000	5.689	1.447	.237
	ISE	Sphericity Assumed	3259285.548	2	1629642.774	.639	.531
		Greenhouse-Geisser	3259285.548	1.569	2076973.253	.639	.495
		Huynh-Feldt	3259285.548	1.632	1997236.427	.639	.501
		Lower-bound	3259285.548	1.000	3259285.548	.639	.429
Error (VIS_INT * DELAYS)	TIME	Sphericity Assumed	2877.456	68	42.316		
		Greenhouse-Geisser	2877.456	59.160	48.639		
		Huynh-Feldt	2877.456	62.077	46.353		
		Lower-bound	2877.456	34.000	84.631		
	TARG	Sphericity Assumed	133.639	68	1.965		
		Greenhouse-Geisser	133.639	58.855	2.271		
		Huynh-Feldt	133.639	61.729	2.165		
		Lower-bound	133.639	34.000	3.931		
	ISE	Sphericity Assumed	173300329.712	68	2548534.260		
		Greenhouse-Geisser	173300329.712	53.354	3248096.808		
		Huynh-Feldt	173300329.712	55.485	3123399.521		
		Lower-bound	173300329.712	34.000	5097068.521		

Table J.11: GLM Univariate Tests - part 4

Source	*Measure*		*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
VIS_INT * TRACKS	TIME	Sphericity Assumed	106.425	4	26.606	.478	.752
		Greenhouse-Geisser	106.425	2.947	36.111	.478	.695
		Huynh-Feldt	106.425	3.257	32.672	.478	.714
		Lower-bound	106.425	1.000	106.425	.478	.494
	TARG	Sphericity Assumed	6.845	4	1.711	1.067	.375
		Greenhouse-Geisser	6.845	3.505	1.953	1.067	.372
		Huynh-Feldt	6.845	3.958	1.730	1.067	.375
		Lower-bound	6.845	1.000	6.845	1.067	.309
	ISE	Sphericity Assumed	87819017.731	4	21954754.433	5.314	.001
		Greenhouse-Geisser	87819017.731	1.538	57100184.171	5.314	.013
		Huynh-Feldt	87819017.731	1.597	55003251.325	5.314	.012
		Lower-bound	87819017.731	1.000	87819017.731	5.314	.027
Error (VIS_INT * TRACKS)	TIME	Sphericity Assumed	7576.377	136	55.709		
		Greenhouse-Geisser	7576.377	100.203	75.611		
		Huynh-Feldt	7576.377	110.750	68.410		
		Lower-bound	7576.377	34.000	222.835		
	TARG	Sphericity Assumed	218.145	136	1.604		
		Greenhouse-Geisser	218.145	119.179	1.830		
		Huynh-Feldt	218.145	134.556	1.621		
		Lower-bound	218.145	34.000	6.416		
	ISE	Sphericity Assumed	561841369.713	136	4131186.542		
		Greenhouse-Geisser	561841369.713	52.291	10744438.664		
		Huynh-Feldt	561841369.713	54.285	10349862.593		
		Lower-bound	561841369.713	34.000	16524746.168		

Table J.12: GLM Univariate Tests - part 5

Source	*Measure*		*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
DELAYS * TRACKS	TIME	Sphericity Assumed	1457.254	8	182.157	3.487	.001
		Greenhouse-Geisser	1457.254	5.078	286.993	3.487	.005
		Huynh-Feldt	1457.254	6.076	239.857	3.487	.003
		Lower-bound	1457.254	1.000	1457.254	3.487	.071
	TARG	Sphericity Assumed	26.287	8	3.286	1.838	.070
		Greenhouse-Geisser	26.287	5.101	5.153	1.838	.106
		Huynh-Feldt	26.287	6.109	4.303	1.838	.092
		Lower-bound	26.287	1.000	26.287	1.838	.184
	ISE	Sphericity Assumed	28587326.982	8	3573415.873	2.010	.045
		Greenhouse-Geisser	28587326.982	2.374	12040387.491	2.010	.132
		Huynh-Feldt	28587326.982	2.564	11147896.337	2.010	.128
		Lower-bound	28587326.982	1.000	28587326.982	2.010	.165
Error (DELAYS * TRACKS)	TIME	Sphericity Assumed	14210.858	272	52.246		
		Greenhouse-Geisser	14210.858	172.640	82.315		
		Huynh-Feldt	14210.858	206.567	68.795		
		Lower-bound	14210.858	34.000	417.966		
	TARG	Sphericity Assumed	486.169	272	1.787		
		Greenhouse-Geisser	486.169	173.434	2.803		
		Huynh-Feldt	486.169	207.695	2.341		
		Lower-bound	486.169	34.000	14.299		
	ISE	Sphericity Assumed	483513895.682	272	1777624.616		
		Greenhouse-Geisser	483513895.682	80.726	5989588.102		
		Huynh-Feldt	483513895.682	87.189	5545611.162		
		Lower-bound	483513895.682	34.000	14220996.932		

Table J.13: GLM Univariate Tests - part 6

Source	*Measure*		*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
VIS_INT * DELAYS * TRACKS	TIME	Sphericity Assumed	341.034	8	42.629	.834	.574
		Greenhouse-Geisser	341.034	4.694	72.658	.834	.521
		Huynh-Feldt	341.034	* 5.537	61.588	.834	.537
		Lower-bound	341.034	1.000	341.034	.834	.368
	TARG	Sphericity Assumed	20.978	8	2.622	1.435	.182
		Greenhouse-Geisser	20.978	5.145	4.078	1.435	.212
		Huynh-Feldt	20.978	6.171	3.399	1.435	.201
		Lower-bound	20.978	1.000	20.978	1.435	.239
	ISE	Sphericity Assumed	23346111.404	8	2918263.926	1.603	.124
		Greenhouse-Geisser	23346111.404	2.226	10487909.080	1.603	.206
		Huynh-Feldt	23346111.404	2.389	9772078.056	1.603	.203
		Lower-bound	23346111.404	1.000	23346111.404	1.603	.214
Error (VIS_INT * DELAYS * TRACKS)	TIME	Sphericity Assumed	13907.337	272	51.130		
		Greenhouse-Geisser	13907.337	159.585	87.147		
		Huynh-Feldt	13907.337	188.270	73.869		
		Lower-bound	13907.337	34.000	409.039		
	TARG	Sphericity Assumed	497.036	272	1.827		
		Greenhouse-Geisser	497.036	174.923	2.841		
		Huynh-Feldt	497.036	209.817	2.369		
		Lower-bound	497.036	34.000	14.619		
	ISE	Sphericity Assumed	495210115.627	272	1820625.425		
		Greenhouse-Geisser	495210115.627	75.684	6543120.984		
		Huynh-Feldt	495210115.627	81.228	6096533.493		
		Lower-bound	495210115.627	34.000	14565003.401		

Table J.14: GLM Univariate Tests - part 7

Source	Measure	VIS_INT	DELAYS	TRACKS	Type III Sum of Squares	df	Mean Square	F	Sig.
VIS_INT	TIME	Linear			700.353	1	700.353	3.762	.061
	TARG	Linear			38.465	1	38.465	11.850	.002
	ISE	Linear			94240900.789	1	94240900.789	10.963	.002
Error (VIS_INT)	TIME	Linear			6330.258	34	186.184		
	TARG	Linear			110.359	34	3.246		
	ISE	Linear			292281732.095	34	8596521.532		
DELAYS	TIME		Linear		2072.294	1	2072.294	16.880	.000
			Quadratic		87.616	1	87.616	2.039	.162
	TARG		Linear		6.613	1	6.613	3.384	.075
			Quadratic		3.695	1	3.695	2.077	.159
	ISE		Linear		55245677.199	1	55245677.199	26.283	.000
			Quadratic		1191467.938	1	1191467.938	.350	.558
Error (DELAYS)	TIME		Linear		4174.090	34	122.767		
			Quadratic		1461.090	34	42.973		
	TARG		Linear		66.442	34	1.954		
			Quadratic		60.500	34	1.779		
	ISE		Linear		71465471.421	34	2101925.630		
			Quadratic		115680489.285	34	3402367.332		
TRACKS	TIME			Linear	5938.732	1	5938.732	49.778	.000
				Quadratic	436.290	1	436.290	6.037	.019
				Cubic	206.190	1	206.190	5.173	.029
				Order 4	507.841	1	507.841	14.781	.001
	TARG			Linear	2.517	1	2.517	1.606	.214
				Quadratic	2.302	1	2.302	1.277	.266
				Cubic	4.275	1	4.275	2.176	.149
				Order 4	1.139	1	1.139	.963	.333
	ISE			Linear	285843983.731	1	285843983.731	79.518	.000
				Quadratic	566165712.005	1	566165712.005	271.754	.000
				Cubic	365107169.052	1	365107169.052	45.396	.000
				Order 4	22559735.017	1	22559735.017	6.206	.018
Error (TRACKS)	TIME			Linear	4056.361	34	119.305		
				Quadratic	2456.965	34	72.264		
				Cubic	1355.083	34	39.855		
				Order 4	1168.171	34	34.358		
	TARG			Linear	53.302	34	1.568		
				Quadratic	61.277	34	1.802		
				Cubic	66.815	34	1.965		
				Order 4	40.242	34	1.184		
	ISE			Linear	122220619.201	34	3594724.094		
				Quadratic	70834715.985	34	2083374.000		
				Cubic	273453587.506	34	8042752.574		
				Order 4	123604628.174	34	3635430.240		
VIS_INT * DELAYS	TIME	Linear	Linear		168.686	1	168.686	3.244	.081
			Quadratic		36.065	1	36.065	1.105	.301
	TARG	Linear	Linear		4.566	1	4.566	2.250	.143
			Quadratic		1.122	1	1.122	.590	.448
	ISE	Linear	Linear		3123243.964	1	3123243.964	2.536	.120
			Quadratic		136041.585	1	136041.585	.035	.852
Error (VIS_INT * DELAYS)	TIME	Linear	Linear		1767.879	34	51.996		
			Quadratic		1109.576	34	32.635		
	TARG	Linear	Linear		69.005	34	2.030		
			Quadratic		64.634	34	1.901		
	ISE	Linear	Linear		41865383.479	34	1231334.808		
			Quadratic		131434946.233	34	3865733.713		

