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**THE IMPACT OF BACKGROUND AND CONTEXT ON CAR  
DISTANCE ESTIMATION**

A thesis

submitted in fulfilment

of the requirements for the degree

of

**Doctor of Philosophy in Psychology**

at

**The University of Waikato**

by

**Fan Zhang**



THE UNIVERSITY OF  
**WAIKATO**  
*Te Whare Wānanga o Waikato*

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Finally, I would like to dedicate this thesis to my mother, who passed away in 2005. Mum, I know that you would be proud of me and this is for you.

## **Abstract**

It is well established that people underestimate the distance to objects depicted in virtual environments and two-dimensional (2D) displays. The reasons for the underestimation are still not fully understood. It is becoming more common to use virtual environment displays for driver training and testing and so understanding the distortion of perceived space that occurs in these displays is vital. We need to know what aspects of the display cause the observer to misperceive the distance to objects in the simulated environments. The research reported in this thesis investigated how people estimate distance between themselves and a car in front of them, within a number of differing environmental contexts. Four experiments were run using virtual environment displays of various kinds and a fifth experiment was run in a real-world setting.

It was found that distance underestimation when viewing 2D displays is very common, even when familiar objects such as cars are used as the targets. The experiments also verified that people have a greater underestimation of distance in a virtual environment compared to a real-world setting. A surprising and somewhat counterintuitive result was that people underestimate distance more when the scene depicts forward motion of the observer compared to a static view. The research also identified a number

of visual features in the display (e.g., texture information) and aspects of the display (e.g., field of view) that affected the perception of distance or that had no effect. The findings should help the designers of driver-training simulators and testing equipment to better understand the types of errors that can potentially occur when humans view two-dimensional virtual environment displays.

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## Chapter 1 Introduction

For decades, researchers have investigated distance estimation, examining judgements of both Egocentric and Exocentric distance. Almost all early research on distance estimation, in the real world or in a laboratory, examined distance judgements in a static world. The only movement allowed was the observer's head movement (to study motion parallax). In reality people are in constant motion and their speed can reach 100 km per hour or more when driving. The question arises, therefore, as to whether or not motion affects distance estimation.

There have been very few studies of distance estimation while the observer is in motion. One study was conducted by Hiro (1996). Hiro (1996) investigated estimation of "objective" distance between a participant's car and the car in front under three conditions – (1) while driving; (2) while sitting in the passenger seat and (3) viewing a video which simulates the driving experience. The study found that the higher the speed, the more the driver underestimated the relative distance between their own car and the car they were following in all three conditions. Hiro suggested that the localisation error mainly arises from visual factors.

There are several reasons why the Hiro (1996) study has been chosen



here. Using a car has more practical value (e.g., in the realm of road safety).

The study focused on egocentric distance and the perception of absolute distance (between the participant and the car that the participant was following) estimation. From a road safety perspective, selecting safe following distance when travelling is very important, as safe following distance enables drivers to adjust in emergency situations and bring their vehicles to a stop safely. Additionally it provides insights into distance estimation in vista space, which is often important for tasks such as driving. Finally, Hiro (1996) has adopted a relatively new way of studying distance estimation using three monitors to display an environment with graphic realism (video recording).

Hiro (1996) investigated distance estimation of vehicles along a road which is a complex experimental environment, compared to standard, laboratory-based distance judgement situations. The road, objects along the road (e.g., buildings and pedestrians) and the target vehicles all provided visual depth cues, such as familiar size cues, linear perspective, and shadows. Historically, distance estimation studies have tended to use a simple environment, where it was easier to isolate individual cues and to study their effect. Additionally, a complex environment contains cognitive knowledge (e.g., the length of vehicles parked on the side of the road) that

is unrelated to distance perception but which can affect distance estimation, especially verbal estimates of distance (Loomis & Knapp, 2003). In reality people have to deal with complex environments every day. Therefore Hiro's (1996) research has a more practical value (e.g., in the realm of road safety).

Additionally, Hiro (1996) studied distance estimation in both action space (2–30 m) and vista space (beyond 30 m). Distance estimation studies often focused on distance judgements in either personal space (within arm's reach) or action space (2–30 m). Distance estimation in vista space (beyond 30 m) was seldomly examined. Hiro (1996) studied distance estimation of moving vehicles, which was equivalent to perceiving distance in action space and vista space. The effectiveness of visual depth cues vary according to the locations of the target. For example, the effects of accommodation and motion parallax tend to diminish beyond 2 m (Beall, Loomis, Philbeck, & Fikes, 1995). However, binocular disparity is an effective absolute depth cue within action space (Foley, 1980). Therefore people could utilise different cues in vista space and in personal space or action space. Hiro (1996) provided insights into distance estimation in vista space.

Finally, Hiro (1996) also investigated distance estimation while viewing a

video which simulated the driving experience. Presentation of the three-dimensional (3D) scene on a 2D display created a Virtual Environment (VE). Hiro (1996) introduced a relatively new way of studying distance estimation (at the time of his experiment) using three monitors to display an environment with graphic realism (video recording). However, he had a very small sample size and no analysis was carried out to compare distance estimation in VEs against judgements in the real world.

The methodology used in Hiro (1996) was not described well enough for exact replication by other researchers. For example, it was debatable whether distance between a participant's car and the car in front was truly "objective" distance, as the observer was sitting in the vehicle and often considered as part of the vehicle. It is difficult to work out from Hiro's description how to define "the objective distance from their car to the equipment car ahead" (Hiro, 1996; p.93); whether it was measured from the driver/ passenger to the target car or from the front of the participant's car to the rear of the target vehicle. It is also unknown from his description how the data was collected and how the conditions were controlled. Additionally, no attempts were made to analyse the distance estimations in different regions (near versus far) and in different visual environments. These deficits, combined with the limited sample size, left more questions than answers.

On the other hand, at the time when the current study commenced there had yet to be much research dedicated to the topics of egocentric distance estimation in VE, other than related to head-mounted displays (HMD). There had also been little research conducted on egocentric distance estimation in vista space, estimation of egocentric distance estimation from motion or distance estimation to moving cars. As a consequence, many questions related to these topics have yet to be answered. Yet these are important in fields such as road safety and driving research.

The research reported in this thesis was designed to replicate and extend Hiro's (1996) experiment by using computer generated Virtual Environments (on two types of displays) and to explore a range of issues surrounding the estimation of egocentric distance in VEs both in static scenes and during self-motion. The main questions addressed by the research are:

1. Can people estimate distance to a vehicle accurately in VE?
2. What affects distance estimation in VE?
3. Does motion affect distance estimation?

Furthermore, this study was designed to establish reliable methodologies to investigate distance estimations in static VEs and to apply these

methodologies when examining distance estimation during self-motion (e.g., while driving a vehicle). Finally, the nature of the driving scenario adopted in this study provides opportunities to examine egocentric distance estimation in vista space, to investigate the effect of the ground on egocentric distance estimation, and to investigate distance estimation in a driving simulator. Building an understanding of what affects distance estimation in simulated driving conditions could provide an insight into many different aspects of road safety such as overtaking distance judgements and following distance judgements.

To begin answering the above questions, the first section of Chapter 2 (2.1) will introduce some important working concepts (e.g., egocentric and exocentric distance, and egocentric regions) and related studies. These concepts can be applied to the study of distance estimation in VE. In the second section (2.2), studies of distance estimation in a static world will be introduced. These studies also address issues that affect distance estimation in VE. Additionally, studies that investigated egocentric and relative distance estimation from motion will also be introduced. Finally the methodological issues in egocentric distance estimation research will be discussed in Chapter 3.

Early studies into distance estimation began in the 1950s, within a static

environment. There were numerous studies which helped develop an understanding of human distance estimation. These studies indicated what information people use to estimate distance, and how well they achieve this outcome or are able to judge distance. It was therefore the objective of this research to take the scientific robustness of the empirical work and apply it to the virtual environment. However, people behave differently within a virtual environment compared to the real world. This will be considered by taking into account recent and substantial developments from both the computer science and psychology disciplines.

Many studies, within both Computer Science and Psychology, have attempted to understand why there are differences between distance estimation conducted in real versus virtual environments. The early sections of this thesis provide more insight into the source of these differences. The middle sections of the thesis examine distance estimation both in a static environment and with simulated motion of the observer. The final part of the thesis examines distance estimation in the real world.

## Chapter 2 Distance Estimation

### 2.1 Terms and Definitions

#### 2.1.1 *Egocentric and Exocentric Distances*

For decades, researchers have investigated distance estimation, examining judgements of both Egocentric and Exocentric distance.

- Egocentric distances are distances “from the object to the observer” (Fukusima, Loomis & Da Silva, 1997, p.86).
- Exocentric distances are distances “between two targets lying in the same visual direction or, more generally, the distance between any two locations” (Fukusima, Loomis & Da Silva, 1997, p.86).
- A perception of absolute distance is “a perception by the observer that an object is a definite particular distance from himself” (Gogel, 1961, pp. 287-288).
- A perception of relative distance is “a perception of a depth between objects, or between different distance positions of the same object at different times” (Gogel, 1961, p.288).

The current study focused on egocentric distance and the perception of absolute distance (between the participant and the car that the participant was following) estimation. From a road safety perspective, selecting safe

following distance when travelling is very important, as safe following distance enables drivers to adjust in emergency situations and bring their vehicles to a stop safely.

There are wide range of measures of perceived egocentric distance, such as verbal measures, blind walking, triangulated blind walking, throwing and perceptual matching. The main experimental design used in the experiments reported in this thesis required participants to estimate relatively long distances in a simulated driving environment. This experiment design limited the options for the distance estimation protocols that could be adopted. For example, blind walking could not be used in the experiment, as it requires large amount of space to estimate long distances, especially when the target is located beyond a screen. Visually imagined driving can be hard to convert to distance measurements as individuals can interpret driving speed differently.

Verbal estimation of distance coupled with a modified perceptual matching protocol was adopted in this study. The advantage of the matching method is that it is perceptual, as it has no reference to units of distance, which minimises the influence of cognitive knowledge. However, it does not provide any indication of absolute distance. The verbal estimate provides this and so the two combined techniques should provide a robust estimate



of the perceived distance. The details of these distance measurement protocols will be introduced and related issues discussed in Chapter 3.

### **2.1.2 Distance Regions**

Grüsser (1978, 1983) divided perceptual space into the two major regions, personal and extrapersonal space. Extrapersonal space can be subdivided into grasping space, near-distant action space (up to 8 m), far-distant action space, and the visual background. Cutting and Vishton (1995) subdivided space into three egocentric regions: personal space (up to 2 m), action space (up to 30 m), and vista space (beyond 30 m, and beyond 70 m as far vista space). Finally, Cardinali, Brozzoli, and Farnè (2009, p.253) used the term “peripersonal” to define “a region immediately surrounding the body, characterised by a high degree of multisensory integration between visual, tactile and auditory information, which differs from farther regions of space.”

### **2.1.3 Distance Cues**

There are many sources of distance information, also known as distance cues such as motion parallax, perspective, relative size, familiar size, aerial perspective, accommodation, occlusion, and texture gradient.

According to Palmer (1999), distance cues can be categorised in different ways. The more frequently used terms are binocular/monocular cues and

relative/absolute distance cues. Binocular cues are available from both eyes, while monocular cues are from just one eye. Relative/absolute distance cues provide information on relative distance or absolute distance respectively. It is also very important to note that some cues provide numerical information on distance (quantitative), while others only specify whether objects are closer or further away (qualitative).

#### **2.1.4 Ground Theory**

Ground theory was first suggested by Gibson (1950), considering "the possibility that there is literally no such thing as a perception of space without the perception of a continuous background surface", (p.6).

According to the "ground theory", the visual world is defined by information presented by the ground that objects rest on (Goldstein, 1981). In distance estimation studies, ground theory specifically refers to using the ground surface, especially the ground surface close to the observer, as an essential reference for judging distance (Sinai et al., 1998; Wu et al., 2004).

#### **2.1.5 Virtual Environments (VE)**

Virtual Environments (VE) are "interactive, virtual image displays enhanced by special processing and by non-visual display modalities, such as auditory and haptic, to convince users that they are immersed in a synthetic

space” (Ellis, 1994, p.17). Different terms have been used to describe the illusion, such as “artificial reality”, “virtual reality”, “cyberspace” and “virtual worlds” (Ellis, 1994). The visual display is one of the crucial technologies for VE, as it “immerses the user in the virtual world and that blocks out contradictory sensory impressions from the real world” (Brooks, 1999, p.16). There are several types of VE displays, for example vehicle simulators, ELBEDOM (a large 360° projection system), head-mounted display (HMD) and Cave Automatic Virtual Environment (CAVE). Cathode ray tube (CRT) / liquid-crystal display (LCD) monitors have also been used to display simulated environments. However, these monitors cannot display life size virtual objects; neither can they block out visual information from the real world (Brooks, 1999). Thus they have a limited ability to create the illusion of immersion.

## **2.2 Distance Estimation in a Static World**

### **2.2.1 Overview**

A number of recent studies have shown that people are generally quite accurate at estimating distance within action space in the real environment (e.g., Elliott, 1987; Steenhuis & Goodale, 1988; Loomis, Da Silva, Fujita, & Fukushima, 1992; Thompson et al., 2004; Creem-Regehr, Willemsen, Gooch, & Thompson, 2005; Sahm, Creem-Regehr, Thompson &

Willemsen, 2005; Interrante, Anderson, & Ries, 2006; Jones, Swan, Singh, Kolstad, & Ellis, 2008; Messing & Durgin, 2005; Swan, Jones, Kolstad, Livingston, & Smallman, 2007). For example, Thompson et al. (2004) found that estimations of distance between 5 and 15 m were about 95% of the actual distance in the real environment. Swan et al. (2007) found that blindfolded walking estimates of distance between 3 and 7 m were 96% of the actual distance in the real environment. Similar results were also found for distance estimation using blind throwing in the real world (Sahm et al., 2005).

On the other hand, it has been found that people tend to overestimate distance within far vista space. Daum and Hecht (2009) conducted three experiments to examine the judgement of distance ranging from 25 to 500 m. In the first experiment participants estimated distance (written down in metres) of small, medium and large-sized targets on a large open field in a planar and an uphill surface condition. Targets were placed at four different distances (54, 217, 335, and 460 m) from the observers. In addition, there were two observer positions (prone and upright).

The results showed that participants overestimated distance and the overestimation increased with actual distance. The smaller targets were estimated to be farther away and vice versa. Finally terrain and observer

positions had no effect on participants' distance estimation. This experiment was then replicated in the laboratory with added observer positions (raised) and a downhill terrain condition, displayed on a large rear projection screen. It was found that the distances were overestimated, but to a smaller extent than in the field experiment. There were also larger individual differences among participants. As the results of the two experiments were different, Daum and Hecht (2009) conducted a third experiment to replicate the overestimation found in the first experiment. This was a field experiment replicating the first experiment but with two more distances and a raised observer position added. They found that distances less than 70 m were underestimated, whereas distances greater than 70 m were overestimated. In addition, both eye height and target size had a significant effect on participants' distance estimation. Participants in the prone position estimated targets to be farther away than did those in the upright or elevated position. Smaller targets were judged to be farther away than larger targets. Based on the findings, Daum and Hecht (2009) suggested that some simple heuristics might be at work when large distances are estimated. In vista space, a number of monocular distance cues are likely to contribute to participants' distance estimates. They believed that the crossover between compression and dilation could be the result of a re-weighting of cues.

Interestingly researchers have found that people underestimate distance in virtual environments, relative to the real world (Loomis et al., 1996; Witmer & Sadowski, 1998; Sahm et al., 2005; Creem-Regehr et al., 2005; Loomis & Knapp, 2003; Messing & Durgin, 2005; Richardson & Waller, 2007; Thompson et al., 2004; Willemsen & Gooch, 2002). For example, in a series of studies conducted by Witmer and his colleagues (Witmer & Kline, 1997; Witmer & Kline, 1998 and Witmer & Sadowski, 1998), participants were asked to estimate egocentric distance to a cylinder placed in a corridor (in a VE or a real corridor). Two methods were used to estimate distance: magnitude estimation and non-visually directed walking. For magnitude estimation, participants gave a number to a standard stimulus, and then made subsequent distance judgements based on the first estimation. For non-visually directed walking, participants were instructed to walk to where they believed the target was with eyes closed. In the VE this was performed on a treadmill. The results showed that participants underestimated distance in both a VE and in the real indoor environment. There was greater distance underestimation in a VE than in a real environment.

In another study conducted by Knapp (1999), participants judged distance between themselves and a target (a Styrofoam sphere or a texture mapped sphere on a wall). Several methods were used to estimate distance

including verbal reports of distance, verbal reports of size, direct walking, triangulation by walking and matching shoulder width. Knapp (1999) found that participants in general underestimated the distance. The underestimation found in this study, according to Knapp (1999), was greater than found in studies conducted by Witmer and his colleagues. Greater distance underestimation was found when participants threw to targets in a VE than in a real environment (Sahm et al., 2005). All these studies suggest that people have greater distance underestimation in VEs than in the real environment.

There have been numerous studies that have helped develop an understanding of human distance estimation. These studies have indicated what information people use to estimate distance, including distance cues, ground theory and environmental context. As mentioned, greater distance underestimation was found when participants judged distance in VEs than in real environments. A number of investigations attempted to explain this bias in behaviour by examining technical aspects of VEs such as limited field of view, problems with binocular stereo in HMDs, quality of computer graphics and HMD mechanics (Knapp & Loomis, 2004; Thompson et al., 2004; Bingham, Bradley, Bailey, & Vinner, 2001; Creem-Regehr et al., 2005). These studies will be discussed in the later part of this chapter

(2.2.5).

## **2.2.2 Distance Cues**

### **2.2.2.1 Monocular**

The effectiveness of distance cues vary depending on the viewing distances. Within action space, accommodation, convergence, and motion parallax are considered to be weak cues for absolute distance (Beall et al., 1995; Gogel, 1961) as their individual effects tend to diminish out past 2 m. However, absolute depth beyond 2 m can be recovered from binocular disparity by using convergence as a scaling factor (Foley, 1980). The familiar size cue can also specify egocentric distance even when the target is far away from observer. Gogel (1976, p.419) stated that “the familiar size of an object, regardless of whether the object is near or far, can provide a cue to distance whenever the physical size of the object at that distance is above the threshold of detection”. Moreover, there is evidence that near distance ground surface cues are important for perceiving farther distances. It has been shown that such angular declination cues can be used to recover absolute distance given a known eye height (Wu et al., 2004). It is generally conceded that cue reduction affects distance estimation. There are many ways to create such a condition. For instance, in a typical



distance estimation paradigm participants can view the target with only one eye, thus eliminating binocular cues. Additionally, instead of using a familiar object, a light point was used as the target in some studies, which did not provide any size information. Furthermore, many distance cues (e.g., linear perspective, texture gradients) are ineffective in a dark environment.

Conducting experiments on distance estimation in a dark room effectively diminishes these cues. Early research (e.g., Gogel & Tietz, 1973, 1979, Foley, 1977) suggests that distance cue reduction leads to inaccurate verbal estimation of distance. Philbeck & Loomis (1997) investigated distance estimation in reduced-cue conditions. In this study, participants viewed a luminous rectangle presented in a dark room for 10 seconds. They then estimated the distance to the target verbally, or they walked, with both eyes shut, to where they believed the target to be. The results showed that participants underestimated distance when the target was farther than 3 m and overestimated the distance when the target was within a 2 m range. On the other hand, if all distance cues are diminished, people produce a nonzero value (about 2.5-3.5 m dependent on what measurement was used) to “correspond to a default value of perceived distance” (Philbeck & Loomis, 1997, p.79). This is called the specific distance tendency (Gogel, 1969).

A number of studies were also conducted investigating the effectiveness and accuracy of depth cues in VE. Surdick and Davis (1997) tested the effectiveness and accuracy of seven visual depth cues: relative brightness, relative size, relative height, linear perspective, foreshortening, texture gradient, and stereopsis. They found that within 2 m of viewing distance, the perspective cues (i.e., linear perspective, foreshortening, and texture gradient) were more effective than other cues. However, in terms of accuracy, the cues did not differ. Murgia and Sharkey (2009) found that estimated distance was less accurate in the absence of perspective cues and the absence of a ceiling in a CAVE environment (surround screens with projected imagery) within 3 m of viewing distance. Both studies (Surdick & Davis, 1997; Murgia & Sharkey, 2009) showed that perspective cues are somewhat strong distance cues within the near action space in VE. On the other hand, the different experimental methodologies (e.g., VE displays, distance estimation protocols and data analysis methods) adopted in these two studies could have contributed to the different results in terms of the accuracy of the perspective cues.

Surdick and Davis (1997) also found that while relative brightness was significantly less effective than any of the other cues, at the 2 m viewing distance, relative brightness, relative size, and relative height became

significantly less effective as well. Witmer and Kline (1998) however found that relative size significantly affected estimated distance in VE. The estimated distance was more accurate for a small cylinder than for a large cylinder. Murgia and Sharkey (2009) compared their results with some other distance estimation studies and found, in their experiments, that the accuracy of participants' distance estimation was improved by providing information about the relative size of the virtual objects presented. Thus, they suggested that relative size played a very important role in estimating distance. Furthermore, Kuhl, Thompson and Creem-Regehr (2006) found that estimated distance was significantly greater (closer to the actual distance) for the minification condition (where graphics were rendered 82% of the normal size) than the control condition (the normal size). Kuhl, Thompson and Creem-Regehr (2006) suggested that three visual cues were changed as a result of minification, including changes to the visual angle of declination from horizon to targets, changes in relative size and changes (decrease) in optic flow during rotations, thus suggesting that these cues could have played a very important role in judging absolute distance. These three studies all suggested that relative size plays an important role as a distance cue within action space.

### **2.2.2.2 Binocular Cues**

The effectiveness and accuracy of stereoscopic cues in VEs have also been investigated in a number of studies. Surdick and Davis (1997) found that some participants had difficulty in perceiving distance information provided by stereopsis cues, although they were able to learn to perceive stereoscopic depth (Expt. 2 conducted by Surdick & Davis, 1997). Roumes, Meehan, Plantier and Menu (2001) conducted an experiment to determine the accuracy of distance judgements obtained from videotaped images of targets in a natural outdoor scene. In the experiment, participants were required to indicate a point that is at a specific distance between the point of observation and another nominated point. Participants judged distances of 20, 40, 80, and 160 m from the camera in three conditions: stereo with near or far zero disparities and binocular non-stereo (biocular) viewing. Roumes et al. (2001) found that stereoscopic presentation did not improve performance in the estimation of mid-distance. It was suggested that the images used in the experiment contained rich monocular cues which can be more informative than disparity. Additionally, Willemsen et al. (2008) investigated the effects of both measured and fixed inter-pupillary distances (IPD), as well as biocular and monocular viewing of graphics on absolute distance judgements. It was found that there was no difference between

stereo, biocular, and monocular viewing conditions. These experiments used different displays, different distance estimation protocol and covered different distance regions, thus suggesting that stereoscopic cues are a very weak distance cue in VE.

### **2.2.2.3 Texture Cues**

The effect of texture cues in distance estimation has also been investigated in VE. Witmer and Kline (1998) conducted an experiment to investigate egocentric distance estimation in a simple VE with static cues for distance. Participants performed a magnitude estimation procedure to judge distances of 10, 30, 50, 70, 90, or 110 feet in 18 conditions (presented in a BOOM2C display) consisting of three levels of pattern texture (none, coarse, fine), two levels of pattern type (a continuous pattern and an intermittent pattern) and two levels of cylinder size (2.5 and 5.0 feet in diameter). Participants also estimated distances in a natural real-world setting. It was found that participants underestimated distances in the real-world environment, to a lesser extent than in the VE. In VE, neither floor texture nor floor pattern affected the estimated distance. The estimated distance was more accurate for the small cylinder than for the large cylinder. Sinai, Krebs, Darken, Rowland and McCarley (1999), on the other hand, found significant effects for the texture pattern under the target and for the

interaction between the texture pattern under the target and distance. The estimated distance was more accurate when the texture pattern under the target was a brick pattern (medium density) compared to grass (low density) or carpet (high density). Sinai et al. (1999) suggested that this improvement can be attributed to the brick pattern's symmetry or its density.

#### **2.2.2.4 Declination Angle**

As mentioned previously, Kuhl et al., (2006) suggested that changes to the visual angle of declination from horizon to targets could play a very important role in judging absolute distance. Messing and Durgin (2005) investigated the use of angular declination from the horizon as a cue to distance (3, 4, 5, 6, or 7 m) in VE. Participants performed both verbal estimation and visually directed action tasks in an outdoor virtual environment with variable horizon line heights. The accuracy was assessed by computing the slope of the least-squares fit to the data in log-log space. For both tasks significantly higher power function exponents were found when the horizon line was lowered. This supports the use of angular declination from the horizon as a distance cue.

Although a number of studies mentioned above found that perspective cues, relative size and the visual angle of declination are strong distance

cues within personal space, and/or action space in VE, Armbrüster, Wolter, Kuhlen, Spijkers and Fimm (2008) found somewhat different results when investigating distance estimation in peri- and extra-personal space in a VE. In their experiment, three types of virtual environments were used, including “no space”, “open space” and “closed space” (Armbrüster et al., 2008). The “no space” scene was blue, infinite in depth, and had no additional distance cues. In the “open space” condition, there was a green floor (without any texture gradient information) and a blue sky with some clouds. The combination of the green floor and blue sky resulted in an induced horizon. The “closed space” was a closed grey room with linear perspective cues. It was found that distances were underestimated in VE; however, there was no difference of estimated distance among the three virtual environments. Therefore, it suggested that participants did not benefit from additional distance cues, such as linear perspective and the visual angle of declination.

In summary, a number of studies have been conducted investigating the effectiveness and accuracy of depth cues in VEs. It was found that perspective cues, relative size and the visual angle of declination are strong distance cues within personal space and/or action space in VEs. However, in extreme conditions (e.g., the no-space conditions used in Armbrüster et

al., 2008 ), the presence of additional distance cues, such as linear perspective and the visual angle of declination did not improve distance estimates. Stereoscopic cues, on the other hand, have been found to be a very weak distance cue. It is also unclear whether texture patterns have an effect on distance estimation.

### **2.2.3 Ground Theory**

He and colleagues conducted a series of studies (Sinai, et al. 1998; He et al., 2004; Wu et al., 2004) to test the “ground theory”. In the Sinai et al., (1998) study, a target was presented on the other side of a gap in the ground. Participants viewed the target, then turned around, closed their eyes and walked a distance that they believed was equal to the distance between themselves and the target. A small number of participants served as a control group and viewed the target on the ground without any gap. It was found that participants overestimated egocentric distance when a gap was present. Another group of participants estimated distance to the target by performing a matching task. The results were consistent with the previous experiment and participants overestimated egocentric distance when a gap appeared. Additionally, when the gap was widened and deepened, participants were found to overestimate egocentric distance as well. Sinai et al. (1998) found that the presence of the gap altered



participants' perceived eye height and thus affected distance estimation.

Finally, when two different textures appeared between observers and the target, participants underestimated the distance as the distance increased (Sinai et al., 1998). Sinai et al. (1998) suggested that a texture discontinuity can affect distance estimation, and leads to distance underestimation.

In another study conducted by Wu et al. (2004), instead of the gap, a box was present between the observer and the target. In the first three experiments, participants viewed the target and then estimated the distance by performing a matching task, a blind-throwing task or a blind-walking task. It was found that participants underestimated the distance when the occluding box was presented. Wu et al. (2004) found that the ground surface is an essential reference for judging distance. The ground surface close to the observer can be used as a reference frame to extrapolate ground surfaces in the distance. Observers made more localisation errors when the near ground surface was disrupted by either a gap or a block, when their view of the ground surface around the target was restricted, and when the ground surface consisted of two different textures. Furthermore, they also found that participants were able to integrate information about the ground surface and were able to overcome all of the disruptions caused by the box or gap.

Not all studies investigating the effect of near ground on distance estimation have come to the same conclusion. Creem-Regehr et al. (2005) investigated the impact of field of view and binocular viewing restrictions on distance estimation in real-world indoor environments. In their first experiment a cardboard circular collar was used to block vision of the participant's body and the floor below her/his feet to about 1.5 m. It was found that wearing the collar did not affect the accuracy of distance estimation. Thus Creem-Regehr et al. (2005) suggested that in full-cue conditions, viewing the near ground is not necessary for accurate distance estimation.

A question that arises from these studies is how ground theory works when people are moving over the ground surface at high speed. In such a situation the image speed of the near ground texture is much higher than the image speed of the distant ground surface (it is a non-linear decrease in visual speed). Additionally, as the ground texture moves quickly towards the observer, the texture may become blurred. Texture with high spatial frequency content may not be able to be perceived, thus creating a surface with different textures. If the ground theory is correct these factors should all affect people's perception of distance.

#### **2.2.4 Environmental Context**

It is commonly assumed that under full-cue viewing conditions perception of distance should be consistent regardless of the type of environment or viewing context. However, several studies have shown inconsistencies in perceived distance under full-cue conditions. For example, in a study conducted by Lappin et al (2006) participants judged the midpoint of the distance to a familiar object in three full-cue environments: a hallway, a lobby, and an open field. It was found that participants overestimated the midpoint in the lobby and hall but not on the lawn (the overestimation was not significant in this case). In addition, the variability of the estimated distance was greater in the hall than in the lobby or on the lawn. As pointed out by Witt, Stefanucci, Riener and Proffitt (2007), several sources could contribute to the results found by Lappin et al (2006). First, the texture of the ground surface was different in each environment. It was grass on the lawn, tiles on the hallway floor and carpet on the lobby floor. Secondly, both the lobby and the hall had landmarks such as windows, doors, wall and stairwells that provided linear perspective cues and familiar size cues. In addition, the features of the environment beyond the target were also different. However, it cannot be determined whether non-depth informative factors within viewer-to-target (VTT) space or within the space beyond the

target caused the differences in apparent distance in the Lappin et al.'s studies (Witt et al., 2007).

To study the effect of environmental context beyond the target on distance estimation, Witt et al (2007) conducted five experiments. In their study, participants performed perceptual matching and blind walking tasks to estimate distance in indoor and outdoor environments. In four of the five experiments, targets were placed at either the bounded (near) or unbounded (far) end of the field or the hallway, and participants viewed the targets and performed the tasks in the opposite end of the environment. The results showed a significant effect of viewing directions for both egocentric and exocentric (in the frontoparallel plane) distances. Targets positioned by the bounded end looked farther away (or farther apart from each other) than targets positioned by the unbounded end. Since in each experiment all VTT depth-related variables were constant, the differences in perceived distance must be explained by variations in the space beyond the target (Witt et al., 2007). The endpoint of the bounded environment was much closer than the endpoint of the unbounded environment. This may have affected participants' visually perceived eye level or perceived terrestrial horizon, thus affecting distance estimation (Witt et al., 2007). However, in experiment three, when participants performed blind walking tasks to

estimate distance in the same end of the hallway as the targets, environmental context had no significant effect. Witt et al., (2007) suggested that this could be attributed to the absence of a comparison between the two ends of the hallway. Note that in the Lappin et al (2006) study, although participants performed the tasks in the same viewing directions as the targets, they have been exposed to all three environmental contexts as it was a within-subjects design study. Thus it is unclear whether the comparison between environmental contexts is necessary to produce a significant effect.

Bodenheimer et al. (2007) investigated distance estimation in VEs and in the real world. Participants performed a bisection task to judge distances of 15 and 30 m in three conditions: VE, real-world and real-world with limited field of view (FOV). For each condition, an indoor hallway and a large lawn were presented. Bodenheimer et al. (2007) found that although across all conditions there was no significant effect of environmental context, in the real world condition, there was a significant effect of environment and significant interactions of condition and environment. However, it was found that participants were more accurate in the indoor environment than in the outdoor environment, which was the opposite effect to that of Lappin et al (2006). Bodenheimer et al. (2007) suggested that Lappin et al (2006) had a

lobby condition that may have affected their results. As Lappin et al (2006) did not control for the order of the environment presented, one of the three environments could have contributed to their findings (Bodenheimer et al., 2007).

### **2.2.5 Distance Estimation in VEs**

As discussed previously, researchers have commonly found that people underestimate distance in virtual environments, relative to the real world. A number of investigations have attempted to explain this bias in behaviour by examining technical aspects of VEs (Knapp and Loomis 2004; Thompson et al., 2004; Bingham et al., 2001; Creem-Regehr et al., 2005). Witmer and Kline (1997) analysed the differences between VEs and the real world and suggested that the greater distance underestimation found in VEs can be attributed to the ineffectiveness of certain distance cues and to system induced cues. In terms of distance cues in VEs, Witmer and Kline (1997) suggested that the low resolution in many VE displays could affect the effectiveness of motion cues and pictorial cues. Additionally, in VEs undefined light sources might limit the value of cues like shadows and shading. Furthermore, VE displays and other image displays, according to Witmer and Kline (1997), do a poor job of providing good physiological depth cues. System induced cues including restricted FOV, reduced

resolution and incongruence of computed and displayed FOV could affect perception (Witmer & Kline, 1997). The following part of this chapter will focus on reviewing research in three areas: quality of graphics and calibration, FOV and the type of VE. These areas are directly related to and are the foundation of the experiments carried out in this thesis.

### **2.2.5.1 Quality of Graphics and Calibration**

Loomis and Knapp (2003) suggested that distance judgements are compressed in VEs because “the rendering of the scenes . . . is lacking subtle but important visual cues (e.g., natural texture, highlights) . . . If this hypothesis is correct, it means that photorealistic rendering of the surfaces and objects in a simulated environment is likely to produce more accurate perception of distance” (p. 40). Several studies have investigated the effect of computer graphic quality on estimated distance in VEs (Willemsen & Gooch, 2002; Thompson et al., 2004; Messing & Durgin, 2005; Kunz, Wouters, Smith, Thompson, & Creem-Regehr, 2009 and Grechkin, Dat Nguyen, Plumert, Cremer, & Kearney, 2010).

Willemsen and Gooch (2002), Messing and Durgin (2005) and Grechkin et al. (2010) compared real world conditions, photo/video based presentation of the real world, and a computer generated virtual world in a distance

estimation experiment. It was found that distance was significantly compressed in VE conditions compared to a real environment. However, there was no difference between VE conditions. Therefore, they concluded that the quality of graphics alone was not responsible for the distance underestimation found in VE. These three studies covered two different estimation protocols, timed imagined walking and direct blindfolded walking, and two types of visual display, HMD and large immersive screen (non-stereoscopic). All three investigated distance estimation in near action space (2-18 m).

Thompson et al. (2004) and Kunz et al. (2009) investigated whether limits on the resolution and the quality of images displayed contributed to the compression of apparent distances in VE. However, their definition of “quality” also included visual details. The two studies compared distance estimation in a realistic VE with distance estimation in a VE with reduced geometry and visual details. Thompson et al. (2004) found that distance estimations in three different VE conditions (360° high-resolution panoramic images, low-quality texture mapped computer graphics, and wireframe renderings), did not vary much from each other. Kunz et al. (2009) on the other hand found that the quality of graphics had little effect on a blind-walking measure of egocentric distance (same method used by



Thompson et al., 2004), but a significant effect on verbal judgements of distance. Estimates were greater for the high-quality environment than for the low-quality environment. The low-quality VE tested in Kunz et al. (2009) had reduced geometry and very little visual detail. The problem with these studies is that a VE with reduced geometry and very little visual details can also be interpreted as a VE with reduced visual cues. Therefore it is unclear whether the quality characteristics of the VE (e.g., spatial-frequency and resolution) or the availabilities of visual cues or both contributed to the results. The VE used in these two studies was very similar to the simplified conditions used in the experiments to be reported in this thesis (more details will be introduced in the following chapters). However, these two studies only covered distance estimation in near action space and a HMD was used.