Table J.15: GLM Tests of Within-Subjects Contrasts - part 1

Source	Measure	VIS_INT	DELAYS	TRACKS	Type III Sum of Squares	df	Mean Square	F	Sig.
VIS_INT * TRACKS	TIME	Linear		Linear	22.570	1	22.570	.600	.444
				Quadratic	44.283	1	44.283	.458	.503
				Cubic	7.728	1	7.728	.146	.705
				Order 4	31.843	1	31.843	.899	.350
	TARG	Linear		Linear	2.634E-02	1	2.634E-02	.016	.901
				Quadratic	1.116	1	1.116	.610	.440
				Cubic	2.069	1	2.069	1.172	.287
				Order 4	3.634	1	3.634	3.158	.084
	ISE	Linear		Linear	3676547.347	1	3676547.347	1.964	.170
				Quadratic	36261876.483	1	36261876.483	16.441	.000
				Cubic	44931316.569	1	44931316.569	5.304	.028
				Order 4	2949277.332	1	2949277.332	.742	.395
Error (VIS_INT * TRACKS)	TIME	Linear		Linear	1278.323	34	37.598		
				Quadratic	3289.590	34	96.753		
				Cubic	1804.123	34	53.062		
				Order 4	1204.341	34	35.422		
	TARG	Linear		Linear	56.819	34	1.671		
				Quadratic	62.185	34	1.829		
				Cubic	60.021	34	1.765		
				Order 4	39.119	34	1.151		
	ISE	Linear		Linear	63652725.609	34	1872138.989		
				Quadratic	74990671.052	34	2205607.972		
				Cubic	288003754.975	34	8470698.676		
				Order 4	135194218.078	34	3976300.532		
DELAYS * TRACKS	TIME		Linear	Linear	787.381	1	787.381	11.233	.002
				Quadratic	10.100	1	10.100	.261	.613
				Cubic	50.124	1	50.124	.620	.436
				Order 4	559.060	1	559.060	10.768	.002
			Quadratic	Linear	.887	1	.887	.019	.891
				Quadratic	23.786	1	23.786	.798	.378
				Cubic	14.906	1	14.906	.277	.602
				Order 4	11.010	1	11.010	.241	.627
	TARG		Linear	Linear	10.193	1	10.193	4.450	.042
				Quadratic	2.046	1	2.046	.963	.333
				Cubic	4.968	1	4.968	1.582	.217
				Order 4	.552	1	.552	.273	.605
			Quadratic	Linear	3.655	1	3.655	3.893	.057
				Quadratic	2.898	1	2.898	2.954	.095
				Cubic	1.793	1	1.793	1.249	.272
				Order 4	.181	1	.181	.133	.718
	ISE		Linear	Linear	2652623.943	1	2652623.943	2.895	.098
				Quadratic	2508330.404	1	2508330.404	2.109	.156
				Cubic	10944120.640	1	10944120.640	5.702	.023
				Order 4	9313743.350	1	9313743.350	6.224	.018
			Quadratic	Linear	266209.539	1	266209.539	.287	.596
				Quadratic	84708.797	1	84708.797	.063	.804
				Cubic	113781.989	1	113781.989	.028	.867
				Order 4	2703808.319	1	2703808.319	1.122	.297

Table J.16: GLM Tests of Within-Subjects Contrasts - part 2

Source	Measure	VIS_INT	DELAYS	TRACKS	Type III Sum of Squares	df	Mean Square	F	Sig.
VIS_INT * TRACKS	TIME	Linear		Linear	22.570	1	22.570	.600	.444
				Quadratic	44.283	1	44.283	.458	.503
				Cubic	7.728	1	7.728	.146	.705
				Order 4	31.843	1	31.843	.899	.350
	TARG	Linear		Linear	2.634E-02	1	2.634E-02	.016	.901
				Quadratic	1.116	1	1.116	.610	.440
				Cubic	2.069	1	2.069	1.172	.287
				Order 4	3.634	1	3.634	3.158	.084
	ISE	Linear		Linear	3676547.347	1	3676547.347	1.964	.170
				Quadratic	36261876.483	1	36261876.483	16.441	.000
				Cubic	44931316.569	1	44931316.569	5.304	.028
				Order 4	2949277.332	1	2949277.332	.742	.395
Error (VIS_INT * TRACKS)	TIME	Linear		Linear	1278.323	34	37.598		
				Quadratic	3289.590	34	96.753		
				Cubic	1804.123	34	53.062		
				Order 4	1204.341	34	35.422		
	TARG	Linear		Linear	56.819	34	1.671		
				Quadratic	62.185	34	1.829		
				Cubic	60.021	34	1.765		
				Order 4	39.119	34	1.151		
	ISE	Linear		Linear	63652725.609	34	1872138.989		
				Quadratic	74990671.052	34	2205607.972		
				Cubic	288003754.975	34	8470698.676		
				Order 4	135194218.078	34	3976300.532		
DELAYS * TRACKS	TIME		Linear	Linear	787.381	1	787.381	11.233	.002
				Quadratic	10.100	1	10.100	.261	.613
				Cubic	50.124	1	50.124	.620	.436
				Order 4	559.060	1	559.060	10.768	.002
			Quadratic	Linear	.887	1	.887	.019	.891
				Quadratic	23.786	1	23.786	.798	.378
				Cubic	14.906	1	14.906	.277	.602
				Order 4	11.010	1	11.010	.241	.627
	TARG		Linear	Linear	10.193	1	10.193	4.450	.042
				Quadratic	2.046	1	2.046	.963	.333
				Cubic	4.968	1	4.968	1.582	.217
				Order 4	.552	1	.552	.273	.605
			Quadratic	Linear	3.655	1	3.655	3.893	.057
				Quadratic	2.898	1	2.898	2.954	.095
				Cubic	1.793	1	1.793	1.249	.272
				Order 4	.181	1	.181	.133	.718
	ISE		Linear	Linear	2652623.943	1	2652623.943	2.895	.098
				Quadratic	2508330.404	1	2508330.404	2.109	.156
				Cubic	10944120.640	1	10944120.640	5.702	.023
				Order 4	9313743.350	1	9313743.350	6.224	.018
			Quadratic	Linear	266209.539	1	266209.539	.287	.596
				Quadratic	84708.797	1	84708.797	.063	.804
				Cubic	113781.989	1	113781.989	.028	.867
				Order 4	2703808.319	1	2703808.319	1.122	.297