Finally, with respect to image quality, Kuhl, Thompson and Creem-regehr (2009) conducted three experiments to examine the effects of pitch miscalibration, pincushion distortion and minification / magnification on distance estimation in VEs presented in a HMD. Despite the fact that the amount of pincushion distortion presented in Kuhl et al. (2009) was greater than that found in most HMDs, and that pitch affects distance judgements in the real world (Ooi, Wu & He, 2001; Andre & Rogers, 2006), it was found

that pitch miscalibration of  $5.7^\circ$  and pincushion distortion had no effect on distance judgements between 3 and 6 m in VEs. It was also found that although participants underestimated distance, minification increased estimated distances and magnification decreased estimated distances. The results suggested that relative size is an effective visual cue in these experiments.

In summary, it is evident that the space compression found in action space in VEs cannot be attributed to the realism of the VE, pitch miscalibration or pincushion distortion. These results have not been tested in vista space nor using verbal estimation techniques. Thus they cannot be generalised to all distance estimation in VEs. Although Kunz et al. (2009) found that distance estimates were greater for the high-quality environment than for the low-quality environment using verbal reporting, it was unclear whether the quality characteristics of the VE or the availability of visual cues contributed to the results. VEs are highly flexible and programmable, thus enabling researchers to present a wide variety of controlled stimuli and to measure a variety of responses. The focus on high graphical realism defeats the purpose of conducting distance estimation experiments in VE, where visual cues can be easily manipulated or removed. Additionally, an increase in the quality of VE graphics, such as realism and resolution, leads to increased

costs and more programming effort with no obvious benefits (Kunz et al., 2009).

### **2.2.5.2 Field of View (FOV) of VE Displays**

Pspotka, Davison and Lewis (1993) investigated the incongruence of computed FOV and displayed FOV. They suggested that people might treat available FOV of an image system as a 180° field leading to a displaced eye station point (cited in Witmer & Kline, 1997). Witmer and Kline (1997) have argued that the displaced eye station point (displaced egocenter) can result in distortion of perceived distance. Many researchers have suggested that a restricted FOV contributes to the large amount of distance underestimation found in VEs. The FOV of the human visual system is 180° vertical and 120° horizontal (Witmer & Sadowski, 1998). Most distance experiments using VEs have adopted a much smaller FOV, for instance 33° vertically x 44° horizontally (Knapp, 1999). A restricted FOV could eliminate peripheral information. According to Witmer and Sadowski (1998), a restricted vertical FOV can “compress objects into a smaller visual frame as they recede into the distance, resulting in distant objects appearing closer in VEs than they would in the real world” (p.486). Kline and Witmer (1996) found that the restricted FOV of a head-mounted display (HMD) results in compressed absolute distance perception.

A number of studies have been conducted to investigate the idea that the FOV contributed to the large amounts of distance underestimation found in VEs (Knapp, 1999; Knapp & Loomis, 2004; Creem-Regehr et al., 2005 and Messing & Durgin, 2005). In these experiments, participants viewed the target under both full FOV and restricted FOV (both horizontally and vertically) in the real world and then estimated the distance to the target using either a verbal report or direct walking. It was found that restricted FOV without head movement led to a greater underestimation of distance. However, when head movement was allowed, a restricted FOV did not affect distance estimation.

There are two differences between these studies and Kline and Witmer's (1996) study. First of all, in the Kline and Witmer (1996) study, head movements were not allowed. Free head movement enables participants to see the entire environment even under restricted FOV. Secondly, these four studies were conducted in the real world, which has more visual cues. It is possible that in the real world people do not rely on the full FOV, because of a wide range of visual cues being available. In VEs, some of those cues may not be available, thus it is more important to have a full FOV in this situation. These methodological differences could contribute to the discrepancies between Kline and Witmer's (1996) study and more recent

work.

The notion of methodological differences contributing to the discrepancies between studies has been further supported by a recent study conducted by Willemsen, Colton, Creem-Regehr and Thompson (2009), where they re-examined the effect of FOV on distance estimation. This study focused not only on FOV but also the HMD mechanical properties (added mass and moments of inertia). It was found that HMD mechanical properties (added mass and moments of inertia) could not account for the distance underestimation found in VEs presented in a HMD. The combination of HMD mechanical properties and FOV, on the other hand, resulted in significant distance underestimation. However, Willemsen et.al (2009) suggested that the combination does not fully account for the magnitude of compression found in VEs presented in a HMD.

In summary, these findings suggest that when combined with restrictions on head movement, FOV restrictions have an influence on the accuracy of distance estimations, but do not fully account for the magnitude of compression found in VEs. Interestingly, although a restricted FOV did not affect distance estimation when head movement was allowed, unrestricted head movement did not enable people to gather more relevant visual information other than that presented on the screen when using a CRT or

LCD monitor to display 3D scene. Instead, they might pick up conflicting visual information from the environment surrounding the monitor. Therefore FOV restrictions may still affect distance estimation using a CRT or LCD monitors, even with unrestricted head movement.

### **2.2.5.3 Types of VE**

As previously discussed, researchers have found that people underestimate distance in virtual environments, relative to the real world. A number of investigations have attempted to explain this bias in behaviour by examining technical aspects of VEs. Virtual environments are commonly displayed using a head-mounted display (HMD) or a large-screen display system. Desktop monitors have also been used to display simulated environments. However, they have a rather limited ability to create the illusion of immersion.

A relatively large number of virtual environment distance estimation studies have used HMD immersive display systems (e.g., Plumert, Kearney, Cremer & Recker, 2005; Kuhl et al., 2009; Grechkin et al., 2010). HMDs typically restrict the user's field of view (FOV) and encumber the user with a helmet that often has significant weight (see section above).

An issue with using a HMD is that potentially it can cause visual cue

conflicts that could affect distance estimation. Accommodation and convergence are often considered to be weak cues for absolute distance (Beall et al., 1995) as they do not directly provide information about absolute distance beyond a few metres. However, it is possible that depth perception of nearby locations obtained via accommodation and convergence combines with other distance information to scale space, thus impacting on distance estimation. Bingham et al. (2001) found that the discrepancy between accommodative distance of a HMD and the target distance resulted in overreaching to near targets; therefore it is possible that a discrepancy in the opposite direction could lead to underestimation of distance.

Another frequently used image system for distance experiments is the CRT or LCD monitor. Similar to HMD, using CRT or LCD monitors can also cause visual cue conflicts and affect distance estimation. CRT and LCD monitors cannot display life size virtual objects; neither can they block out visual information from the real world (Brooks, 1999). Thus they have limited ability to create the illusion of immersion. Dixon, Wraga, Proffitt and William (2000) investigated the eye-height scaling of absolute size in comparable immersive (presented in a HMD) and non-immersive conditions (presented on a TV screen). They defined immersion as “the objective

viewing context provided by the display, whether or not the displayed environment surrounds the observer and whether or not the ground plane is below the observer's feet" (Dixon et al., 2000, p. 582). Dixon et al. (2000) found that participants made more accurate size judgements in immersive viewing conditions than those in non-immersive conditions. Eye-height manipulations affected participants' size judgements in immersive viewing conditions but not in non-immersive conditions. Furthermore, more participants perceived that they were a part of the environment in immersive viewing conditions than in non-immersive conditions. Finally, it was also found that the reduced field of view in non-immersive conditions could not account for the participants' inaccurate size judgements. Since in the experiment few cues were available for size judgement, eye-height scaling had a large effect on participants' size judgements. In the non-immersive viewing conditions, the fact that more participants were in the low subjective immersion group suggested that there might be dissociation between the horizon and one's own eye height (Dixon et al., 2000). Thus participants were not able to use absolute eye-height scaling effectively in the non-immersive viewing conditions.

Additionally, CRT and LCD monitors typically have a black frame surrounding the screen, which could lead to reduced perceived depth of the



3D scene. Eby and Braunstein (1995) conducted three experiments to examine the effect of a frame around a 3D scene on slant judgements and judgement of an object's shape. It was found that an illuminated frame or a frame added to the scene resulted in reduced judged slant. It also affected the shape judgements: objects were judged to be narrower (Eby & Braunstein, 1995). Eby and Braunstein (1995) suggested that a visible frame reduced the perceived depth of the 3D scene. Knapp (1999) conducted an experiment to compare distance estimation under 2D and 3D projection of the same scene. Participants viewed both projections within the VE. Then they were asked to judge distance between themselves and the target (texture mapped spheres). They made the judgement using either a verbal report of distance and size or triangulation by walking. The results showed that there was greater distance underestimation under 2D projection of the scene. The slopes of regression, fit to a scatterplot of estimated distance versus actual distance under 2D conditions, were about half of the slopes of regression plotted using 3D projections. These two studies demonstrated that the 2D frame of a CRT and LCD monitors can affect distance estimation and lead to distance underestimation.

As mentioned earlier, another problem with using CRT or LCD monitors is the restricted FOV. By contrast, large-screen immersive display (LSID)

systems can provide a wider FOV and create an immersive experience.

Additionally, the projection surface of a LSID is often located beyond the effective range of accommodation, convergence, and motion parallax (2 m), therefore effectively minimising cue conflicts.

In an experiment conducted by Bakdash, Augustyn and Proffitt (2006), participants were instructed to explore a VE of a city on either a small (25") or large (72") screen. There were five target locations placed throughout the VE. Participants then viewed the same VE through a HMD and were instructed to stand at each of the target locations and point at the other unseen targets using a tracked wand. It was found that for the small display condition the absolute angular pointing error was significantly greater compared to the large display condition. As the visual angle of both displays was fixed at the same angle, Bakdash et al. (2006) suggested that using a large screen improved participants' spatial knowledge of the targets and this can be attributed to the more immersive nature of large screens.

At the time of designing the initial studies described in this thesis (in 2006), there were no studies that the author was aware of that compared distance estimation in a VE displayed on a HMD or CRT monitors versus a LSID or CAVE system. This led to a second motivation for the current study: to compare distance estimation in VEs displayed on different display systems.

Subsequent to the initial studies being carried out, there have been a number of studies published investigating this issue (e.g., Klein, Swan II, Schmidt, Livingston, & Stadt, 2006; Sciarini, Kemper, Guay & Nicholson, 2008; Saracini, Franke, Blumel & Belardinelli, 2009; Grechkin et al., 2010). It has now been found that there is no difference in the estimates made using a projection (without stereoscopic cues) and a laptop (Sciarini et al., 2008), or between non-stereoscopic three-wall projection and a HMD (Grechkin et al., 2010).

When comparing distance estimations in VEs displayed using either a four-wall stereoscopic CAVE or a stereoscopic tiled wall, Klein et al. (2006) found a greater underestimation of egocentric distances in the wall condition compared with the CAVE, especially for the timed walking and verbal estimation protocols. It was suggested that the peripheral scenery provided by the CAVE has contributed to the more accurate distance estimation relative to the Wall condition. Finally, Saracini et al. (2009) examined distance estimation in VEs using four types of displays: CAVE, Elbedom, Engineering Workstation and laptop. CAVE and the Engineering Workstation provide stereoscopic cues, whereas the Elbedom system and the laptop do not support stereoscopic view. Saracini et al. (2009) found that with numerical measurements participants underestimated egocentric distances, especially in the CAVE and the Engineering Workstation. This

study raised the question as to whether the combination of stereoscopic cues and the use of LSID might have somehow resulted in the less accurate estimates.

In summary, a number of recent studies have shown that people are generally quite accurate at estimating distance within action space in the real environment (e.g., Elliott, 1987; Steenhuis & Goodale, 1988). On the other hand, it has been found that people tend to overestimate distance within far vista space. Certain distance cues (e.g., perspective cues, relative size and the visual angle of declination), environment context and the ground surface the observer stands on can provide distance information and enable observers to make distance judgements. Additionally, researchers have found that people underestimate distance in virtual environments, relative to the real world. A number of investigations have attempted to explain this bias in behaviour by examining technical aspects of VEs. However, because of the wide range of techniques/ methodologies used and the diversity of findings, it is difficult to make a general conclusion about distance estimation in VEs.

### **2.3 Motion and Distance Estimation**

There have been very few studies of distance estimation during motion of the observer. In addition to Hiro (1996), Baumberger and Fluckiger (2004)

tested the ability of humans to estimate egocentric distance while experiencing full-field patterns of image motion similar to those experienced during forward or backward transmission through the world (optic flow). Texture patterns were projected onto a moving ground surface (simulating forward motion at normal walking speeds) to create the optic flow. In the first experiment, participants (children aged 8, 10 and 12, and adults) were asked to view the target presented within either a stationary or an approaching texture condition (presentation phase). The target was then removed and participants were required to direct a laser pointer to the target's estimated position within either a stationary or approaching texture condition (reproduction phase). The results show that the distance between the participants and the target was perceived as being more compressed in the approaching texture conditions (with a moving texture during either presentation phase or reproduction phase, or with a moving texture during both phases). Children perceived a more compressed space than adults did in the approaching texture conditions. Additionally, participants were asked whether they perceivedvection (a feeling of self-motion) under the approaching texture condition. It was found that there was no difference on estimated distance between groups who reportedvection and those who did not.

In the second experiment by Baumberger and Fluckiger, participants viewed the target and performed the pointing task from two different heights under the approaching texture condition. It was found that there was still a difference between children's performance and adults, thus indicating that the difference was not solely attributable to the height of the participants (Baumberger & Fluckiger, 2004). Later an analysis of retinal speed found that localisation errors were proportional to retinal speed (Baumberger & Fluckiger, 2004). In the last experiment, participants were exposed to either approaching or receding surroundings and also to conditions in which central vision was either available or not. This experiment found that the distance was underestimated when the surrounding is approaching and overestimated when the background is receding. However, the difference between localisation errors observed in receding texture and those with fixed texture was not significant. Thus Baumberger and Fluckiger (2004) suggested that distance estimation was more influenced by the approaching texture rather than the receding one. It was also found that the availability of central vision did not have an influence on the effect of moving texture.

Baumberger and Fluckiger (2004) suggested that the error of perceived distance estimation might result from eithervection or a compensation

mechanism, where “the visual system is conceived in such a manner as to compensate the perceptual effects of the movement” (Baumberger & Fluckiger, 2004, p.1096). To test which one (vection or compensation) is responsible, they also suggested that a similar study should be carried out in the real world where optic flow is generated by the observer’s own movement, instead of vection. The Baumberger and Fluckiger study found some interesting results relevant to this current thesis, especially the fact that people tend to underestimate distance when surroundings are approaching. Of special significance is the fact that they found that there is a linear relationship between retinal speed and localisation errors.

Baumberger, Fluckiger, Paquette, Bergeron and Delorme (2005) also studied human perception of relative distance in a driving simulator.

Participants were required to park the front of a car (car A) at the middle distance between two other moving cars (car B and C). Later they were also asked to park the front of a car (car A) abreast with car C. This study found that observers generally underestimate the relative distance. The distance was more compressed when the surroundings were approaching.

Baumberger et al. (2005) also found that increased driving speed and a shorter distance between car B and C did improve the participants’ performance.

Overall, the three studies discussed above indicate that humans' perception of distance (egocentric and relative distance) is generally compressed while moving forwards through the world. However, a number of questions and problems emerge from these studies. (1) Since these studies investigated either egocentric distance estimation or relative distance estimation, their results are not directly comparable. One may say that Hiro's (1996) study is closer to the one conducted by Baumberger and Fluckiger (2004), because the distance between drivers and the front of the leading car was constant. However, the driver's view is partially obstructed by their own car. This may lead to a loss of important visual cues such as the near ground surface, but the driver's own car may also provide extra visual cues to distance for the driver. (2) Baumberger and Fluckiger (2004) conducted their study in a reduced-cue situation where the environment was not well-lit, and the target was only a single diode, not a full sized object such as a car. Previous studies (Ohtsuka, Ujike, & Saida, 1999) indicate that depth perception in reduced-cue conditions differs from depth perception in full-cue conditions. The other two studies (i.e., Hiro, 1996; Baumberger et al., 2005) were conducted in a rather richer visual environment. However all the visual cues presented were not controlled, thus it remains unknown how these cues aided in the task. Furthermore, there is also the possibility that perceptual distortion was caused by the competition between two-dimensional and



three-dimensional visual cues in Hiro's (1996) study. (3) The explanations given in these three studies cover different areas and they have not yet been supported by empirical data. They are also not exclusive, because there may be many other possible reasons that can explain the findings as well. (4) The speed of the approaching surroundings was not systematically controlled in these studies. To solve these problems, we need a more controlled study to test the ability of humans to estimate egocentric (or relative) distance from optic flow, and to explore the relationship between the observer's own speed and the accuracy of their distance estimates. Further studies are also required to find out the most likely mechanism(s) that facilitate distance estimation in the presence of optic flow.

## **Chapter 3 Methodological Issues**

Studies of distance estimation, whether in VEs or in the real world, often vary widely in their experimental methodologies. In this section of the thesis, the methodological issues of distance estimation will be discussed.

### **3.1 Protocols**

Distance perception and estimated distance are two different concepts. A number of different measurement protocols have been used to obtain depth

estimation in VEs. This section will introduce some of the widely-used protocols and discuss their advantages and disadvantages.

Verbal measures remain a major measurement protocol for investigating distance perception (Knapp, 1999; Knapp, 1999; Willemsen & Gooch, 2002; Knapp & Loomis, 2004; Messing & Durgin, 2005; Richardson & Waller, 2007; Kunz et al., 2009). It requires that the participant reports the target distance in a particular unit, such as feet or metres. Verbal measures of distance are very easy to collect. However, the assumption that the observer's numerical estimation or motoric response "are driven by perception alone, uncontaminated by what the observer knows... especially in connection with numerical estimation, is likely not to be true in general" (Loomis & Knapp, 2003, p.20). For example, Pagano and Isenhower (2008) found that manipulation of the expected range of possible target distances affected verbal judgements of distance, but not the blind manual reach protocol judgements. Additionally, some researchers have suggested that verbal measures tend to be more variable and less accurate than visually directed actions (Pagano & Bingham, 1998; Pagano, Grutzmacher, & Jenkins, 2001; Andre & Rogers, 2006; Kelly, Loomis, & Beall, 2004; Loomis & Philbeck, 2008). On the other hand, Messing and Durgin (2005) found a similar performance between verbal estimation and visually directed action

tasks in an experiment investigating the use of angular declination from the horizon as a cue to distance in VEs. Distance estimation from verbal estimation was also found to be more accurate than estimation from triangulated blind walking (Klein et al., 2006). Additionally, Bergmann et al. (2011) found that beyond 100 m, distance from locomotor estimates was less accurate than it was from verbal estimation.

Visually guided action is another widely-used protocol category for distance estimation. It requires participants to view a target, and then undertake reaching, walking, or throwing without vision of the target to indicate the distance to the target. With real world targets, blind walking in the real environment is close to veridical out to at least 20 metres (Loomis & Knapp, 2003). Sahm et al. (2005) conducted an experiment to investigate distance estimation in VEs and the real world using blind throwing and blind walking. It was found that there was no significant effect of different protocols on performance accuracy, thus showing that there was no difference between the two tasks. Visually guided action also has its limitations. It often requires a large amount of space. Therefore it cannot be used to indicate a depth judgement in a large-screen immersive display, because there is not enough room to blindly walk to a target that is located beyond the display's screen. (Knapp, 1999; Knapp & Loomis, 2004;

Interrante et al., 2006; Richardson & Waller, 2007; Swan et al., 2007; Thompson et al., 2007; Jones et al., 2008; Grechkin et al. 2010).

Triangulation has also been used as a form of visually guided action. One of the most popular triangulation methods is triangulation-by-walking. It requires the observer to view a target, turn to face an oblique angle to the target and walk forward without vision. Fukusima, Loomis and Da Silva (1997) found that with real world targets under full-cue conditions, triangulation is very accurate out to 15 metres. Additionally, participants slightly underestimate target distances between 15 and 25 m (Fukusima et al., 1997). Again triangulation methods often require space for observers to perform the tasks. Klein et al. (2006) studied distance perception (2 to 15 m) in a real world outdoor field and in VEs using timed imagined walking, verbal estimation, and triangulated blind walking. In the study the VE was displayed using large-screen immersive displays. Distance estimations from timed imagined walking and verbal estimation were very similar in all three environments. In the two VE conditions participants had greater underestimation of distance from the triangulated blind walking measurement. This was attributed to the insufficient physical space to use a triangulated blind walking measurement (Klein et al., 2006).

Visually imagined walking is a protocol that is closely related to visually

directed walking. In visually imagined walking, instead of performing the action (i.e., walking), the observer imagines walking to the target. The time it takes to the imagined target is recorded, and then combined with their measured walking rate to produce distance estimations (Plummeted al., 2005; Ziemer, Plumert, Cremer, & Kearney, 2009; Klein et al., 2006).

Visually imagined walking is a good alternative method to visually directed walking, as it is easier to collect data and it does not require a large space.

Visually imagined walking and visually directed walking yield similar estimations for real-world targets (Plumert et al., 2005). Finally, the effect of the HMD encumbrance affects visually directed walking measures of distance but not visually imagined walking (Grechkin et al., 2010). One limitation of visually imagined walking is that systematic bias can be introduced when converting the direct measure of time to a measure of distance (Grechkin et al., 2010).

Finally, distance can also be expressed as the distance to a matching object. This method is called the perceptual matching protocol. The matching object can either be positioned to the same side of the target object or positioned in a different direction to the target object (Ellis & Menges, 1997; Sinai et al., 1999; Swan et al., 2007; Bodenheimer et al., 2007). The distance to the matching object is either manipulated to match

the target distance (or sometimes the midpoint to the target object, called bisection) or judged to determine whether it is shorter or longer than the target distance (called perceptual matching). The main advantage of the perceptual matching protocol is that it relies only on visual perception; the disadvantage is that it does not give an absolute measurement of perceived distance (Bodenheimer et al., 2007).

As mentioned above, Sinai et al. (1999) investigated whether texture pattern and object size affected distance estimation using a perceptual matching task. It was found that overall, participants overestimated the distance to the comparison object (or underestimated the target distance) by about 7%, which is relatively accurate compared with other studies, such as Witmer and Kline (1997) and Witmer and Sadowski (1998). Sinai et al. (1999) suggested that this could have been due to the perceptual matching task used in the study, which may have achieved better results compared with verbal estimation. The findings of Sinai et al. (1999) have been partly supported by the study of Bodenheimer et al. (2007) where it was found that at 15 m, the bisection estimation of distance in VEs is similar to estimation in the real world and more accurate than estimation in VEs reported elsewhere (Bodenheimer et al., 2007). Between 15 m and 30 m however, there were noticeable differences between bisection estimation in VEs and

in the real world. According to Bodenheimer et al., (2007), bisection estimation in a VE displays nonlinear compression similar to the compression in space reported by Gilinsky, (1951).

The other debatable issue around distance estimation protocols is whether different protocols tap into fundamentally different internal representations of perceived space (Creem & Proffitt, 1998; Philbeck & Loomis, 1997).

Philbeck and Lommis (1997) investigated the relation between verbal distance estimation and open-loop walking distance estimation. In this study, the participants viewed a rectangle presented in either a well-lit or dark environment. Their task was to judge the distance between themselves and the target verbally or walk to where they thought the target was with eyes closed. When verbally estimated distance and open-loop walking estimation were plotted as a function of physical distance, the data patterns for these two methods were similar (Philbeck & Lommis, 1997).

When average distance was measured using open-loop walking and was plotted as a function of verbally estimated distance, Philbeck and Lommis (1997) discovered a linear co-variation between data from the two methods.

Thus they suggested that it is very likely that estimated distance from the two methods comes from the same internal representation of perceived distance.

Pagano et al. (2001), however, disagreed with Philbeck and Lommis's (1997) conclusion. They pointed out that the linear co-variation found in Philbeck and Lommis's (1997) study may be attributed to the "common relation to actual target distance" (Pagano et al., 2001, p.198). Pagano et al. (2001) proposed that instead of looking for linear co-variation, the researcher should focus on whether errors for the two methods are correlated. In their study, participants estimated the distance to the target by verbal report, reaching to the target with eyes closed or reaching to a target with concurrent verbal judgement. The results showed that the slopes of the regression fit to a scatterplot of estimated distance versus actual distance were more variable for verbal estimation (Pagano et al., 2001). More importantly, residual analysis found that errors in verbal estimation and the reaching task were not correlated. In a second experiment, participants made their distance estimation after either 6 s or 12 s delay. Pagano et al. (2001) found that with the delay the random errors for both methods were correlated. Pagano et al. (2001) suggested that estimated distance from the two methods did not come from the same internal representation of perceived distance. Instead, there are two visual systems: one for perception and one for visual direct action. When a delay was imposed, the motor system "relies on the cognitive (verbal) perceptual system for spatial information", as it has no memory of its own (Pagano et al., 2001, p.207).



## 3.2 Individual Differences

Another issue with the experimental methods adopted in the studies of distance estimation in virtual environments is whether to use a between or within subject design. One of the disadvantages to using a between-subjects design is individual variability. Armbrüster et al. (2005) conducted two experiments to investigate the inter-individual differences and intra-individual stabilities in distance estimation in VEs. In the experiments, participants verbally estimated the egocentric distance and retinal image size of one or more spheres presented on the screens (a VR application with stereoscopic visualisation for the first experiment and a standard CRT screen for the second experiment). Target distances ranged from 60 cm to 330 cm. High inter-individual differences were found in both experiments. However, participants were able to judge the relative positions of the targets (i.e., the closest target close and the farthest target far away). There was also a linear relationship between estimated and true distance, thus suggesting high intra-individual stability. Armbrüster, et al. (2008) investigated distance estimations in peri- and extra-personal space in VEs. In their study inter-individual differences and intra-individual stabilities were also found among participants. Additionally, in the second experiment by Grechkin et al. (2010), when using a blind walking task to estimate distance,

the results for the the real world condition presented on HMD were heavily influenced by two outliers. This shows that individual differences could have a big impact on distance estimation studies using between-subjects design.

There are several sources of individual differences in distance estimation in VEs. Armbrüster et al. (2005) found gender differences in their two experiments. When a stereopsis cue is present, binocular ability is a source of individual differences. Surdick and Davis (1997) reported that participants who perceived stereoscopic depth had a larger JND (just noticeable difference). The JND is a measure of the smallest change in depth necessary for participants to perceive the change. Armbrüster et al. (2008) used the TITMUS Vision Tester to test visual acuity. It was found that there were significant correlations between underestimations/overestimations and binocular ability. The higher participants scored in the stereopsis test, the more underestimations they made; the lower they scored the more overestimations they made (Armbrüster et al., 2008).

Vianin, Baumberger and Fluckiger (2004) suggested that in order to estimate egocentric distance in VEs, observers have to “transpose perceptively their own observation point in order to assume their virtual body position”, which could be affected by the field dependence/

independence factor (FDI) (p.561). They conducted an experiment to investigate whether there is any difference in distance estimation in VEs between field-independent and field-dependent participants. There were four conditions in the experiment: egocentric/exocentric distance estimations and centred/non-centred camera orientation. It was found that participants underestimated both the egocentric and exocentric distance. In addition, distance underestimations were greater in the non-centered-camera condition than in the centred-camera condition. Field-dependent participants were less affected by the position of the camera than field-independent participants, if affected at all. Vianin et al. (2004) suggest that field-independent participants are less immersed than field-dependent participants in VEs.

### **3.3 Order Effects**

When adopting a within-subjects design in distance estimation studies, carry over effects can confound experiment results, as participants are often exposed to a number of conditions. Plumert et al. (2005) investigated distance estimation in real and virtual environments using an LSID system. The participants made estimates in the following conditions: (1) real environment first, virtual environment second; (2) virtual environment first, real environment second. It was found that distance estimations in VEs

were less accurate in the virtual–real condition than estimates made in the real–virtual condition. Likewise, in the real environment estimates were more accurate in the real–virtual condition than in the virtual–real condition. Thus Plumert et al. (2005) suggested that the order affected distance estimation in both real and virtual environments.

Ziemer et al. (2009) also investigated the effect of order of conditions presented on distance estimates. In their study, participants estimated distance in one of four conditions: (1) real environment first, virtual environment second; (2) virtual environment first, real environment second; (3) real environment first, real environment second; or (4) virtual environment first, virtual environment second. Two protocols were used in the study, visually imagined walking in Expt. 1 and visually directed walking in Expt. 2 (Ziemer, et al., 2009). It was found that distance estimations were made significantly more accurate in the real environment than those in the VE (Ziemer, et al., 2009). Ziemer, et al. (2009) also found clear evidence of order affecting estimating distances in real and virtual environments. In virtual–real conditions, the presence of a VE led to greater distance estimation in real world condition; likewise in the real–virtual condition the presence of the real world condition resulted in more accurate estimation in the VE.

### 3.4 Summary

The previous sections demonstrate that there have been many studies of distance estimation in both the real world and in VEs. Not many studies have looked at distance estimation in the case where a car is used as the target. Hiro (1996) investigated estimation of “objective” distance between a moving participant’s car and the car in front and found that the higher the speed, the more the driver underestimated the relative distance. This also occurred when the participants viewed video recordings of the driver’s view. On the face of it, this is an unusual finding and seems to suggest that the higher the fidelity of the display the worse the performance on a distance estimation task. This has important implications with regard to the use of VEs for driver training and assessment and so it is worth verifying if this result is robust.

A number of recent studies have shown that people are generally quite accurate at estimating distance within action space in the real environment (e.g., Elliott, 1987; Steenhuis & Goodale, 1988). On the other hand, it has been found that people tend to overestimate distance within far vista space. Additionally, researchers have found that people underestimate distance in virtual environments, relative to the real world. A number of investigations have attempted to explain this bias in behaviour by examining technical

aspects of VEs. However, because of the wide range of techniques/ methodologies used and the diversity of findings, it is difficult to make a general conclusion about distance estimation in VEs. These factors need to be systematically examined using the same methodology.

Previous studies have suggested that verbal reports of distance tend to be more variable and less accurate than action based measures of distance (Andre & Rogers, 2006; Kelly et al., 2004; Loomis & Philbeck, 2008).

Cognitive knowledge that is unrelated to the perception of distance is known to confound verbal distance estimation (Loomis & Knapp, 2003). Moreover, several studies have indicated that other verbal distance judgements may result in non-linear estimation, i.e., compression of space increasing with distances (Loomis et al 1992; Loomis et al., 1996). The main experimental design used for the experiments reported in this thesis is a variation on part of Hiro's (1996) experiment using a computer generated VE presented on a CRT monitor. Participants were required to estimate relatively long distances in a simulated driving environment. This experiment design limited the distance estimation protocols that could be used. For example, blind walking could not be used in the experiment, as it requires large amount of space to estimate long distances, especially when the target is located beyond a screen. Triangulated blind walking was less accurate

compared with verbal estimation in a confined indoor environment (Klein et al., 2006). Furthermore, walking or throwing might not be very efficient in measuring distance in a simulated driving environment, as the visual cues (e.g., eye height and ground continuity) involved can be very different among these actions. Finally, several studies have employed visually imagined actions to measure distance (Plumert et al., 2005; Ziemer et al., 2009). Visually imagined actions do not require any space and were found to have good accuracy (Plumert et al., 2005). However, this method is an indirect measure of distance (i.e., a direct measure of time). Converting such estimations to distance could result in a systematic bias (Ziemer et al., 2009). In this study distance estimations in a simulated driving environment were investigated, and visually imagined driving can be hard to convert to distance measurements as individuals can interpret driving speed differently. To overcome the problem of verbal estimation of distance, a modified perceptual matching protocol (a sliding scale) was used. The advantage of the matching method is that it is perceptual, as it has no reference to units of distance, which minimises the influence of cognitive knowledge. However, it does not provide any indication of absolute distance. The verbal estimate provides this and so the two combined techniques should provide a robust estimate of the perceived distance.

Another issue with the experimental methods adopted in the studies of distance estimation in virtual environments is whether to use between or within subject design. One of the disadvantages for between-subjects design is individual variability. A number of studies have found that verbal estimation of distance in the real world were more variant than action based measures of distance (Pagano & Bingham, 1998; Pagano et al., 2001; Kelly et al., 2004; Andre & Rogers, 2006). There are several other sources of individual differences in distance estimation. Armbrüster et al. (2005) found gender differences in their two experiments. In this thesis, no attempt was made to recruit males and females with similar age, backgrounds or driving histories. It is possible that the participants chosen were not entirely representative of their respective gender. Vianin et al. (2004) found that field-independent participants are less immersed than field-dependent participants in VEs. Nevertheless inter-individual differences and intra-individual stabilities were both found in verbal estimation of distance in VEs (Armbrüster et al., 2005), thus suggesting that a within-subjects design is appropriate coupled with verbal estimation.

The majority of previous studies have found that the quality of the computer generated VE had little effect on distance estimation (Willemsen & Gooch, 2002; Messing & Durgin, 2005; Grechkin et al., 2010). Therefore for the



experiments carried out in this thesis the quality of the computer generated VE was not specifically controlled for and was not tested separately.

### **3.5 Outline of the Thesis Study**

This study began by considering the question of how image motion may affect egocentric distance estimation within action and vista space (10-100 m) and it attempted to replicate part of Hiro's (1996) experiment in a computer generated VE. Two main issues were addressed: distance estimation in a static VE and distance estimation in the presence of simulated forward motion.

Chapter 2 introduces a pilot study designed to replicate Hiro's (1996) results and to test a preliminary experimental design as well as identify potential problems in the methodology. The first series of experiments, addressed in Chapters 4-7 were intended to establish reliable distance estimations in a static VE and to establish a baseline for further experimental manipulations. Expt. 1 was designed to examine the effect of the horizontal field of view (HFOV) and environmental context on distance estimation. Expt. 2 further investigated the effect of environmental context on distance estimation.

Participants estimated distance in six environments where a number of visual cues were manipulated in a driving simulator consisting of three CRT monitors. Expt. 3 was designed to replicate Expt. 2 using a more immersive

virtual environment (a driving simulator). These experiments were designed to answer the following types of questions. Does HFOV affect distance estimation? Does the size of the texture on the ground affect participants' estimation? Does a reduced-cue condition lead to compression of distance in a VE? Does the width of the road affect participants' estimation? Is there any difference in distance estimation between the VE presented using CRT displays and using a driving simulator?

A second issue addressed in this thesis is introduced in Chapter 8, namely how background motion affects distance estimation in a VE. Participants' distance estimation performance was compared in four different environments, some of which included simulated movement of the car being observed. Finally Expt. 5 (Chapter 9) was designed to field-test the findings from the previous experiments. One aim was to provide a direct comparison of VEs and an actual real-world environment. Another aim was to examine whether participants behaved differently in the simulated environments compared to how they would in reality, and whether the findings from the simulators can be generalised to actual real-world environments.

## Chapter 4 Pilot Study

This study was conducted to test a preliminary experimental design and identify potential problems. It was an attempt to replicate part of Hiro's (1996) experiment in a computer generated VE presented on a CRT monitor. The purpose of this experiment and the Hiro (1996) study was to test people's judgement of the distance to a car. One of the aims was to verify the Hiro result whereby distance estimates were worse for cases in which the observer was moving (actual or simulated) compared to when they were still. This counterintuitive result was the motivation and starting point for the thesis research.

There were three main differences between this experiment and the Hiro (1996) experiment. First of all, in the third experimental condition presented by Hiro (1996), participants viewed a video recording of a real world driving experience. In this study, the computer generated simulation displayed was a simplified environment with only a car and a black and white textured ground plane. Thus this study used a reduced-cue condition and had lower background complexity. Additionally, in the Hiro (1996) experiment, the horizontal field of view of the display was 180° (three screens). In this study, it was either 35° or 50°. Furthermore, in this study a chin rest was used to ensure that participant's eyes were focused on the centre of the screen and

also to limit participant's head movement (which was apparently not controlled in the Hiro (1996) experiment).