Table J.16: GLM Tests of Within-Subjects Contrasts - part 2

Source	Measure	VIS_INT	DELAYS	TRACKS	Type III Sum of Squares	df	Mean Square	F	Sig.
Error (DELAYS * TRACKS)	TIME		Linear	Linear	2383.263	34	70.096		
				Quadratic	1316.919	34	38.733		
				Cubic	2747.169	34	80.799		
				Order 4	1765.237	34	51.919		
			Quadratic	Linear	1596.095	34	46.944		
				Quadratic	1014.057	34	29.825		
				Cubic	1832.375	34	53.893		
				Order 4	1555.743	34	45.757		
	TARG		Linear	Linear	77.873	34	2.290		
				Quadratic	72.252	34	2.125		
				Cubic	106.752	34	3.140		
				Order 4	68.844	34	2.025		
			Quadratic	Linear	31.927	34	.939		
				Quadratic	33.349	34	.981		
				Cubic	48.814	34	1.436		
				Order 4	46.358	34	1.363		
	ISE		Linear	Linear	31155985.129	34	916352.504		
				Quadratic	40432558.760	34	1189192.905		
				Cubic	65254984.393	34	1919264.247		
				Order 4	50875896.143	34	1496349.887		
			Quadratic	Linear	31587800.833	34	929052.966		
				Quadratic	46036790.131	34	1354023.239		
				Cubic	136251515.825	34	4007397.524		
				Order 4	81918364.468	34	2409363.661		
VIS_INT * DELAYS * TRACKS	TIME	Linear	Linear	Linear	1.445	1	1.445	.052	.821
				Quadratic	1.052	1	1.052	.018	.894
				Cubic	171.993	1	171.993	1.773	.192
				Order 4	2.804E-02	1	2.804E-02	.000	.982
			Quadratic	Linear	85.051	1	85.051	2.385	.132
				Quadratic	16.444	1	16.444	.910	.347
				Cubic	27.094	1	27.094	.433	.515
				Order 4	37.928	1	37.928	.713	.404
	TARG	Linear	Linear	Linear	4.761	1	4.761	1.966	.170
				Quadratic	.190	1	.190	.093	.762
				Cubic	8.428	1	8.428	2.676	.111
				Order 4	3.644E-03	1	3.644E-03	.002	.967
			Quadratic	Linear	1.570	1	1.570	1.525	.225
				Quadratic	2.581	1	2.581	2.872	.099
				Cubic	2.323	1	2.323	1.432	.240
				Order 4	1.121	1	1.121	.820	.372
	ISE	Linear	Linear	Linear	4192463.622	1	4192463.622	6.374	.016
				Quadratic	2862117.672	1	2862117.672	2.296	.139
				Cubic	8948673.930	1	8948673.930	3.955	.055
				Order 4	3555739.229	1	3555739.229	2.611	.115
			Quadratic	Linear	1272014.701	1	1272014.701	1.282	.265
				Quadratic	50928.392	1	50928.392	.028	.868
				Cubic	718888.896	1	718888.896	.200	.657
				Order 4	1745284.962	1	1745284.962	.661	.422

Table J.17: GLM Tests of Within-Subjects Contrasts - part 3

Source	Measure	VIS_INT	DELAYS	TRACKS	Type III Sum of Squares	df	Mean Square	F	Sig.
Error (VIS_INT * DELAYS * TRACKS)	TIME	Linear	Linear	Linear	940.280	34	27.655		
				Quadratic	1999.429	34	58.807		
				Cubic	3297.627	34	96.989		
				Order 4	1907.594	34	56.106		
			Quadratic	Linear	1212.641	34	35.666		
				Quadratic	614.676	34	18.079		
				Cubic	2126.480	34	62.544		
				Order 4	1808.612	34	53.194		
	TARG	Linear	Linear	Linear	82.339	34	2.422		
				Quadratic	69.210	34	2.036		
				Cubic	107.090	34	3.150		
				Order 4	71.216	34	2.095		
			Quadratic	Linear	34.997	34	1.029		
				Quadratic	30.561	34	.899		
				Cubic	55.138	34	1.622		
				Order 4	46.484	34	1.367		
	ISE	Linear	Linear	Linear	22363374.787	34	657746.317		
				Quadratic	42376850.515	34	1246377.956		
				Cubic	76919624.149	34	2262341.887		
				Order 4	46309858.946	34	1362054.675		
			Quadratic	Linear	33722591.165	34	991840.917		
				Quadratic	61555745.470	34	1810463.102		
				Cubic	122125299.944	34	3591920.587		
				Order 4	89836770.650	34	2642257.960		

Table J.18: GLM Tests of Within-Subjects Contrasts - part 4

Source	Measure	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	TIME	593398.883	1	593398.883	899.142	.000
	TARG	122.214	1	122.214	38.157	.000
	ISE	4522397546.306	1	4522397546.306	355.180	.000
Error	TIME	22438.672	34	659.961		
	TARG	108.899	34	3.203		
	ISE	432911711.330	34	12732697.392		

Transformed Variable: Average

Table J.19: GLM Tests of Between-Subjects Effects

Appendix K

Analysis of Variance Results for Central Executive Disruption Experiments

The analysis of variance was calculated using the General Linear Model (GLM) for Repeated Measures in SPSS.

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General Linear Model

Notes

| ---------------------------------------------- | ----------------------------------------------------------------------- |
| Output Created                                 | 04-DEC-2002 20:51:25                                                    |
| ---------------------------------------------- | ----------------------------------------------------------------------- |
| Comments                                       |                                                                         |
| ------------- | ------------------------------ | ----------------------------------------------------------------------- |
| Input         | Data                           | C:\Documents and Settings\Phil Day\My Documents\phil\experiments\all.sav |
|               | ------------------------------ | ----------------------------------------------------------------------- |
|               | Filter                         | <none>                                                                  |
|               | ------------------------------ | ----------------------------------------------------------------------- |
|               | Weight                         | <none>                                                                  |
|               | ------------------------------ | ----------------------------------------------------------------------- |
|               | Split File                     | <none>                                                                  |
|               | ------------------------------ | ----------------------------------------------------------------------- |
|               | N of Rows in Working Data File | 30                                                                      |
| ------------- | ------------------------------ | ----------------------------------------------------------------------- |
| Missing Value | Definition of Missing          | User-defined missing values are treated as missing.                    |
| Handling      | ------------------------------ | ----------------------------------------------------------------------- |
|               | Cases Used                     | Statistics are based on all cases with valid data for all variables in the model. |
| ------------- | ------------------------------ | ----------------------------------------------------------------------- |
| Syntax                                         | GLM                                                                     |
|                                                | time_sn time_mn time_cn time_si time_mi time_ci targ_sn targ_mn targ_cn |
|                                                | targ_si targ_mi targ_ci ise_sn ise_mn ise_cn ise_si ise_mi ise_ci       |
|                                                | /WSFACTOR = int 2 Polynomial trk_com 3 Polynomial                       |
|                                                | /MEASURE = time targ ise                                                |
|                                                | /METHOD = SSTYPE(3)                                                     |
|                                                | /PRINT = DESCRIPTIVE                                                    |
|                                                | /CRITERIA = ALPHA(.05)                                                  |
|                                                | /WSDESIGN = int trk_com int*trk_com .                                   |
|                                                |                                                                         |
| ------------- | ------------------------------ | ----------------------------------------------------------------------- |
| Resources     | Elapsed Time                   | 0:00:00.07                                                              |
| ------------- | ------------------------------ | ----------------------------------------------------------------------- |


Within-Subjects Factors

| ------- | --- | ------- | ------------------ |
| Measure | INT | TRK_COM | Dependent Variable |
| ------- | --- | ------- | ------------------ |
| TIME    | 1   | 1       | TIME_SN            |
|         |     | ------- | ------------------ |
|         |     | 2       | TIME_MN            |
|         |     | ------- | ------------------ |
|         |     | 3       | TIME_CN            |
|         | --- | ------- | ------------------ |
|         | 2   | 1       | TIME_SI            |
|         |     | ------- | ------------------ |
|         |     | 2       | TIME_MI            |
|         |     | ------- | ------------------ |
|         |     | 3       | TIME_CI            |
| ------- | --- | ------- | ------------------ |
| TARG    | 1   | 1       | TARG_SN            |
|         |     | ------- | ------------------ |
|         |     | 2       | TARG_MN            |
```

K Analysis of Variance Results for Central Executive Disruption Experiments

```
|         |     | ------- | ------------------ |
|         |     | 3       | TARG_CN            |
|         | --- | ------- | ------------------ |
|         | 2   | 1       | TARG_SI            |
|         |     | ------- | ------------------ |
|         |     | 2       | TARG_MI            |
|         |     | ------- | ------------------ |
|         |     | 3       | TARG_CI            |
| ------- | --- | ------- | ------------------ |
| ISE     | 1   | 1       | ISE_SN             |
|         |     | ------- | ------------------ |
|         |     | 2       | ISE_MN             |
|         |     | ------- | ------------------ |
|         |     | 3       | ISE_CN             |
|         | --- | ------- | ------------------ |
|         | 2   | 1       | ISE_SI             |
|         |     | ------- | ------------------ |
|         |     | 2       | ISE_MI             |
|         |     | ------- | ------------------ |
|         |     | 3       | ISE_CI             |
| ------- | --- | ------- | ------------------ |
```

```
Descriptive Statistics

| ------------------------------ | --------- | -------------- | -- |
|                                | Mean      | Std. Deviation | N  |
| ------------------------------ | --------- | -------------- | -- |
| av time: simple track, no int  | 14.9599   | 1.28538        | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av time: med track, no int     | 16.2250   | 2.19515        | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av time: complex track, no int | 18.2585   | 2.01100        | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av time: simple track, int     | 14.8746   | .80756         | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av time: med, int              | 16.4791   | 2.47688        | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av time: complex, int          | 18.3379   | 2.01777        | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av targ: simple track, no int  | .072077   | .0413576       | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av targ: med, no int           | .265067   | .7898475       | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av targ: com, no int           | .121087   | .0460852       | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av targ: sim, int              | .066574   | .0420408       | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av targ: med, int              | .285252   | .7772319       | 30 |
| ------------------------------ | --------- | -------------- | -- |
| av targ: com, int              | .120438   | .0565382       | 30 |
| ------------------------------ | --------- | -------------- | -- |
| ise: simple, no int            | 1.3577    | 1.62826        | 30 |
| ------------------------------ | --------- | -------------- | -- |
| ise: med, no int               | 1793.9281 | 188.94413      | 30 |
| ------------------------------ | --------- | -------------- | -- |
| ise: com, no int               | 1487.5100 | 168.07817      | 30 |
| ------------------------------ | --------- | -------------- | -- |
| ise: sim, int                  | 1.4596    | 1.91492        | 30 |
| ------------------------------ | --------- | -------------- | -- |
| ise: med, int                  | 2057.9896 | 1351.99054     | 30 |
| ------------------------------ | --------- | -------------- | -- |
| ise: com, int                  | 1495.8027 | 230.44873      | 30 |
| ------------------------------ | --------- | -------------- | -- |
```

```
Multivariate Tests(b)

| ---------------------------------------- | ------- | ----------- | ------------- | -------- | ---- |
| Effect                                   | Value   | F           | Hypothesis df | Error df | Sig. |
| -------- | ---------- | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
| Between  | Intercept  | Pillai's Trace     | .997    | 2951.582(a) | 3.000         | 27.000   | .000 |
| Subjects |            | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          |            | Wilks' Lambda      | .003    | 2951.582(a) | 3.000         | 27.000   | .000 |
|          |            | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          |            | Hotelling's Trace  | 327.954 | 2951.582(a) | 3.000         | 27.000   | .000 |
|          |            | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          |            | Roy's Largest Root | 327.954 | 2951.582(a) | 3.000         | 27.000   | .000 |
| -------- | ---------- | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
| Within   | INT        | Pillai's Trace     | .065    | .624(a)     | 3.000         | 27.000   | .606 |
| Subjects |            | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          |            | Wilks' Lambda      | .935    | .624(a)     | 3.000         | 27.000   | .606 |
|          |            | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          |            | Hotelling's Trace  | .069    | .624(a)     | 3.000         | 27.000   | .606 |
|          |            | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          |            | Roy's Largest Root | .069    | .624(a)     | 3.000         | 27.000   | .606 |
|          | ---------- | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          | TRK_COM    | Pillai's Trace     | .995    | 848.362(a)  | 6.000         | 24.000   | .000 |
|          |            | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          |            | Wilks' Lambda      | .005    | 848.362(a)  | 6.000         | 24.000   | .000 |
|          |            | ------------------ | ------- | ----------- | ------------- | -------- | ---- |
|          |            | Hotelling's Trace  | 212.090 | 848.362(a)  | 6.000         | 24.000   | .000 |
```

K Analysis of Variance Results for Central Executive Disruption Experiments

		Roy's Largest Root	212.090	848.362(a)	6.000	24.000	.000
	INT * TRK_COM	Pillai's Trace	.064	.274(a)	6.000	24.000	.944
		Wilks' Lambda	.936	.274(a)	6.000	24.000	.944
		Hotelling's Trace	.069	.274(a)	6.000	24.000	.944
		Roy's Largest Root	.069	.274(a)	6.000	24.000	.944

a Exact statistic
b Design: Intercept
Within Subjects Design: INT+TRK_COM+INT*TRK_COM

Mauchly's Test of Sphericity(b)

Within Subjects Effect	Measure	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon(a)		
						Greenhouse-Geisser	Huynh-Feldt	Lower-bound
INT	TIME	1.000	.000	0	.	1.000	1.000	1.000
	TARG	1.000	.000	0	.	1.000	1.000	1.000
	ISE	1.000	.000	0	.	1.000	1.000	1.000
TRK_COM	TIME	.761	7.635	2	.022	.807	.848	.500
	TARG	.014	120.205	2	.000	.503	.504	.500
	ISE	.154	52.359	2	.000	.542	.546	.500
INT * TRK_COM	TIME	.774	7.188	2	.027	.815	.857	.500
	TARG	.019	111.334	2	.000	.506	.505	.500
	ISE	.068	75.361	2	.000	.518	.519	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.
a May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.
b Design: Intercept
Within Subjects Design: INT+TRK_COM+INT*TRK_COM

Tests of Within-Subjects Effects

Multivariate(c,d)

Within Subjects Effect		Value	F	Hypothesis df	Error df	Sig.
INT	Pillai's Trace	.065	.624(a)	3.000	27.000	.606
	Wilks' Lambda	.935	.624(a)	3.000	27.000	.606
	Hotelling's Trace	.069	.624(a)	3.000	27.000	.606
	Roy's Largest Root	.069	.624(a)	3.000	27.000	.606
TRK_COM	Pillai's Trace	1.554	66.225	6.000	114.000	.000
	Wilks' Lambda	.038	77.029(a)	6.000	112.000	.000
	Hotelling's Trace	9.718	89.084	6.000	110.000	.000
	Roy's Largest Root	7.696	146.225(b)	3.000	57.000	.000
INT * TRK_COM	Pillai's Trace	.039	.376	6.000	114.000	.893
	Wilks' Lambda	.961	.372(a)	6.000	112.000	.896
	Hotelling's Trace	.040	.367	6.000	110.000	.898
	Roy's Largest Root	.035	.671(b)	3.000	57.000	.573

a Exact statistic
b The statistic is an upper bound on F that yields a lower bound on the significance level.
c Design: Intercept
Within Subjects Design: INT+TRK_COM+INT*TRK_COM
d Tests are based on averaged variables.

Univariate Tests

Source	Measure		Type III Sum of Squares	df	Mean Square	F	Sig.

K Analysis of Variance Results for Central Executive Disruption Experiments

INT	TIME	Sphericity Assumed	.308	1	.308	.090	.766
		Greenhouse-Geisser	.308	1.000	.308	.090	.766
		Huynh-Feldt	.308	1.000	.308	.090	.766
		Lower-bound	.308	1.000	.308	.090	.766
	TARG	Sphericity Assumed	9.845E-04	1	9.845E-04	.005	.947
		Greenhouse-Geisser	9.845E-04	1.000	9.845E-04	.005	.947
		Huynh-Feldt	9.845E-04	1.000	9.845E-04	.005	.947
		Lower-bound	9.845E-04	1.000	9.845E-04	.005	.947
	ISE	Sphericity Assumed	371161.347	1	371161.347	.925	.344
		Greenhouse-Geisser	371161.347	1.000	371161.347	.925	.344
		Huynh-Feldt	371161.347	1.000	371161.347	.925	.344
		Lower-bound	371161.347	1.000	371161.347	.925	.344
Error(INT)	TIME	Sphericity Assumed	99.340	29	3.426		
		Greenhouse-Geisser	99.340	29.000	3.426		
		Huynh-Feldt	99.340	29.000	3.426		
		Lower-bound	99.340	29.000	3.426		
	TARG	Sphericity Assumed	6.291	29	.217		
		Greenhouse-Geisser	6.291	29.000	.217		
		Huynh-Feldt	6.291	29.000	.217		
		Lower-bound	6.291	29.000	.217		
	ISE	Sphericity Assumed	11638428.870	29	401325.133		
		Greenhouse-Geisser	11638428.870	29.000	401325.133		
		Huynh-Feldt	11638428.870	29.000	401325.133		
		Lower-bound	11638428.870	29.000	401325.133		
TRK_COM	TIME	Sphericity Assumed	345.534	2	172.767	51.784	.000
		Greenhouse-Geisser	345.534	1.615	213.999	51.784	.000
		Huynh-Feldt	345.534	1.696	203.761	51.784	.000
		Lower-bound	345.534	1.000	345.534	51.784	.000
	TARG	Sphericity Assumed	1.377	2	.689	3.470	.038
		Greenhouse-Geisser	1.377	1.007	1.368	3.470	.072
		Huynh-Feldt	1.377	1.008	1.367	3.470	.072
		Lower-bound	1.377	1.000	1.377	3.470	.073
	ISE	Sphericity Assumed	122267006.215	2	61133503.107	205.165	.000
		Greenhouse-Geisser	122267006.215	1.084	112844463.289	205.165	.000
		Huynh-Feldt	122267006.215	1.093	111892015.953	205.165	.000
		Lower-bound	122267006.215	1.000	122267006.215	205.165	.000
Error(TRK_COM)	TIME	Sphericity Assumed	193.507	58	3.336		
		Greenhouse-Geisser	193.507	46.825	4.133		
		Huynh-Feldt	193.507	49.178	3.935		
		Lower-bound	193.507	29.000	6.673		
	TARG	Sphericity Assumed	11.508	58	.198		
		Greenhouse-Geisser	11.508	29.199	.394		
		Huynh-Feldt	11.508	29.221	.394		
		Lower-bound	11.508	29.000	.397		
	ISE	Sphericity Assumed	17282423.695	58	297972.822		
		Greenhouse-Geisser	17282423.695	31.422	550018.918		

K Analysis of Variance Results for Central Executive Disruption Experiments

		Huynh-Feldt	17282423.695	31.689	545376.563		
		Lower-bound	17282423.695	29.000	595945.645		
INT * TRK_COM	TIME	Sphericity Assumed	.864	2	.432	.177	.838
		Greenhouse-Geisser	.864	1.631	.530	.177	.794
		Huynh-Feldt	.864	1.714	.504	.177	.805
		Lower-bound	.864	1.000	.864	.177	.677
	TARG	Sphericity Assumed	5.588E-03	2	2.794E-03	.014	.986
		Greenhouse-Geisser	5.588E-03	1.009	5.535E-03	.014	.909
		Huynh-Feldt	5.588E-03	1.010	5.530E-03	.014	.910
		Lower-bound	5.588E-03	1.000	5.588E-03	.014	.908
	ISE	Sphericity Assumed	675797.491	2	337898.746	.965	.387
		Greenhouse-Geisser	675797.491	1.035	652893.903	.965	.337
		Huynh-Feldt	675797.491	1.039	650501.185	.965	.337
		Lower-bound	675797.491	1.000	675797.491	.965	.334
Error(INT*TRK_COM)	TIME	Sphericity Assumed	141.691	58	2.443		
		Greenhouse-Geisser	141.691	47.293	2.996		
		Huynh-Feldt	141.691	49.719	2.850		
		Lower-bound	141.691	29.000	4.886		
	TARG	Sphericity Assumed	11.832	58	.204		
		Greenhouse-Geisser	11.832	29.275	.404		
		Huynh-Feldt	11.832	29.304	.404		
		Lower-bound	11.832	29.000	.408		
	ISE	Sphericity Assumed	20308629.212	58	350148.780		
		Greenhouse-Geisser	20308629.212	30.017	676563.635		
		Huynh-Feldt	20308629.212	30.128	674084.171		
		Lower-bound	20308629.212	29.000	700297.559		

Tests of Within-Subjects Contrasts

Source	Measure	INT	TRK_COM	Type III Sum of Squares	df	Mean Square	F	Sig.
INT	TIME	Linear		.308	1	.308	.090	.766
	TARG	Linear		9.845E-04	1	9.845E-04	.005	.947
	ISE	Linear		371161.347	1	371161.347	.925	.344
Error(INT)	TIME	Linear		99.340	29	3.426		
	TARG	Linear		6.291	29	.217		
	ISE	Linear		11638428.870	29	401325.133		
TRK_COM	TIME		Linear	342.921	1	342.921	175.720	.000
			Quadratic	2.613	1	2.613	.554	.463
	TARG		Linear	7.937E-02	1	7.937E-02	58.337	.000
			Quadratic	1.298	1	1.298	3.281	.080
	ISE		Linear	66625146.871	1	66625146.871	2406.762	.000
			Quadratic	55641859.344	1	55641859.344	97.916	.000
Error(TRK_COM)	TIME		Linear	56.594	29	1.952		
			Quadratic	136.913	29	4.721		
	TARG		Linear	3.946E-02	29	1.361E-03		
			Quadratic	11.469	29	.395		
	ISE		Linear	802791.892	29	27682.479		

K Analysis of Variance Results for Central Executive Disruption Experiments

			Quadratic	16479631.803	29	568263.166		
INT * TRK_COM	TIME	Linear	Linear	.203	1	.203	.150	.701
			Quadratic	.661	1	.661	.187	.669
	TARG	Linear	Linear	1.768E-04	1	1.768E-04	.091	.765
			Quadratic	5.411E-03	1	5.411E-03	.013	.909
	ISE	Linear	Linear	503.164	1	503.164	.039	.844
			Quadratic	675294.327	1	675294.327	.982	.330
Error(INT*TRK_COM)	TIME	Linear	Linear	39.234	29	1.353		
			Quadratic	102.457	29	3.533		
	TARG	Linear	Linear	5.606E-02	29	1.933E-03		
			Quadratic	11.776	29	.406		
	ISE	Linear	Linear	370684.795	29	12782.234		
			Quadratic	19937944.418	29	687515.325		

Tests of Between-Subjects Effects
Transformed Variable: Average

Source	Measure	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	TIME	49138.687	1	49138.687	7690.667	.000
	TARG	4.329	1	4.329	20.137	.000
	ISE	233794476.957	1	233794476.957	945.108	.000
Error	TIME	185.292	29	6.389		
	TARG	6.234	29	.215		
	ISE	7173821.819	29	247373.166		

K.1 Analysis of Variance Results for track complexity on random number generation

The analysis of variance was calculated using the General Linear Model (GLM) for Repeated Measures in SPSS.