## **4.1 Methodology**

### **4.1.1 Participants**

Participants consisted of 10 adults aged between 20 and 40 years old with an average age of 27 years ( $SD = 6.2$ ). Five were female and five were male. All participants had normal or corrected-to-normal visual acuity. All were naïve to the purpose of the study. All participants had more than one year driving experience in New Zealand. Participants from an introductory psychology class at the University of Waikato received one course credit for research participation. Ethics approval for this experiment was granted by the Waikato University Ethics Committees and written informed consent was obtained from all participants prior to the experiment.

### **4.1.2 Design**

The study was a 4 x 10 design. The two independent variables were speed (0, 50, 80, and 100 km/h) and distance (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 m). The experiment lasted for about one hour. It consisted of 4-6 sessions with each participant, with each session having 40 experiment trials.

As this was only a pilot study, different participants were exposed to multiple experimental conditions to test the basic overall design and to identify problems. Table 1 lists the different conditions that were used. For participants 001-005, the horizontal field of view was 35°. The distance between them and the computer screen was 60 cm. The camera height (i.e., participants' eye height in the virtual scene) was set at 1 m. They were given only basic instructions (see Appendix 1). Participant 006 had a 50° horizontal field of view. The distance between this participant and the computer screen was then 41 cm. Participant 006 was given basic instructions first. Then after three trials she was given extra information about the design of the experiment including the scale of the ground plane and some feedback on her performance in previous trials. Participants 007 and 009 had a 50° horizontal field of view in the first three trials and then 35° horizontal field of view in the remaining three trials. They were given only basic instructions. Participants 008 and 010 had a 50° horizontal field of view during the experiment. The camera height was set at 1 m in the first three trials and then 1.3 m in the remaining three trials. They were also only given only basic instructions.

Table 1 *Experimental Conditions*

| <b>Par #</b> | <b>Gender</b> | <b>FOV</b> | <b>Camera Height</b> | <b>Instruction</b> | <b>Sessions</b> |
|--------------|---------------|------------|----------------------|--------------------|-----------------|
| 1            | M             | FOV_35     | CH_1.0               | I                  | 4               |
| 2            | M             | FOV_35     | CH_1.0               | I                  | 6               |
| 3            | F             | FOV_35     | CH_1.0               | I                  | 6               |
| 4            | F             | FOV_35     | CH_1.0               | I                  | 6               |
| 5            | M             | FOV_35     | CH_1.0               | I                  | 6               |
| 6            | F             | FOV_50     | CH_1.0               | I                  | 3               |
| 6            | F             | FOV_50     | CH_1.0               | EI                 | 3               |
| 7            | F             | FOV_50     | CH_1.0               | I                  | 3               |
| 7            | F             | FOV_35     | CH_1.0               | I                  | 3               |
| 8            | M             | FOV_50     | CH_1.0               | I                  | 3               |
| 8            | M             | FOV_50     | CH_1.3               | I                  | 3               |
| 9            | M             | FOV_50     | CH_1.0               | I                  | 3               |
| 9            | M             | FOV_35     | CH_1.0               | I                  | 3               |
| 10           | M             | FOV_50     | CH_1.0               | I                  | 3               |
| 10           | M             | FOV_50     | CH_1.3               | I                  | 3               |

*Note.* FOV\_35: the horizontal field of view (FOV) was 35°; FOV\_50: the horizontal field of view (FOV) was 50°. CH\_1.0: camera height (i.e., participants' eye height) was 1 m; CH\_1.3: camera height was 1.3 m; I: basic experimental instruction; EI: extra instruction.

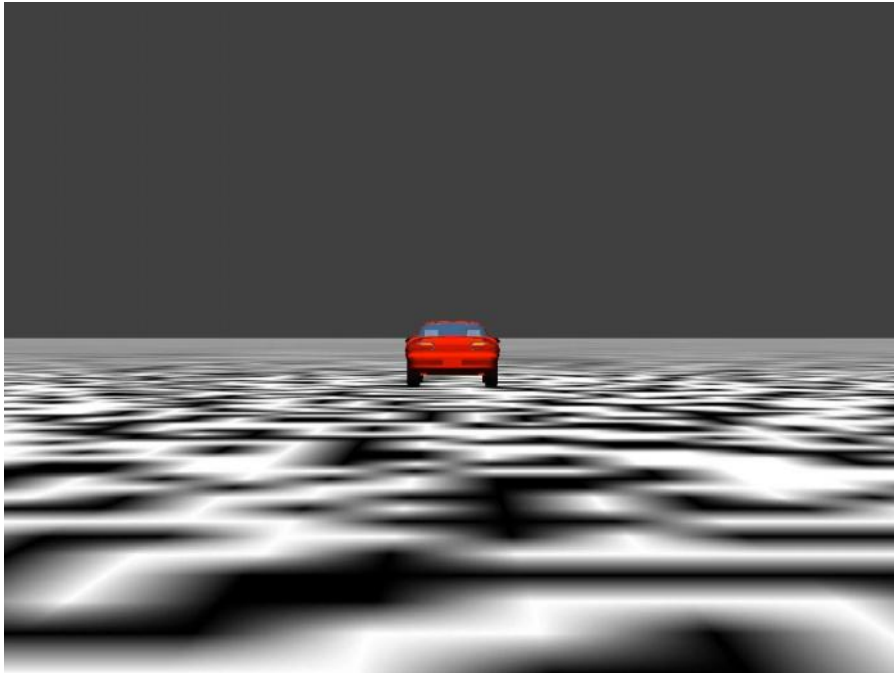
### **4.1.3 Stimuli and Apparatus**

The research was conducted in the Human Visual Navigation laboratory at the University of Waikato. The stimuli were presented on a computer screen (38 x 28.4 cm). The screen resolution was 1280 x 960 pixels. Participants were seated on an adjustable-height office chair in front of the screen.

There was also a chin rest in front of the screen. This was to ensure that the participant's eyes were focused on the centre of the screen and it also limited the participant's head movement. The lighting in the lab was fixed during the experiment and the room was darkened with only a reading lamp illuminating the area behind the participant. The distances between the observer and the computer screen were set at either 60 cm or 41 cm. This resulted in a field of view of 35° horizontal x 26° vertical and 50° horizontal x 37.5 ° vertical respectively.

The stimuli displayed contained a car and a horizontal ground plane (see Fig. 1). A texture map from 3Ds-Max library (AutoDesk) was used as the ground plane. The texture consisted of spatially filtered rectangular tiles randomly coloured black and white. The car was a 2 x 5 m three-door hatch. The car was static and located a certain distance away (i.e., 10 different distances). The textured ground plane was still or approaching at either 80 or 100 km/hr. This motion was designed to create vection (i.e., induced

self-motion) and to give the impression that the target car was travelling at the same speed as the observer. Thus the distance between the car and the observer was constant during a trial.



*Figure 1.* Static view of the simulation displayed to the participants.

#### **4.1.4 Procedure**

All participants signed informed consent forms prior to the experiment and were read the instructions for the distance estimation tasks. When participants were ready to begin the experiment, they were asked to press the space key on the keyboard in front of them. A car appeared ahead them on the screen for 10 seconds. Their task was to estimate the distance between themselves and the car, and also their own speed. After the trial,



the screen went blank and participants verbally reported the estimated distance of the car ahead and their own speed. Participants then pressed the space key when they were ready to commence the next trial. There were 40 trials in each session, and 4-6 sessions for each participant. Participants took a two-minute break after each session.

#### **4.1.5 Data Analysis**

Participants' responses were recorded using a recording sheet. For each participant, a linear regression was conducted to calculate the slope of the linear function (i.e.,  $y=mx +b$ ) that relates perceived distance to actual distance for each speed. If the participant overestimated the distance, the slope will be larger than one. If the slope is below one, the participant underestimated the distance. The mean estimated distance was calculated for each participant and analysed in an analysis of variance (ANOVA).

## **4.2 Results**

Figure 2 shows the scatter plot of estimated distances against actual distances and the fitted regression line for four speeds from a typical participant (Participant 001). Table 2 shows the functions between estimated distance and actual distance in each condition. Seven participants underestimated the distance between themselves and the car

ahead. Two participants overestimated the distance. The slope of regression fit ranged from 0.07 to 1.84 ( $M = 0.60$ ,  $SD = 0.51$ ), indicating large individual differences. The slope did not change according to the speed ( $F=0.832$ ,  $p=.491$ ). Therefore the results did not support the Hiro (1996) finding that distance estimation was worse for high speeds. There was also some evidence suggesting that FOV might affect participants' judgement. Participants had slightly better performance when the FOV was set at 35°. On the other hand, participants' eye height did not affect their distance estimation.

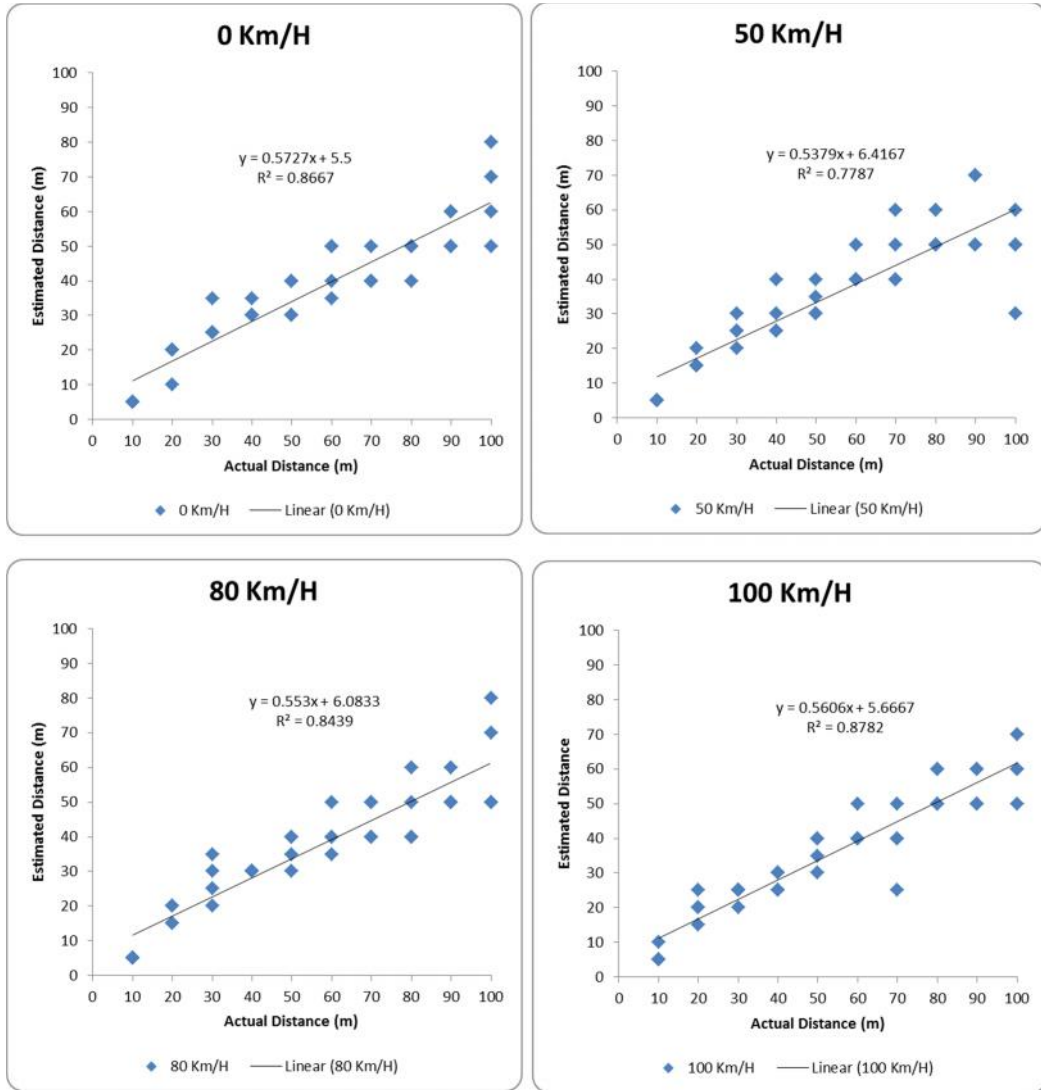


Figure 2. Scatter plot of estimated distances against actual distances and the fitted regression line for four speeds from Participant 001.

Table 2 *Regression Coefficients between Estimated Distance and Actual Distance*

| <b>Par #</b> | <b>Gender</b> | <b>Conditions</b>  | <b>0 Km/H</b> | <b>50 Km/H</b> | <b>80 Km/H</b> | <b>100 Km/H</b> |
|--------------|---------------|--------------------|---------------|----------------|----------------|-----------------|
| 1            | M             | FOV_35/ CH_1.0/ I  | 0.57          | 0.54           | 0.55           | 0.56            |
| 2            | M             | FOV_35/ CH_1.0/ I  | 0.55          | 0.54           | 0.54           | 0.54            |
| 3            | F             | FOV_35/ CH_1.0/ I  | 0.27          | 0.26           | 0.28           | 0.27            |
| 4            | F             | FOV_35/ CH_1.0/ I  | 1.08          | 1.13           | 1.1            | 1.16            |
| 5            | M             | FOV_35/ CH_1.0/ I  | 1.5           | 1.49           | 1.62           | 1.4             |
| 6            | F             | FOV_50/ CH_1.0/ I  | 0.07          | 0.08           | 0.07           | 0.07            |
| 6            | F             | FOV_50/ CH_1.0/ EI | 0.63          | 0.61           | 0.56           | 0.66            |
| 7            | F             | FOV_50/ CH_1.0/ I  | 0.11          | 0.12           | 0.13           | 0.15            |
| 7            | F             | FOV_35/ CH_1.0/ I  | 0.15          | 0.16           | 0.15           | 0.16            |
| 8            | M             | FOV_50/ CH_1.0/ I  | 0.1           | 0.13           | 0.09           | 0.09            |
| 8            | M             | FOV_50/ CH_1.3/ I  | 0.12          | 0.13           | 0.12           | 0.12            |
| 9            | M             | FOV_50/ CH_1.0/ I  | 1.36          | 1.7            | 1.66           | 1.84            |
| 9            | M             | FOV_35/ CH_1.0/ I  | 1.21          | 1.18           | 1.23           | 1.25            |
| 10           | M             | FOV_50/ CH_1.0/ I  | 0.45          | 0.49           | 0.46           | 0.46            |
| 10           | M             | FOV_50/ CH_1.3/ I  | 0.57          | 0.45           | 0.47           | 0.47            |

### 4.3 Discussion

The result showed that participants on average tended to underestimate the distance to the car ahead. However, there was little evidence that the simulated observer speed had an impact on the participants' distance estimation. It was clear that the majority of participants in this experiment exhibited a large amount of distance underestimation (60%). Other studies of distance perception have also found that participants underestimate distance in a VE. Across a wide range of studies the overall ratio of perceived distance to actual distance ranged from 42% to 93% (Witmer & Kline, 1997; Witmer & Kline, 1998; Witmer & Sadowski, 1998; Sinai et al., 1999; Knapp, 1999; Willemsen & Gooch, 2002; Loomis & Knapp, 2003; Thompson et al., 2004; Creem-Regehr et al., 2005; Messing & Durgin, 2005; Richardson & Waller, 2007; Sahm et al., 2005). However, the current pilot study was very different from these studies on a number of dimensions such as display technology, the visual targets and settings, the range of distances examined, and the experimental methods. Therefore it is difficult to make a direct comparison with these studies.

A comparison with Hiro's (1996) results is more meaningful. Participants in this experiment had greater distance underestimation compared to those in

Hiro's (1996) experiment. In fact, the average participant's estimation of distance (mean = 58%) for a static target (speed = 0 km/h) is close to or even worse than that for a moving target in Hiro's (1996) experiment (mean = 61% for his TV observation condition at a speed of more than 80 km per hour). This leads to the conclusion that in the pilot study, something in addition to speed caused a distortion of distance perception.

The simulation and experimental settings used in the pilot study provided the participants several cues for distance estimation including familiar size, height in the visual field, texture gradients, relative size, accommodation and convergence. Strictly speaking, relative size should not be listed as a distance cue here, as only one object (the car) was displayed. However, it was likely that participants compared the size of the car with previous trials and then made a judgement about its distance. Among these distance cues, the last two are distance cues that conflict with others. Although the simulation should be perceived as a 3D scene where a car is running on a textured ground plane, it was actually a 2D "picture" 40-60 cm away from participants. Accommodation and convergence would convey to the participants' visual systems that the car is on the screen. These conflicting cues may well have contributed to the underestimation of the car distances in this experiment (Bingham et al., 2001).

In the pilot study, the horizontal FOV of the display was either 35° or 50°.

Many researchers have suggested that a restricted FOV could lead to distance underestimation in a virtual environment (Witmer & Sadowski, 1998; Knapp, 1999; Kline & Witmer, 1996), but not in the natural environment (Knapp, 1999; Creem-Regehr et al., 2005). In contrast other researchers have suggested restricted FOV alone could not explain the distance underestimation found in VEs, especially when head rotation was allowed (Knapp & Loomis, 2004; Messing & Durgin, 2005; Creem-Regehr et al., 2005). Most of these studies were conducted in a real world environment using mock HMDs (has the same mass, moment of inertia and FOV as a real HMD). A mock HMD allowed head rotation, enabling the participants to scan the environment. In this experiment, the simulation was presented on a CRT monitor. Even with unrestricted head movement, participants could not gather more relevant visual information other than that presented on the screen. Thus it was still possible that a restricted FOV contributed to the space distortion found in the pilot experiment. A restricted FOV might have also affected the size perception of the target vehicle, reducing the effectiveness of the familiar size cue. In general a target is proportionally bigger in a smaller visual field, which may lead to distance underestimation. It was interesting that in this experiment, participants performed slightly better when the FOV was set at 35° than at 50°. In this

experiment, in order to change the FOV from 35 to 50°, the monitor was moved closer to the observers and the image projective geometry was calculated with a higher FOV value. This further supports the idea that accommodation and convergence cues may have contributed to the results.