```
General Linear Model

Notes

| --------------------------------------------- | -------------------------------------------------------------------------- |
| Output Created                                | 22-JAN-2003 20:36:00                                                       |
| --------------------------------------------- | -------------------------------------------------------------------------- |
| Comments                                      |                                                                            |
| ------------ | ------------------------------ | -------------------------------------------------------------------------- |
| Input        | Data                           | C:\Documents and Settings\Phil Day\My                                      |
|              |                                | Documents\phil\phd\post_viva_analysis                                      |
|              |                                | umbers.sav                                                                 |
|              | ------------------------------ | -------------------------------------------------------------------------- |
|              | Filter                         | <none>                                                                     |
|              | ------------------------------ | -------------------------------------------------------------------------- |
|              | Weight                         | <none>                                                                     |
|              | ------------------------------ | -------------------------------------------------------------------------- |
|              | Split File                     | <none>                                                                     |
|              | ------------------------------ | -------------------------------------------------------------------------- |
|              | N of Rows in Working Data File | 30                                                                         |
| ------------ | ------------------------------ | -------------------------------------------------------------------------- |
| Missing Value | Definition of Missing         | User-defined missing values are treated as missing.                        |
| Handling     | ------------------------------ | -------------------------------------------------------------------------- |
|              | Cases Used                     | Statistics are based on all cases with valid data for all variables in the model. |
| ------------ | ------------------------------ | -------------------------------------------------------------------------- |
| Syntax                                        | GLM                                                                        |
|                                               | r_sim r_med r_com                                                          |
|                                               | /WSFACTOR = trk 3 Polynomial                                               |
|                                               | /MEASURE = r_num                                                           |
|                                               | /METHOD = SSTYPE(3)                                                        |
|                                               | /CRITERIA = ALPHA(.05)                                                     |
|                                               | /WSDESIGN = trk .                                                          |
|                                               |                                                                            |
| ------------ | ------------------------------ | -------------------------------------------------------------------------- |
| Resources    | Elapsed Time                   | 0:00:00.23                                                                 |
| ------------ | ------------------------------ | -------------------------------------------------------------------------- |


Within-Subjects Factors
Measure: R_NUM

| --- | ------------------ |
| TRK | Dependent Variable |
| --- | ------------------ |
| 1   | R_SIM              |
| --- | ------------------ |
| 2   | R_MED              |
| --- | ------------------ |
| 3   | R_COM              |
| --- | ------------------ |


Multivariate Tests(b)

| ------------------------ | ------ | ---------- | ------------- | -------- | ---- |
| Effect                   | Value  | F          | Hypothesis df | Error df | Sig. |
| --- | ------------------ | ------ | ---------- | ------------- | -------- | ---- |
| TRK | Pillai's Trace     | .985   | 920.296(a) | 2.000         | 28.000   | .000 |
|     | ------------------ | ------ | ---------- | ------------- | -------- | ---- |
|     | Wilks' Lambda      | .015   | 920.296(a) | 2.000         | 28.000   | .000 |
|     | ------------------ | ------ | ---------- | ------------- | -------- | ---- |
|     | Hotelling's Trace  | 65.735 | 920.296(a) | 2.000         | 28.000   | .000 |
|     | ------------------ | ------ | ---------- | ------------- | -------- | ---- |
|     | Roy's Largest Root | 65.735 | 920.296(a) | 2.000         | 28.000   | .000 |
| --- | ------------------ | ------ | ---------- | ------------- | -------- | ---- |

a Exact statistic
b Design: Intercept
 Within Subjects Design: TRK

Mauchly's Test of Sphericity(b)
Measure: R_NUM

| --------------------- | --------- | ---------- | -- | ---- | ---------------------------------------------- |
|                       | Mauchly's | Approx.    | df | Sig. | Epsilon(a)                                     |
| --------------------- | W         | Chi-Square |    |      | ------------------ | ----------- | ----------- |
| Within Subjects Effect |          |            |    |      | Greenhouse-Geisser | Huynh-Feldt | Lower-bound |
| --------------------- | --------- | ---------- | -- | ---- | ------------------ | ----------- | ----------- |
| TRK                   | .953      | 1.343      | 2  | .511 | .955               | 1.000       | .500        |
| --------------------- | --------- | ---------- | -- | ---- | ------------------ | ----------- | ----------- |
```

K.1 Analysis of Variance Results for track complexity on random number generation

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.
a May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.
b Design: Intercept
Within Subjects Design: TRK

Tests of Within-Subjects Effects
Measure: R_NUM

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
TRK	Sphericity Assumed	3.958E-02	2	1.979E-02	746.877	.000
	Greenhouse-Geisser	3.958E-02	1.911	2.072E-02	746.877	.000
	Huynh-Feldt	3.958E-02	2.000	1.979E-02	746.877	.000
	Lower-bound	3.958E-02	1.000	3.958E-02	746.877	.000
Error(TRK)	Sphericity Assumed	1.537E-03	58	2.650E-05		
	Greenhouse-Geisser	1.537E-03	55.405	2.774E-05		
	Huynh-Feldt	1.537E-03	58.000	2.650E-05		
	Lower-bound	1.537E-03	29.000	5.300E-05		

Tests of Within-Subjects Contrasts
Measure: R_NUM

Source	TRK	Type III Sum of Squares	df	Mean Square	F	Sig.
TRK	Linear	3.327E-02	1	3.327E-02	1472.392	.000
	Quadratic	6.314E-03	1	6.314E-03	207.680	.000
Error(TRK)	Linear	6.553E-04	29	2.260E-05		
	Quadratic	8.817E-04	29	3.040E-05		

Tests of Between-Subjects Effects
Measure: R_NUM
Transformed Variable: Average

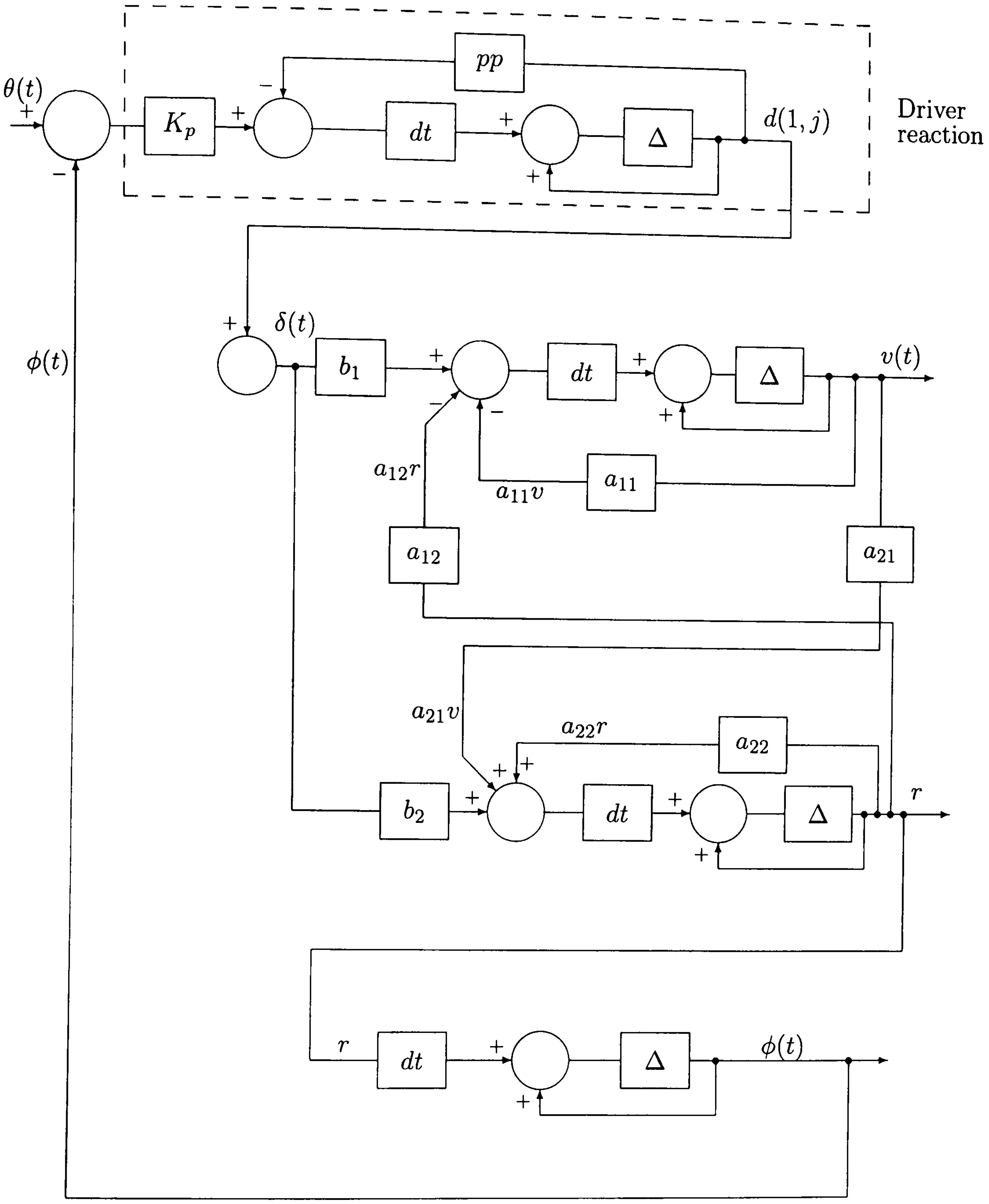
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.389	1	.389	2806.049	.000
Error	4.021E-03	29	1.387E-04		

Appendix L

Control System Modelling

L.1 Modelling Vehicle Dynamics

The control system used to model the dynamics of a vehicle (including the reaction time of the human controller as part of the system) is shown in Figure L.1.



where $\delta(t)$: heading control, $v(t)$: lateral speed, $\phi(t)$: actual heading and $\theta(t)$: reference heading

Figure L.1: Model of vehicle dynamics

Appendix M

Control Systems Model - Matlab implementation

```
% v26.m  taken from vr231.m by GTR
% additional work PND

% changes since v24:  change variable names to avoid
% confusion between delay and delta terms
% and remove redundant code

% change since v25:  actual track start on reference trajectory
% rather than at some point off the track

%GT Russell re-visit 04.07.01   (29.02.00)
%to include delay in feedback
%automatic track following simulation

% for evaluation purposes change delay_magnitude from 0, 70, 140 (delayed feedback)
%   change vis_int from 0 (false) to 1 (true)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Global flags / settings for code
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Flag to just use dummy data (1) or real data (0)
dummy=0;

% Flag to perform analysis of integral of squared tracking error (1) or not
analysis=0;

% Flag to include visual inteference tasks (1) or not
vis_int=1;

% Magnitude of constant (visual feedback) delay in system
delay_magnitude=140;  % sets value of omega (delayed feedback).
% 0 small, 70 medium, 140 large

% distance between x values of reference curve
% (used when creating new reference curve for analysis)
% smaller increment gives better sampling of curve
x_increment = 0.01;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% vehicle simulation
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%time period and sample rate
T = 100;
n = 1000;
dt = T/n;   % = 0.1
t = 0:dt:T; % array from 0 to 100 in 0.1 increments
tp1 = 50;
tp2 = 20;
N = max(size(t));  % = 1001

%vehicle parameters
a11 = 10;
a12 = 0.5;
a21 = 1;
a22 = 10;
b1 = 1e-1;  % 1 * 10^-1 i.e. 0.1
b2 = 1;
b3 = 5;

cd = 0.5;
Kp = 50;
pp = 3;
Ks = b2;
K = Ks*Kp;       % = 50
N1 = 1:(N-(tp2/dt)-(tp1/dt));  %array from 1..301

%trajectory
p = 60;
Xmax = 200;
dp = Xmax/p;      % = 3.33
XX = 0:dp:Xmax;  % array from 0..200 in 3.33 inc
betat = 0.1;
alphat = (1/(betat*sqrt(2*pi)));
H = (exp(-0.5*((XX/Xmax-0.5)/betat).^2));
X = XX;
Y = 200*(H);

dX = diff(X);
dY = diff(Y);

grad = dY./dX;
rate = diff(grad);

%forward speed of the vehicle
ud = 0.6;

%number of way points on the curve
H0 = 20;


%number of samples between the way points
nn = 200;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% human controller model
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%GT Russell   -   28.02.01
%definition of a confusion function
%related to vision feedback control systems

%number of samples on the vehicle path
nc = nn*H0;
%time on vehicle path
Tc = dt*nc;
tc = 0:dt:Tc;
Cp = 1; %complexity measure in range 0 to 0.9
alpha = 5; %task A complexity
beta = alpha - Cp; %task B complexity
gamma = 1.5; %

%human in the loop
%secondary task sequence per unit values of run time (run time = 4000 samples)
% tasks positioned just before and after bend as in VR experiments
task10 = 0.1;  % i.e. task1 starts at 400 samples
task11 = 0.1;  % i.e. task1 lasts for 400 samples
task20 = 0.1;  % i.e. task2 starts 400 samples after task1 ends
task21 = 0.1;  % task2 ends after 400 samples
task30 = 0;    % not used as only modelling 2 tasks
task31 = 0;    %
task40 = 1-(task10+task11+task20+task21+task30+task31);
%task complexity factor
z1 = 0.8;
z2 = 0.8;
z3 = 0;
t10 = 0:dt:task10*Tc;
t11 = 0:dt:task11*Tc;
t20 = 0:dt:task20*Tc;
t21 = 0:dt:task21*Tc;
t30 = 0:dt:task30*Tc;
t31 = 0:dt:task31*Tc;
t40 = 0:dt:task40*Tc;