In this experiment a reduced-cue condition was also used. This condition was designed to limit the background complexity and to enable better control and manipulation of the distance cues. As discussed in the introduction, verbal estimation of distance can be confounded with cognitive knowledge (Loomis & Knapp, 2003). Participants were unfamiliar with the simplified environment used in this experiment, thus minimising the risk of cognitive knowledge influencing verbal estimation. On the other hand, previous studies (e.g., Ohtsuka et al., 1999) suggested that depth perception in reduced-cue conditions differed from depth perception in full-cue conditions. Loomis et al. (1996) found that people tended to underestimate distance in reduced-cue conditions when the target was farther than 3 m. This might explain why participants reported greater distance underestimation in this current experiment. Because it was not fully understood how information provided by different sources was combined and utilised in distance estimation (Proffitt, 2006), it was difficult



to identify the missing source(s) of information that led to the space distortion found in this experiment. Participants may require the combination of absolute distance cues and additional relative distance cues to judge distance. They may also use estimated distance to nearer objects (e.g., trees and houses) to scale far space. In addition, people may judge the size of the target based on the size of near objects.

In the pilot experiment, verbal estimation was used to measure perceived egocentric distance. The preliminary experimental design used in this experiment was a replication of part of Hiro's (1996) experiment in a computer generated VE presented on a CRT monitor. Participants were required to estimate relatively long distances in a simulated driving environment. The experimental design was limited in the types of distance estimation protocols that could be adopted. However, because verbal estimates are prone to cognitive influences (Loomis and Knapp, 2003) the next series of experiments also included a perceptual matching task to provide a second measure of perceived distance.

Finally, large individual differences were found in the pilot experiment. This was expected as a number of studies have found that verbal estimation of distance in the real world was more variable than action based measures of distance (Pagano & Bingham, 1998; Pagano et al. 2001; Kelly et al., 2004;

Andre & Rogers, 2006). Inter-individual differences and intra-individual stabilities were both found in verbal estimation of distance in VEs (Armbrüster et al., 2005), thus suggesting that a within-subject design is appropriate coupled with verbal estimation.

## **Chapter 5 Distance Estimation in a Static Environment**

In the pilot experiment described in the preceding chapter, it was found that participants typically underestimated the distance to a car in front of them. The pilot study failed to replicate the finding reported by Hiro (1996) that distance underestimation gets worse as the motion of the observer increases. This leads to the conclusion that factors other than motion may have contributed to the distortion of distance estimation. Four factors appeared to have contributed to the results of this experiment: a restricted FOV, reduced-cue conditions, conflicting cues and an apparent ineffectiveness of the familiar size cue. This chapter introduces the first of three experiments investigating egocentric distance estimation in a static VE that were designed to provide more insights into the role of these four factors. Expt. 1 was designed to examine the effect of the horizontal field of view (HFOV) and environmental context on distance estimation. It compared participants' distance estimation performance in a simulated

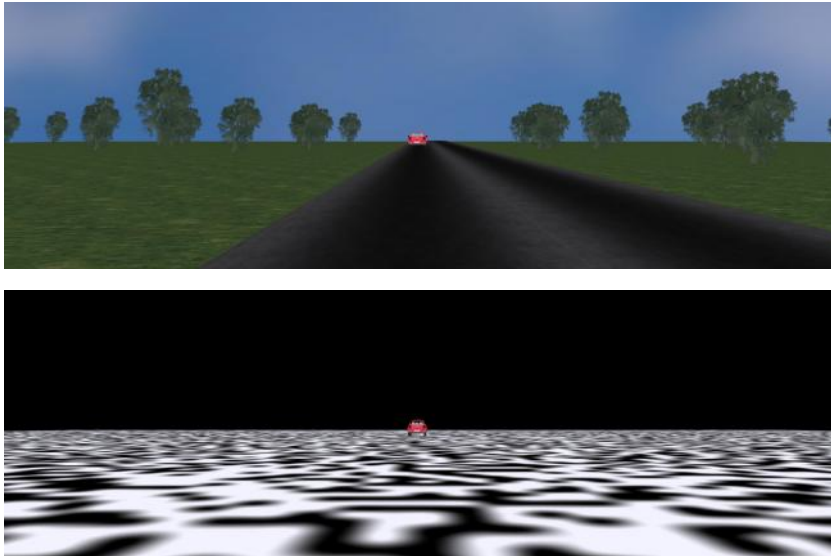
“real world” scenario (although this scene is called the “real world”, it is still a simplification of reality) and in a simulated simplified environment (Fig. 3).

## **5.1 Expt. 1 Scene Backgrounds and Horizontal Field of View (HFOV)**

This experiment was designed to examine the effect of two factors on distance estimation of static objects. It compared participants’ distance estimation performance in a simulated “real world” scenario and in a simulated simplified environment (Fig. 3). It also investigated the effect of HFOV on participants’ performance.

Compared with the simplified environment, the simulated “real world” scenario provided participants with more distance cues. It also provided a more familiar environment. The size of the target vehicle was more meaningful in the “real world”, as people were able to judge the size of the target based on other references (e.g., trees and the road). At the time of this experiment, only one study existed that compared distance estimation in a realistic VE with distance estimation in a VE with reduced geometry and visual details, similar to the design of this experiment. Thompson et al. (2004) found that distance estimates in three different VE conditions, 360° high-resolution panoramic images, low-quality texture mapped computer graphics, and wireframe renderings, did not vary much from each other.

However, there are two differences between the design of this experiment and that of Thompson et al. (2004). First of all Thompson et al. (2004) used a between-subjects design, and this experiment used a within-subject design. Additionally Thompson et al. (2004) used a blind-walking measure to estimate egocentric distance whereas this experiment used verbal and perceptual matching tasks. Early research (e.g., Gogel & Tietz, 1973, 1979, Foley, 1977) suggested that distance cue reduction led to underestimated verbal estimation of distance. Therefore it was expected that participants would have a greater degree of underestimation in the simplified environment than in the “real world” environment. In addition, it was possible that a restricted FOV contributed to the space distortion found in the pilot experiment. Thus it was expected that participants would display a greater degree of underestimation in the narrow HFOV conditions.



*Figure 3.* Examples of stimuli used in Expt. 1.

*Note.* Top panel: the simulated “real world” scenario consisted of a vehicle, a stretch of road, blue sky and roadside areas. Bottom panel: the simulated simplified environment consisted of a textured ground surface and a dark sky (the same as the environment used in the pilot study).

### **5.1.1 Methodology**

#### **5.1.1.1 Participants**

Twenty new participants were recruited, aged between 18 and 45 years old with an average age of 25 years ( $SD=7.07$ ). Thirteen were female and seven were male. The recruitment procedure and criteria were the same as that of the pilot study. Ethics approval for this experiment was granted by the Waikato University Ethics Committees and written informed consent

was obtained from all participants prior to the experiment.

#### **5.1.1.2 Design**

The experiment was a within-subjects design study. The independent variables were (a) the simulated backgrounds - a simulated “real world” scenario and a simulated simplified environment, (b) HFOV - 30° and 70° (see Fig. 4) and (c) simulated distance of the car from the participants - 10, 30, 50, 70 and 100 metres. Participants were presented with 10 replications of 20 conditions (2 backgrounds x 2 HFOV x 5 distances) distributed across four experiment sessions. Wide/narrow HFOV conditions were presented in either ABAB or BABA order for each participant where “A” represents a wide HFOV session and “B” represents a narrow HFOV session. Trials within each session were presented in a predefined randomised order. Participants were given five practice trials at the beginning of the experiment without feedback.

#### **5.1.1.3 Stimuli and Apparatus**

Participants were shown simulated outdoor virtual environments, generated using 3Ds-Max (Autodesk). Customised software was written in MatLab (The Mathworks) to display the virtual world on three computer screens. The projected view of the simulated scenes was designed using an eye

height of 1 m for the simulated car driver. The vertical field of view (VFOV) was 27°. The distance between the eye and the display was 60 cm. The target object used in the experiment was a red VW Golf (exterior dimensions: 160.40 in. length, 66.7 in. width and 56.2 in. height). The size of the vehicle was consistent with its location on the plane. Thus the visual angle subtended at the observer's eye was the same as for an actual car at the specified distances.

The displays were presented on a driving simulator consisting of three monitors – one 21 inch (53.34 cm) in the centre, and two 17 inch (43.18 cm) screens on either side (Fig. 4). A chin rest was used as per the pilot study.



*Figure 4.* Driving simulator used in Expt. 1.

*Note.* Left panel: wide HFOV (WHFOV) - 73°. Right panel: narrow HFOV (NHFOV) – 30°.

#### **5.1.1.4 Procedure**

At the beginning of the experiment, instructions and consent forms were given to the participants and the experimental procedures were fully explained to them. They were then given five practice trials without feedback. Participants clicked the OK button on the screen using a mouse to start the experiment trials. The object then appeared on the screen for 10 seconds. Participants were instructed to estimate the distance of the car from themselves. For each trial two judgements were collected. One involved a report of target distance in metres. A rolling number (in metres) appeared on the screen, participants clicked the arrow to select the estimated distance. The other judgement was recorded using a ruler-like scale (Fig. 5). Participants moved the slider and to indicate the distance of



the car. The two judgements were presented in a predefined randomised order. Participants had a five-minute break at the end of each session. At the end of the experiment, three questions were asked to gather data on participants' age, ethnicity and driving experience.



Figure 5. Left panel: reporting of target distance in metres (verbal). Right panel: Perceptual matching response method using a ruler-like scale (scale).

#### 5.1.1.5 Data Analysis

For each participant, linear regression was conducted to calculate the slope of the linear function that relates perceived distance to actual distance for 2 background x 2 HFV conditions. The mean estimated distance was calculated for each participant for the 20 conditions (2 backgrounds x 2 HFOV x 5 distances) and analysed in an analysis of variance (ANOVA).

The scale responses produced numbers from 1-10. As the scale has no reference to units of distance, to summarise the scale results, data was

normalized by Z score transformation for each participant for all conditions and all distances. The mean value of the scale responses was also calculated for each participant for the 20 conditions and analysed in an analysis of variance (ANOVA).

### **5.1.2 Results**

Figure 6 shows the scatter plot of estimated distances against actual distances and the fitted regression line for four conditions (2 backgrounds x 2 HFOV) from a typical participant (Participant 017). See Appendix A for R squared values, F and P values for all participants. 19 out of 20 (95%) participants underestimated distance consistently across all conditions; the slopes of the regression line were less than one (for more details see Table 3). The slopes ranged from 0.05 to 1.16 indicating large individual differences. Among all participants, two grossly underestimated the distances, ten were of the middle range (40-60% underestimation) and three were relatively accurate.

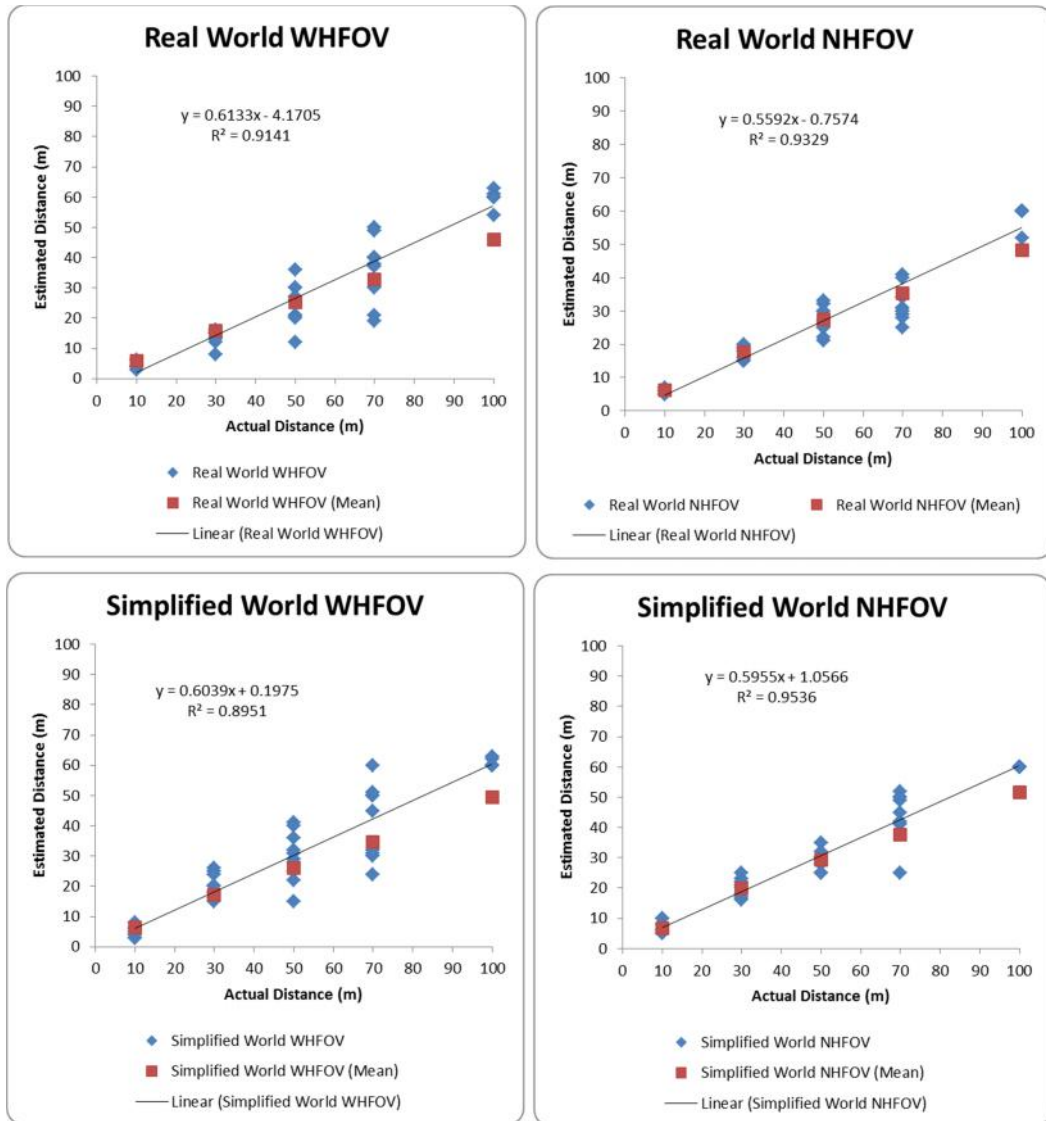


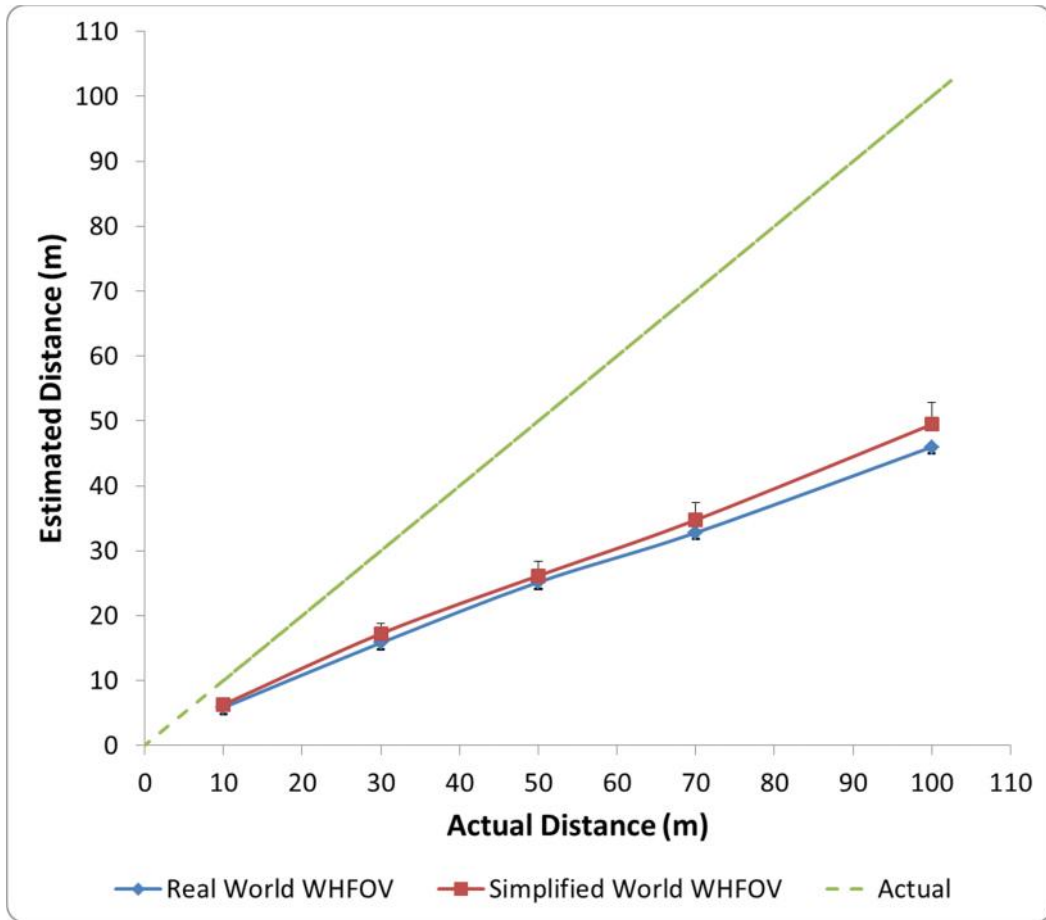
Figure 6. Scatter plot of estimated distances against actual distances and the fitted regression line for four conditions (2 backgrounds x 2 HFOV) from a typical participant (Participant 017) and the group mean (red).