N10 = size(t10);
N11 = size(t11);
N20 = size(t20);
N21 = size(t21);
N30 = size(t30);
N31 = size(t31);
N40 = size(t40);

uc1 = [zeros(N10) z1*ones(N11) zeros(N20) z2*ones(N21) zeros(N30) z3*ones(N31)
 zeros(N40)];

%for the given secondary task sequence,
%determine the confusion function (cfus) over the time that the vehicle moves
```

```
for jj = 1:1:nc;
   xc(1,1) = 0;
yc(1,1) = 0;
cfus(1,1) = 0;
xc(1,jj+1) = (uc1(1,jj) - xc(1,jj))*(1/alpha)*dt + xc(1,jj);
   if xc(1,jj) < 0.9;
      qc(1,jj) = 1;
   else qc(1,jj) = 0;
   end
yc(1,jj+1) = (uc1(1,jj) - yc(1,jj))*(1/beta)*dt + yc(1,jj);

c(1,jj) = gamma*(yc(1,jj) - xc(1,jj));
   cfus(1,jj+1) = dt*c(1,jj) + cfus(1,jj);
end

%determine the delay time over the time that the vehicle moves
td = 25; % was 20
% td is a porportion of the whole time (to do task)
delay = (td/T)*n;
% delay is a shift in time
dtau1 = delay*(cfus);
% ie. dtau1 = amount of delay due to confusion caused by interpolated tasks

%constant delay over the whole period
% i.e. dtau2 is analagous to delayed visual feedback
dd = max(size(dtau1));
Nd = 1:dd;
%omega is magnitude of constant delay (200 = 1 period of sampling)
% i.e. omega is analagous to size of visual delay for experiment
omega = delay_magnitude;
dtau2 = omega*ones(size(Nd));

%total confusion
%ie. total confusion = confusion due to interpolated tasks
%+ confusion due to external delay
if (vis_int)
   dtau = dtau1+dtau2;
   % confusion due to interploted task + confusion due to external delay
else
   dtau = dtau2;  % confusion due to external delay
end

%determine the vehicle trajectory between the way points
for h = 1:1:H0;
x1(1,1) = 80;  %80;
y1(1,1) = 140; %was 140 (off the ref trajectory) or 121.3061 on ref
   v1(1,1) = 0;
u1(1,1) = ud;
r1(1,1) = 0;
   th0 = 80;
phi1(1,1) = th0*(pi/180);
d1(1,1) = 0;

x(1,1) = x1(1,h);
```

```
y(1,1) = y1(1,h);
v(1,1) = v1(1,h);
r(1,1) = r1(1,h);
phi(1,1) = phi1(1,h);
u(1,1) = u1(1,h);
d(1,1) = d1(1,h);
%pref(1,1) = 80;

   %human in the loop
   %calculation of the reference heading
   %assuming a constant speed on bends

   RR = ud*nn*dt;

   %alternative assumption of variable speed on bends
   %RRv = 8*(2 - abs(rate));

   %calculate the reference heading angle

   xd1(1,1) = x(1,1);
   yd1(1,1) = y(1,1);

   for q = 1:1:p-1;
      dP = 1/2000;

      xr(1,1) = x1(1,h) + 10;
      xs(1,q) = (xr(1,q) - xd1(1,h)).^2;
      yr(1,q) = (exp(-0.5*(((xr(1,q)/200)-0.5)/betat).^2));
      ys(1,q) = (200*yr(1,q) - yd1(1,h)).^2;
      er(1,q) = (RR.^2 - ys(1,q) - xs(1,q));
      xr(1,q+1) = er(1,q)*dP + xr(1,q);
   end

   deltay = (200*yr(1,p-1)-yd1(1,h));
   deltax = (xr(1,p-1)-xd1(1,h));
   theta = (180/pi)*atan(abs(deltay)./abs(deltax));

   if deltay > 0 & deltax > 0;
      theta0 = theta;
   elseif deltay > 0 & deltax < 0;
      theta0 = 180 + theta;
   elseif deltay <0 & deltax > 0;
      theta0 = -theta;
   elseif deltay < 0 & deltax < 0;
      theta0 = -180 + theta;
   end

   th(1,h+1) = theta0;

   %vehicle model with sample time increment dt

   for j = 1:1:nn;
      m = nn*(h-1);
```

```
      %driver reaction time transfer function
      e(1,j) = (th(1,h+1) - (180/pi)*phi(1,j));
      d(1,j+1) = (e(1,j)*Kp - pp*d(1,j))*dt + d(1,j);
      del(1,j) = d(1,j);

      %vehicle
      v(1,j+1) = dt*(b1*del(1,j)-a12*r(1,j)-a11*v(1,j))+v(1,j);
      r(1,j+1) = dt*(b2*del(1,j)+a21*v(1,j)-a22*r(1,j))+r(1,j);
      phi(1,j+1) = (pi/180)*(dt*r(1,j))+phi(1,j);

      u(1,j+1) = dt*(b3)*(ud-u(1,j))+u(1,j);

      V(1,j) = (u(1,j)+i*(v(1,j)))*(exp(i*phi(1,j)));
      VW(1,j) = V(1,j);

      %vehicle trajectory between the waypoints
      dx(1,j) = real(VW(1,j));
      dy(1,j) = imag(VW(1,j));
      x(1,j+1) = dt*dx(1,j)+x(1,j);
      y(1,j+1) = dt*dy(1,j)+y(1,j);
   end

   %construct the total vehicle trajectory
   x0((h-1)*nn+1:h*nn) = x(1:nn);
y0((h-1)*nn+1:h*nn) = y(1:nn);
v0((h-1)*nn+1:h*nn) = v(1:nn);
u0((h-1)*nn+1:h*nn) = u(1:nn);
r0((h-1)*nn+1:h*nn) = r(1:nn);
phi0((h-1)*nn+1:h*nn) = phi(1:nn);
V0((h-1)*nn+1:h*nn) = V(1:nn);
d0((h-1)*nn+1:h*nn) = d(1:nn);

   %set initial conditions for the next period
   %including the constant delay dl

   x1(1,h+1) = x(1,nn);
   y1(1,h+1) = y(1,nn);
   v1(1,h+1) = v(1,nn);
   u1(1,h+1) = u(1,nn);
   r1(1,h+1) = r(1,nn);
   phi1(1,h+1) = phi(1,nn);
   d1(1,h+1) = d(1,nn);
   %use the constant delay values to calculate the reference heading
   dl = 100;
   nd = nn-dl;
   %xd1(1,h+1) = x0(1,h*nn-dl);
   %yd1 (1,h+1) = y0(1,h*nn-dl);

   %use the variable delay values from the confusion function
   dtaud(1,h) = dtau(1,h*nn-dl);
   xd1(1,h+1) = x0(1,h*nn-dtaud(1,h));
   yd1 (1,h+1) = y0(1,h*nn-dtaud(1,h));
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% next section calculates integral of squared (tracking) error
% by finding closest point on reference trajectory for each point
% on actual trajectory
% Phil Day 21/08/2001
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% initialise variables
ise = 0;  % running total of squared error values

if analysis
   % define variables
   lower_limit = 80;  % lower limit on integration - first waypoint 80
   upper_limit = 150; % upper limit - set bigger than largest value on actual
   % track to ensure that reference curve always extends for all x values that
   % actual curve does

   if dummy
      % use small data sets for dummy run (for testing algorithm!)

      % define dummy reference curve
      X_lim = 1:1:10;
      Y_lim = [1 1 2 2 3 3 2 2 1 1];

      % redefine actual curve (with dummy data)
      x0 = 1:1:10;
      y0 = [1 2 3 4 4 3 2 2 1 1];
   else
      % use real data as not a dummy (test) run

      % calculate new values for reference curve between limits with
      % smaller increment
      X_lim = lower_limit:x_increment:upper_limit;
      % array from 80..137 in 0.01 increments
      H_lim = (exp(-0.5*((X_lim/200-0.5)/betat).^2));
      Y_lim = 200*(H_lim);
   end % if dummy

   [tmp,num_samples] = size(x0);  % number of points on actual trajectory
   [tmp,num_samples_ref] = size(X_lim); % number points on reference trajectory

   % for each point on actual trajectory
   for actual_posn_count=1:num_samples
      % intialise vars
      l = 999;       % variable for storing distance between actual and ref points
      min_l = 999;

      % current posn on actual traj
      x_actual = x0(actual_posn_count);
      y_actual = y0(actual_posn_count);

      % find closest point on reference trajectory
      for ref_point_count=1:num_samples_ref
         % for each point on ref trajectory
```

```
         % find distance between actual posn and current posn on ref traj
         % l = square root of (x_ref - x_actual)^2 + (y_ref - y_actual)^2
         l = sqrt( (((X_lim(ref_point_count)-x_actual)^2) +
((Y_lim(ref_point_count)-y_actual)^2)) );

         % if smaller than minimum value set as minimum
         if l<min_l
            min_l = l;
         end % if l<min_l

         % display vars for debugging
         %if actual_posn_count==5
         %   disp(strcat('actual:',num2str(actual_posn_count),'
         %ref:',num2str(ref_point_count),' l:',num2str(l),' min_l:',num2str(min_l)));
         %end % if actual_posn_count
      end % for ref_point_count