Table 3 *Regression Coefficients between Estimated Distance and Actual*

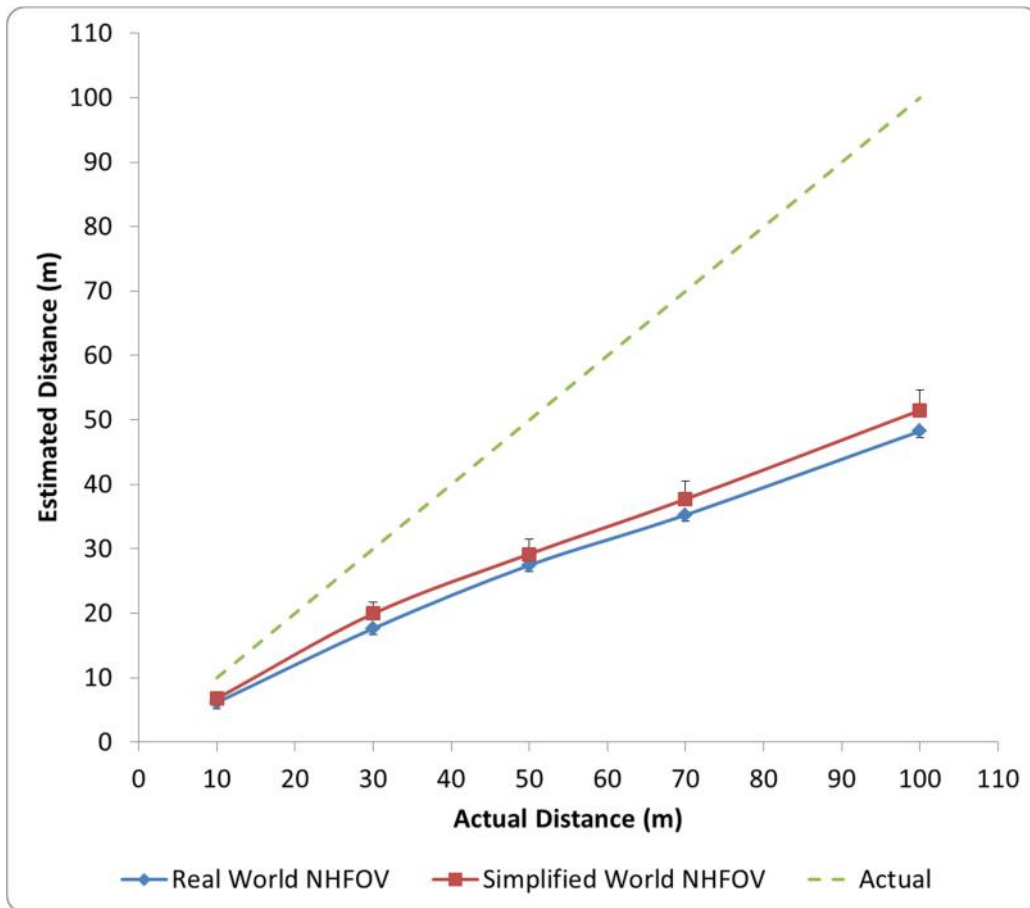
*Distance*

| Par# | WHFOV      |                  | NHFOV      |                  |
|------|------------|------------------|------------|------------------|
|      | Real World | Simplified World | Real World | Simplified World |
| 1    | 0.65       | 0.75             | 0.62       | 0.63             |
| 2    | 0.55       | 0.68             | 0.59       | 0.58             |
| 3    | 0.34       | 0.36             | 0.34       | 0.35             |
| 4    | 0.38       | 0.34             | 0.68       | 0.65             |
| 5    | 0.63       | 0.74             | 0.6        | 0.59             |
| 6    | 0.11       | 0.13             | 0.13       | 0.19             |
| 9    | 0.4        | 0.5              | 0.35       | 0.57             |
| 10   | 0.87       | 1.02             | 0.88       | 1.16             |
| 11   | 0.3        | 0.26             | 0.3        | 0.32             |
| 12   | 0.27       | 0.28             | 0.27       | 0.34             |
| 13   | 0.84       | 0.83             | 0.84       | 0.82             |
| 14   | 0.05       | 0.06             | 0.06       | 0.08             |
| 15   | 0.54       | 0.46             | 0.53       | 0.49             |
| 16   | 0.47       | 0.53             | 0.39       | 0.48             |
| 17   | 0.61       | 0.6              | 0.56       | 0.6              |
| 18   | 0.53       | 0.59             | 0.67       | 0.69             |
| 19   | 0.41       | 0.48             | 0.41       | 0.4              |
| 20   | 0.69       | 0.71             | 0.83       | 0.8              |
| Mean | 0.48       | 0.52             | 0.5        | 0.54             |

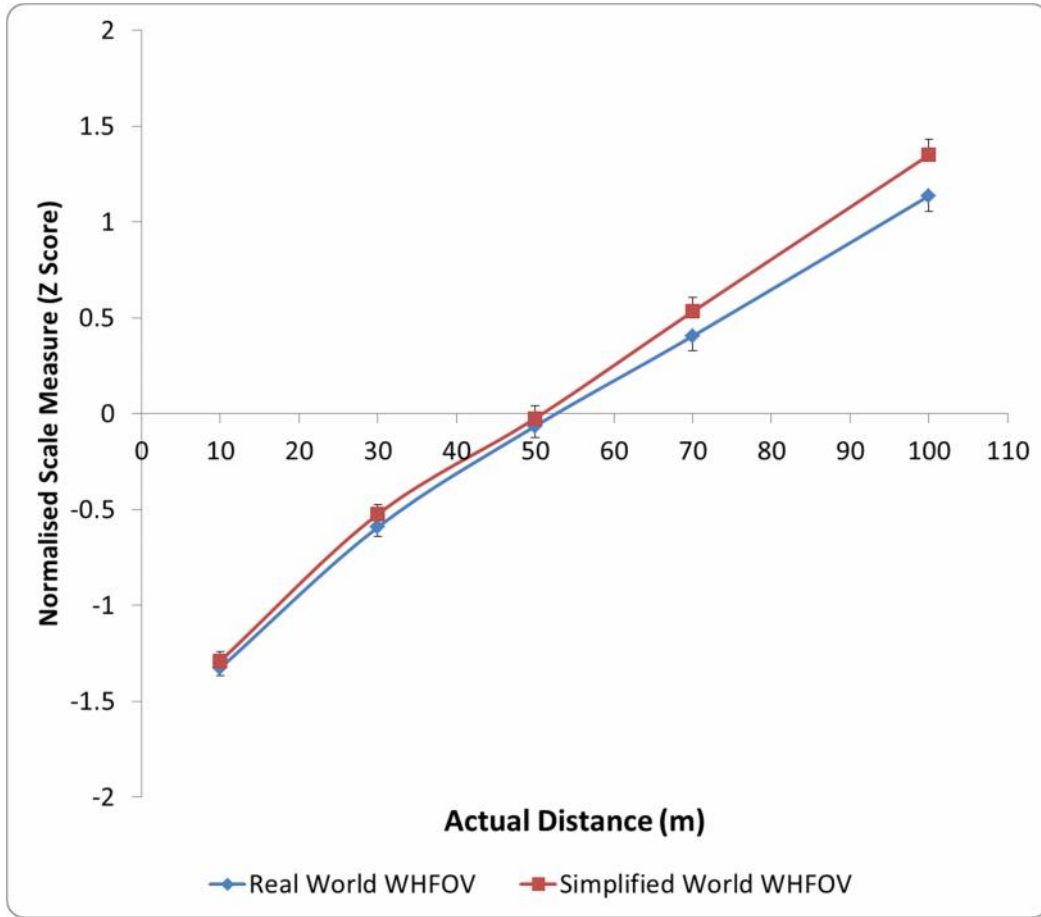
The main effect of background was significant for both forms of judgement ( $F(1, 19) = 19.54, p < .001, \eta_p^2 = 0.507$  for verbal;  $F(1, 19) = 31.34, p < .001, \eta_p^2 = 0.623$  for scale). Participants had greater distance underestimation in the simulated “real world” scenario than in the simulated simplified environment. The main effect of distances was significant for both judgement types ( $F(4, 16) = 21.08, p < .001, \eta_p^2 = 0.840$  for verbal;  $F(4, 16) = 78.43, p < .001, \eta_p^2 = 0.951$  for scale). The estimated distances for different backgrounds are shown as an average across participants in Figures 7 and 8. The normalised scale measurements of distances for different backgrounds averaged across all participants are shown in Figures 9 and 10.



*Figure 7.* The verbal estimations of distances for different backgrounds averaged across all participants in WHFOV. Error bars represent the 95% confidence interval (CI) of the mean.



*Figure 8.* The verbal estimations of distances for different backgrounds averaged across all participants in NHFOV. Error bars represent the 95% confidence interval (CI) of the mean.



*Figure 9.* The normalised scale measurements of distances for different backgrounds averaged across all participants in WHFOV. Error bars represent the 95% confidence interval (CI) of the mean.



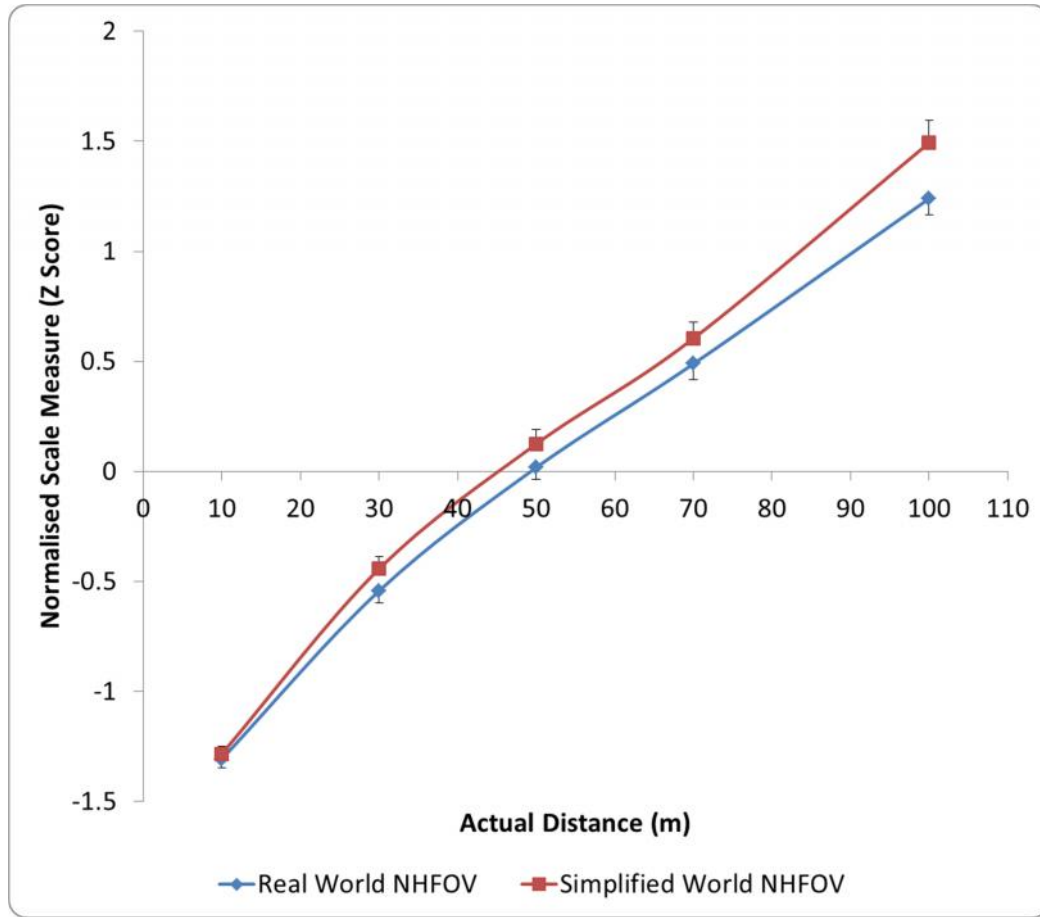


Figure 10. The normalised scale measurements of distances for different backgrounds averaged across all participants in NHFOV. Error bars represent the 95% confidence interval (CI) of the mean.

There was also a significant interaction between background and target distance ( $F(4, 16) = 3.66, p = .027, \eta_p^2 = 0.478$  for verbal;  $F(4, 16) = 7.22, p = .002, \eta_p^2 = 0.664$  for scale judgments). Participants had greater distance underestimation especially when the targets were further away. In addition, the main effect of HFOV was not significant for both judgments ( $F(1, 19) = 3.51, p = .077, \eta_p^2 = 0.156$  for verbal;  $F(1, 19) = 1.42, p = .248,$

$\eta_p^2=0.070$  for scale).

Correlation analysis of the two methods was conducted. It was found that the two methods correlate well at individual participant level (Table 4). The correlation coefficient dropped when it was calculated for each condition (Table 5). This was expected as the individual variance of scale measurement leads to lower correlation coefficients.

Table 4 *Correlation Coefficients between verbal estimation and scale measurements for each participant*

| Participants | WHFOV      |                  | NHFOV      |                  |
|--------------|------------|------------------|------------|------------------|
|              | Real World | Simplified World | Real World | Simplified World |
| 1            | 0.99       | 0.98             | 0.99       | 1.00             |
| 2            | 0.99       | 0.99             | 0.96       | 0.98             |
| 3            | 0.97       | 0.95             | 0.98       | 0.97             |
| 4            | 0.86       | 0.83             | 0.85       | 0.86             |
| 5            | 0.92       | 0.92             | 0.93       | 0.94             |
| 6            | 0.99       | 0.96             | 0.86       | 0.91             |
| 7            | 0.90       | 0.96             | 0.97       | 0.98             |
| 8            | 1.00       | 1.00             | 0.99       | 0.99             |
| 9            | 0.84       | 0.88             | 0.89       | 0.94             |
| 10           | 0.99       | 0.99             | 0.97       | 0.96             |
| 11           | 0.97       | 0.97             | 0.99       | 0.99             |
| 12           | 0.89       | 0.97             | 0.94       | 0.94             |
| 13           | 0.95       | 0.97             | 1.00       | 1.00             |
| 14           | 0.99       | 0.99             | 0.97       | 0.97             |
| 15           | 0.97       | 0.95             | 0.94       | 0.94             |
| 16           | 0.97       | 0.99             | 0.83       | 0.91             |
| 17           | 0.98       | 0.96             | 0.98       | 0.98             |
| 18           | 0.99       | 0.99             | 0.98       | 0.97             |
| 19           | 0.96       | 0.97             | 0.98       | 0.98             |
| 20           | 0.97       | 0.98             | 0.96       | 0.96             |

Table 5 *Correlation Coefficients between verbal estimation and scale measurements for each condition*

| <b>FOV</b> | <b>Cue Condition</b> | <b>Correlation Coefficient</b> |
|------------|----------------------|--------------------------------|
| WHFOV      | Real World           | 0.71                           |
| WHFOV      | Simplified World     | 0.71                           |
| NHFOV      | Real World           | 0.71                           |
| NHFOV      | Simplified World     | 0.71                           |

### **5.1.3 Discussion**

First, there was reliable distance compression in all conditions for all but one participant. Even though this experiment used a car for a target, the findings were consistent with other studies of distance estimation in VE (Witmer & Kline, 1997; Witmer & Kline, 1998; Witmer & Sadowski, 1998; Sinai et al., 1999; Knapp, 1999; Willemsen & Gooch, 2002; Loomis & Knapp, 2003; Thompson et al., 2004; Creem-Regehr et al., 2005; Messing & Durgin, 2005; Richardson & Waller, 2007; Sahm et al., 2005). The mean slope of the function that related the estimated distance to the actual distance for all participants was approximately 0.5, at the lower end of the range of estimated distance found in these studies (42% to 93% of actual distance).

Many researchers have suggested that a restricted FOV leads to distance estimation in Virtual Environment (Witmer & Sadowski, 1998; Knapp, 1999;

Kline & Witmer, 1996). In contrast, other researches have suggested that a restricted FOV alone cannot explain the distance underestimation found in VE, especially when head rotation is allowed (Knapp & Loomis, 2004; Messing & Durgin, 2005; Creen-Regehr et al., 2005). It is interesting that in this experiment, the main effect of FOV was not significant for both judgement types. Therefore the results agree with the suggestion that a restricted horizontal FOV alone cannot explain the distance underestimation found in VE.

There was one subtle surprising aspect of the results. Participants performed slightly better in the simplified VE. The simplified VE was considered to be a reduced cue condition. Previous studies found that participants tended to underestimate distance in reduced cue conditions when the target was farther than 3m (e.g., Loomis et al., 1999). The real world condition also provided a more familiar environment. Participants were expected to utilize the relative size of the target vehicle more effectively in the “real world” scenario than in the simplified environment. Therefore it was expected that participants would have greater distance underestimation under reduced cue conditions and not vice versa.

Two other studies compared distance estimation in a realistic VE with distance estimation in VE with reduced geometry and visual details.

Thompson et al. (2004) found that distance estimations in three different VE conditions did not vary much from each other: 360° high-resolution panoramic images, low-quality texture-mapped computer graphics, and wireframe renderings. Kunz et al. (2009) on the other hand, found that the quality of graphics had a significant effect on verbal judgements of distance. Estimates were greater for the high-quality environment than for the low-quality environment (reduced geometry and very little visual detail, similar to the simplified VE used in Expt. 1). However, this finding was very different from the results of Expt. 1, where participants performed slightly better in the simplified VE.

There were two major differences in methodology between Expt. 1 and these two studies. Both Thompson et al. (2004) and Kunz et al. (2009) investigated distance estimation in action space (2-30 m) using HMD, but in Expt. 1 participants estimated distance mostly in vista space. Additionally, in Expt. 1 the VEs were presented using CRT monitors. There are a number of differences between HMD and CRT monitors. For example, a HMD provides stereoscopic viewing which is unavailable with CRT monitors. HMD also restricts a participant's FOV. Moreover, a HMD has significant weight which often lies off-centre of a participant's head causing a tipping torque (Willemsen et.al, 2009). However, none of these characteristics can

easily explain the difference in distance estimation in simplified VEs between this experiment and the experiments of Thompson et al. (2004) and Kunz et al. (2009).