      % display vars for debugging
      %disp(strcat('actual:',num2str(actual_posn_count),' min_l:',num2str(min_l)));

      % at end of this loop min_l will be the distance between
      % current posn on actual traj
      % and closest point on ref trajectory
      ise = ise+((min_l)^2);
   end % for actual_posn_count
end %if analysis

% create output string to show conditions
if analysis
   output_string = strcat('Delay:',num2str(delay_magnitude),' Visual inteference:'
,num2str(vis_int), ' x inc:',num2str(x_increment),' ISE:',num2str(ise));
else
   output_string = strcat('Delay:',num2str(delay_magnitude),' Visual inteference:'
,num2str(vis_int));
end % if analysis
disp(output_string);
% output to command window


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% end of ISE calcs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%plot the reference trajectory, the waypoints and
%actual vehicle trajectory.
subplot(2,1,1),plot(X,Y,'b',x1,y1,'gx',x0,y0,'g'),xlabel('x - co-ordinate'),
ylabel('y - co-ordinate'),title(output_string);
%plot(X,Y,'b',x1,y1,'gx',x0,y0,'g'),xlabel('x - co-ordinate'),
%ylabel('y - co-ordinate'),title(output_string);

%plot the delay due to the confusion function
subplot(2,1,2),plot(dtau),xlabel('sample (200/waypoint)'),
ylabel('delay'),title('Confusion (dtau) due to delay');
```

```
%step response of the vehicle heading phi

%a0 = (a11+(b1*a21)/b2);
%a1 = 1;
%a2 = 0;
%a3 = 0;
%a4 = 0;
%b00 = K*(a0);
%b11 = ((a11*a22 + a12*a21)*pp + K);
%b22 = (a11 + a22 + a11*a22 + a12*a21);
%b33 = (a11 + a22 + pp);
%b44 = 1;

%num = [K*a4 K*a3 K*a2 K*a1 K*a0];
%den = [b44 b33 b22 b11 b00];

%figure
%step(num,den),title('Transient Response of Vehicle Heading
%phi to a Unit Step Input');
```

Appendix N

Supplementary Experimental Materials - central executive loading

N.1 Experimental Script - central executive loading

Thank you for agreeing to take part in this study. Please could you fill out the following questionnaire.

[Pre-experiment questionnaire]

Thanks very much. The aim of this study is to investigate the effects that performing 2 tasks at once has on performance. The experiments will consist of a combination of 2 tasks; driving down a virtual track towards a target, and saying random numbers. This is not a test of your ability to control the vehicle, but instead, is simply a method of investigating the effects of multiple tasks on performance. Any data that is collected will be strictly anonymous.

[Show user the setup]

You will be wearing the following headset, which will be used to display the simulation. Movements of the head to the left and right will result in a change in direction of the vehicle that you are driving, while movements up and down will just change the view angle. Forward movement is achieved by pressing the left most button on the top surface of the 3D mouse. Reversing is achieved by pressing the right most button.

The aim of the task is to keep the vehicle in the middle of the track (shown by the boundary markings), and to hit the target as close to the middle (marked by a vertical green line) as possible.

As well as controlling the vehicle, there is an additional task that you will have to complete at various points during the experiment. This task will involve you saying a random number between 1 and 10 every time you hear a beep. It is important that you try to ensure that each number is a random choice.

On completion of the experiment, you will be asked to fill out a questionnaire giving your judgement of how much the tasks affected you. In addition to this, it would be useful if you could explain any problems that you have at the time, e.g. "I've stopped moving because I'm lost". If at any time you feel unwell or upset and wish to stop, please tell me and we will halt the experiment.

The computer will say "Participant N" at the beginning of the experiment. There will be a short pause at the beginning of each task while the system loads the track.

During this time, the headset will initially display whatever was last seen, will then go black for a short time, and then the new track will be displayed. In addition the computer will say "Trial N" for whatever trial you are on (1-10). As soon as this new track appears, you may start the driving task. The task finishes when you hit the target at the end of the track. The display will then freeze. Between each task, there will be brief time to wait while the equipment is reset for the next task. During this time you will probably find it helpful to face forwards agin (towards the screens) so that you are in the right direction for the next track.

[put on equipment]

Before we start I'll adjust the sound.

[trial1.aiff]

Now we need to adjust the microphone gain - could you please talk to me?

We will now perform some practice tasks in order to allow you to become more familiar with the equipment.

[track1]

Try driving forward by pressing the left most mouse button. Try turning your whole body slightly to one side to turn the vehicle, and then turn back onto the road. Now drive towards the target and hit it.

[track4]

Try driving forward as before. This time to turn, try rotating your whole body. Experiment with tilting your head forward and back to see more or less of the track. Now drive towards the target and hit it.

[track1_int]

Now try driving as before. Each time you hear a beep say a random number between 1 and 10. Try to continue driving while you do this and drive towards the target and hit it.

Do you have any questions or difficulties with the equipment? Then we will begin the experiment.

[Experiment]

The experiment is now finished. Please could you complete this final questionnaire.

[Post-experiment questionnaire]

Thank you very much for your participation. Are there any more questions that you would like to ask? Thanks for your help and time. Goodbye!

N.2 Pre-experiment Questionnaire - central executive loading

Participant no: ☐

Please tick (√) the appropriate box for the answer. If any of the questions are unclear, feel free to ask for clarification.

1. Age: <21 ☐ 21-30 ☐ 31-40 ☐ 41-50 ☐ 51-60 ☐ >60 ☐
2. Sex: Male ☐ Female ☐
3. Which is your dominant hand? Left ☐ Right ☐
4. Do you normally wear spectacles or contact lenses? No ☐ Yes ☐
5. If you normally wear spectacles or contact lenses, are you wearing them now?
   No ☐ Yes ☐ n/a ☐
6. Do you suffer from epilepsy or any other complaints that can be triggered by using low resolution screens? No ☐ Yes ☐
7. Do you have any physical problems that could interfere with controlling a vehicle (please give details)?
   No ☐ Yes ☐ Details: ____________________________
8. Using the scale, how frequently do use a personal computer including both work and recreational use? *(Mark a cross, X, on the line.)*
   Little 1 2 3 4 5 *Lots*
9. Using the scale, how would you rate your experience with video editing and production? *(Mark a cross, X, on the line.)*
   No experience 1 2 3 4 5 *Very experienced*
10. Using the scale, how would you rate your experience with immersive graphics such as computer games or virtual reality?
    No experience 1 2 3 4 5 *Very experienced*
11. How much driving experience do you have (in years)?
    <1 ☐ 1-5 ☐ 6-10 ☐ >10 ☐
12. Have you ever had a driving accident? No ☐ Yes ☐
13. If so, how long ago was this accident (in years)?
    <1 ☐ 1-5 ☐ 6-10 ☐ >10 ☐

14. Using the scale, how would you describe your feelings about driving?

    Hate it 1 2 3 4 5 *Love it*

15. Using the scale, how would you rate your experience with remotely controlled vehicles or computer based driving simulations?

    No experience 1 2 3 4 5 *Very experienced*

N.3 Post-experiment Questionnaire - central executive loading

Participant no: ☐

Please tick (√) or number the appropriate box for the answer. If any of the questions are unclear, feel free to ask for clarification.

1. Using the scale, how much do you consider that the number generation task affected your *ability* to control the vehicle? *(Mark a cross, X, on the line.)*

   Little 1 2 3 4 5 *Lots*

2. Using the scale, how much do you consider that the number generation task affected your *enjoyment* when controlling the vehicle?

   Little 1 2 3 4 5 *Lots*

3. Using the scale, how easy did you find the vehicle to control with the 3D mouse?

   Very difficult 1 2 3 4 5 *Very easy*

4. Using the scale, how easy did you find the vehicle to control with the VR headset?

   Very difficult 1 2 3 4 5 *Very easy*

5. Using the following scales, what were your impressions of the overall system *without* the number generation task?

   (a) *Frustrating* 1 2 3 4 5 *Satisfying*
   (b) *Confusing* 1 2 3 4 5 *Not confusing*
   (c) *Tiring* 1 2 3 4 5 *Not tiring*
   (d) *Difficult* 1 2 3 4 5 *Easy*

6. Using the following scales, what were your impressions of the overall system *with* the number generation task?

   (a) *Frustrating* 1 2 3 4 5 *Satisfying*
   (b) *Confusing* 1 2 3 4 5 *Not confusing*
   (c) *Tiring* 1 2 3 4 5 *Not tiring*
   (d) *Difficult* 1 2 3 4 5 *Easy*

7. Please rank the following categories according to how important you think they are in making the vehicle easier to control. *(1=very important, 9=less important, X=not significant)*

Size of display ☐
Resolution of display ☐
Colour of objects in simulation ☐
Realism of simulation ☐
Frame rate of display ☐
Delay in display ☐
Number generation tasks ☐
Angle of view ☐
Difficulties in using the VR equipment ☐

8. Any other comments: ______________________________
(continue beneath if required)