It has been suggested that the effectiveness of visual depth cues vary according to the locations of the target in the world. For example, the effect of accommodation and motion parallax effects tend to diminish out beyond 2 m (Beall et al., 1995). However, binocular disparity is an effective absolute depth cue within action space (Foley, 1980). Thus the difference in verbal estimation of distance in simplified VEs between Expt. 1 and the Kunz et al (2009) experiment might be attributed to the different depth cues adopted by the participants in different distance regions.

## **Chapter 6 Effect of Backgrounds**

### **6.1 Expt. 2. Background Manipulation**

Significant amounts of distance compression were found in all conditions in Expt. 1. However, participants performed better in the simplified VE which is a counterintuitive result similar to the static versus motion result of Hiro (1996). Normally one would expect that adding more realism to a scene should improve perceptual skills such as distance estimation. Adding detail to VE scenes is computationally and labour intensive so it is of significant

interest to software designers if the addition of extra detail not only does not improve performance but actually diminishes it.

Therefore Expt. 2 further investigated the effect of environmental context on distance estimation. It was an extension of the first experiment and it compared participants' distance estimation performance in six environments where a number of visual cues were manipulated. The purpose of this experiment was to answer the following questions:

1. Does the road itself have any impact on distance estimation (with/without the road scenarios, and wide/narrow road scenarios)?

These conditions were designed to examine the impact of linear perspective on distance estimation.

2. What effect does the size and density of the ground plane texture have on participants' performance (big/small texture scenarios)? As discussed in Chapter 2 it is unclear whether texture patterns have an effect on distance estimation. Witmer and Kline (1998) found that the estimated distance was more accurate when the texture pattern under the target was a brick pattern (medium density) compared to grass (low density) or carpet (high density). Sinai et.al. (1999) suggested that this improvement can be attributed to the brick pattern's symmetry or its density. In this experiment two black and



white conditions were used to examine the impact of the size and density of the texture pattern. The Background 4 (B&W Texture 2) condition (Fig. 11) was the same simplified environment used in previous experiments. The Background 5 (B&W Texture 0.5) condition contained textures that were four times smaller than those in Background 4. By manipulating the size of the texture pattern, the density of the texture pattern was also changed.

3. The simplified scenes in the previous experiments produced better performance. Taken to the extreme, one may well ask what would the participants' performance be if tested in an environment that has no textured ground plane at all under the car? The Horizon-only condition was very similar to the "open space" condition used in the experiment of Armbrüster et al. (2008) where the combination of the green floor and blue sky resulted in an induced horizon. As it was found in Expt. 1 that participants performed better in the simplified VE, participants were expected to perform even better in this condition which contained even fewer cues than the simplified VE condition in Expt. 1.

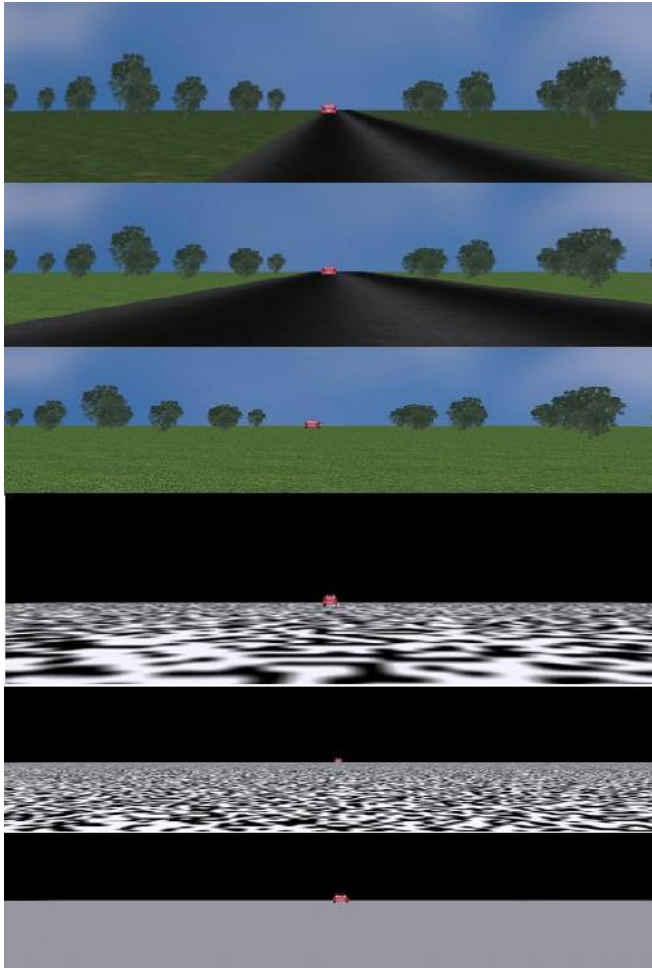


Figure 11. Examples of stimuli used in Expt. 2.

Note. From the top down: Background 1 (Real World): the simulated “real world” scenario; Background 2 (Real World Wider Road): the road was twice as wide as the road in Background 1; Background 3 (Real World No Road); Background 4 (B&W Texture 2): the simulated simplified environment; Background 5 (B&W Texture 0.5): the simulated simplified environment; and Background 6 (Horizon-only): the simulated simplified environment consisted of a grey ground surface and a dark sky.

## **6.1.1 Methodology**

### **6.1.1.1 Participants**

Thirty-one new participants were recruited, aged between 18 and 66 years old with an average age of 26 years ( $SD=10.28$ ). Fifteen were female and 16 were male. All participants had normal or corrected-to-normal visual acuity. All were naïve to the purpose of the study. All participants had more than 1 year driving experience in New Zealand. Participants from the PSYC 103 class at the University of Waikato received one course credit for research participation. Other participants received a \$10 MTA voucher for one hour research participation. Ethics approval for this experiment was granted by the Waikato University Ethics Committees and written informed consent was obtained from all participants prior to the experiment. One male participant was later removed from the data set because of technical errors with the recording equipment.

### **6.1.1.2 Design**

The experiment was a within-subjects design study. The independent variables were (a) the simulated backgrounds and (b) simulated distance of an object from the participants - 10, 30, 50, 70 and 100 metres. Participants were presented with six replications of 30 conditions (6 backgrounds x 5

distances) in a total of three experiment sessions. For half of the participants trials within each session were presented in a predefined randomised order, for the other half trials were presented in a predefined order. Participants were given five practice trials at the beginning of the experiment.

#### **6.1.1.3 Stimuli and Apparatus**

The stimuli and apparatus used in this experiment were the same as those used in Expt. 1. All scenes were generated using 3Ds-Max. The simulated scenes were designed using an eye height corresponding to a car driver (1 m). The vertical field of view (VFOV) was 27° and the horizontal field of view (HFOV) was 30°. The distance between the eye and the display was 60 cm. The object used in the experiment was a red VW Golf. The size of the vehicle is consistent with its location on the plane, i.e., simulated distance from the participants.

#### **6.1.1.4 Procedure**

The procedure was the same as that of Expt. 1.

#### **6.1.1.5 Data Analysis**

For the judgement involving a report of target distance in metres (verbal),

estimated distances were plotted as a function of the actual distances and fitted linear regressions to the data points. The slope of the fitted regression indicated the accuracy of the distance estimation. The mean estimated distance was calculated for each participant for the total 180 conditions (6 backgrounds x 5 distances x 6 replication orders) and analysed in an analysis of variance (ANOVA).

The scale responses produced numbers from 1-10. Data was normalized by Z score transformation for each participant for all conditions and all distances. The mean value of the scale judgement was also calculated for each participant for the 180 conditions and analysed in an analysis of variance (ANOVA). Pairwise comparison of the main effect of backgrounds was also conducted using a Bonferroni correction for P value adjustments. Furthermore, for both judgements presentation order was tested as a between-subjects factor (i.e., randomised or predefined). Finally, for verbal judgement, a between-subjects analysis was conducted to compare estimations between Expt. 1 and Expt. 2 for two conditions, Real World and B&W Texture 2.

### **6.1.2 Results**

Figure 12 shows the scatter plot of estimated distances against actual distances and the fitted regression line for six backgrounds from a typical

participant (Participant 001). See Appendix B for R squared values, F and P values for all participants.

In Expt. 2, 19 out of 30 (63%) participants underestimated distance consistently across all conditions; the slopes of the regression line were less than one (for more details see Appendix C). The slopes ranged from 0.16 to 10.83 again indicating large individual differences. Figure 13 shows the average estimated distances for different backgrounds across all but participants. 23 and 28. Figure 14 shows the normalised scale measurements of distances for different backgrounds averaged across all but participants 023 and 028. These two participants overestimated the distance by over 100% and would distort the overall patterns if included. Their data was also excluded from the between-subjects analysis. Notably, compared with the first experiment a higher percentage of participants had relatively accurate estimation. A between-subjects comparison indicated significant difference between Expt. 1 and Expt. 2 ( $F(1, 48) = 5.94$ ,  $p = .019$ ,  $\eta_p^2 = 0.11$ ), with participants performing better in Expt. 2.

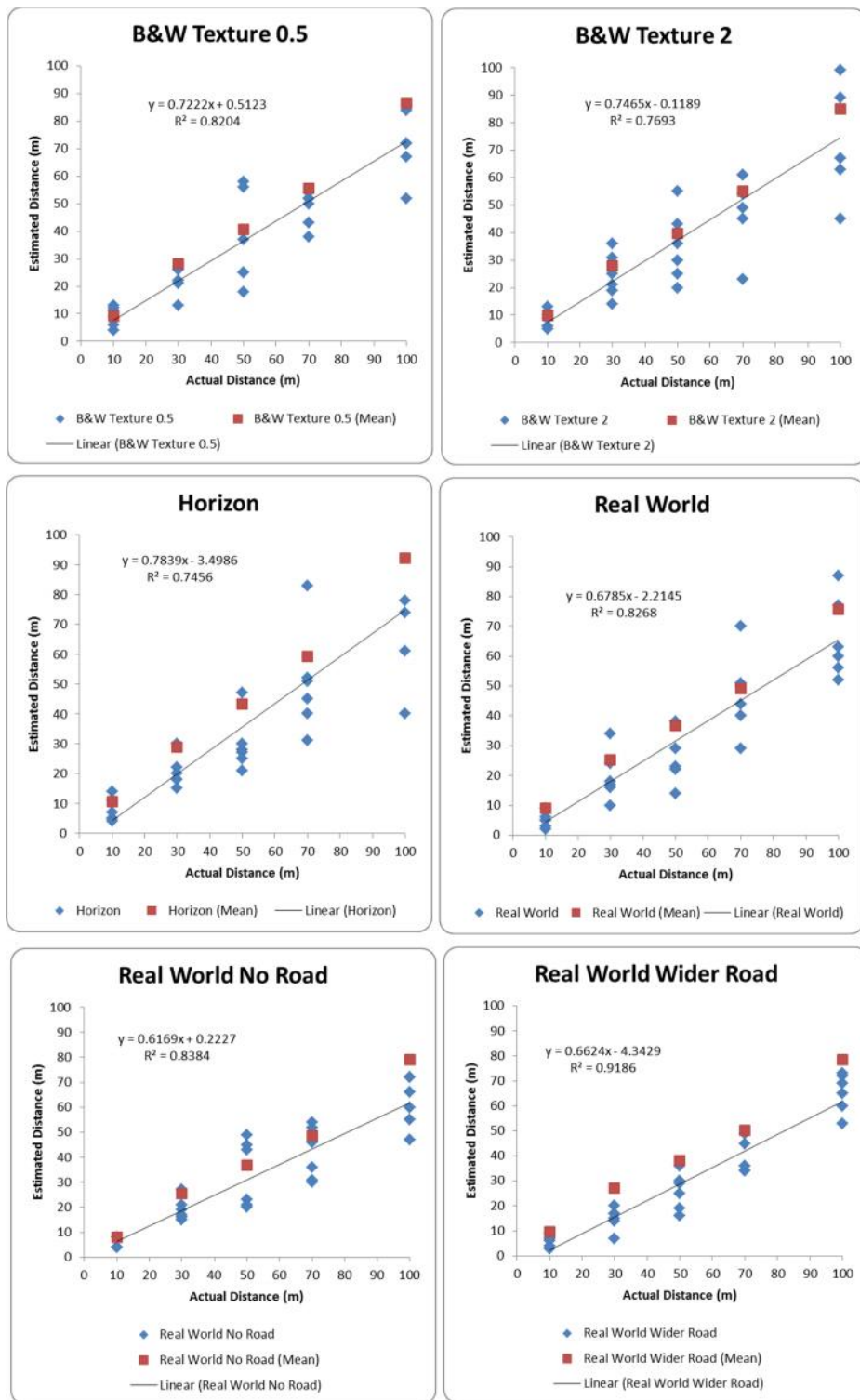


Figure 12. Scatter plot of estimated distances against actual distances and the fitted regression line for six backgrounds from a typical participant (Participant 001) and the group mean (red).

For both judgements, significant main effects were found for the backgrounds ( $F(5, 24) = 3.66, p = .013, \eta_p^2 = 0.432$  for verbal judgement;  $F(5, 24) = 9.24, p < .001, \eta_p^2 = 0.658$  for scale judgement), and the distances ( $F(4, 25) = 26.44, p < .001, \eta_p^2 = 0.809$  for verbal judgement;  $F(4, 25) = 100.54, p < .001, \eta_p^2 = 0.941$  for scale judgement). There was a significant interaction between background and target distance, but only for the scale judgements ( $F(20, 9) = 3.06, p = .026, \eta_p^2 = 0.890$ ). For the verbal judgement, although the interaction was not significant ( $F(20, 9) = 1.61, p = .234, \eta_p^2 = 0.782$ ), the large effect size (Partial Eta Squared) value suggested that this could be due to the limited sample size. Thus overall the further away the target was, the bigger the difference was between the backgrounds. Furthermore, significant main effects were found for replication order for scale judgement ( $F(5, 24) = 3.49, p = .016, \eta_p^2 = 0.420$ ), but not for verbal judgement ( $F(5, 24) = 0.59, p = .706, \eta_p^2 = 0.110$ ), which again may be attributed to the limited sample size. Finally, it was found that presentation order, randomised or predefined, had no significant effect on participants' estimation.



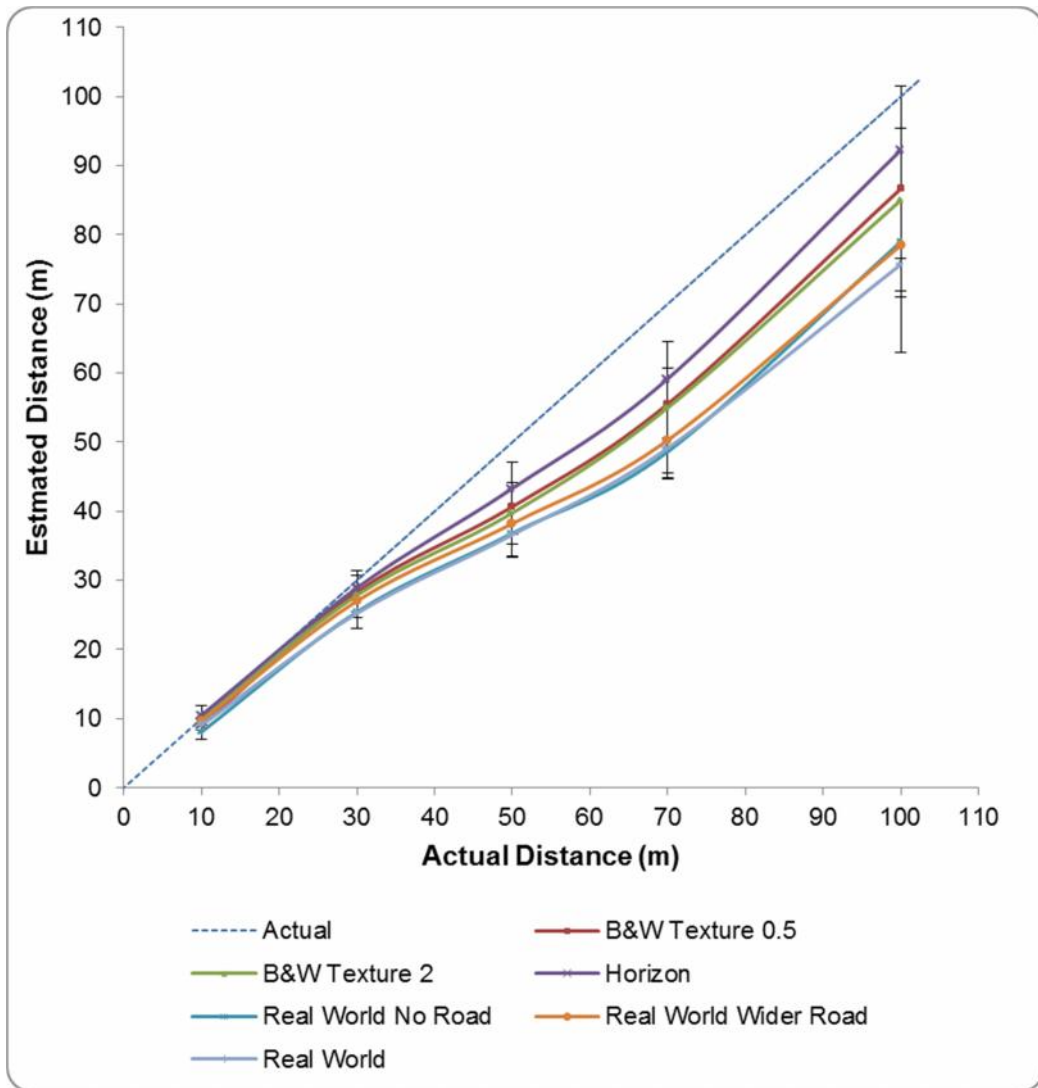


Figure 13. The estimated distances for different backgrounds averaged across all but participants 023 and 028. Error bars represent the 95% confidence interval (CI) of the mean.

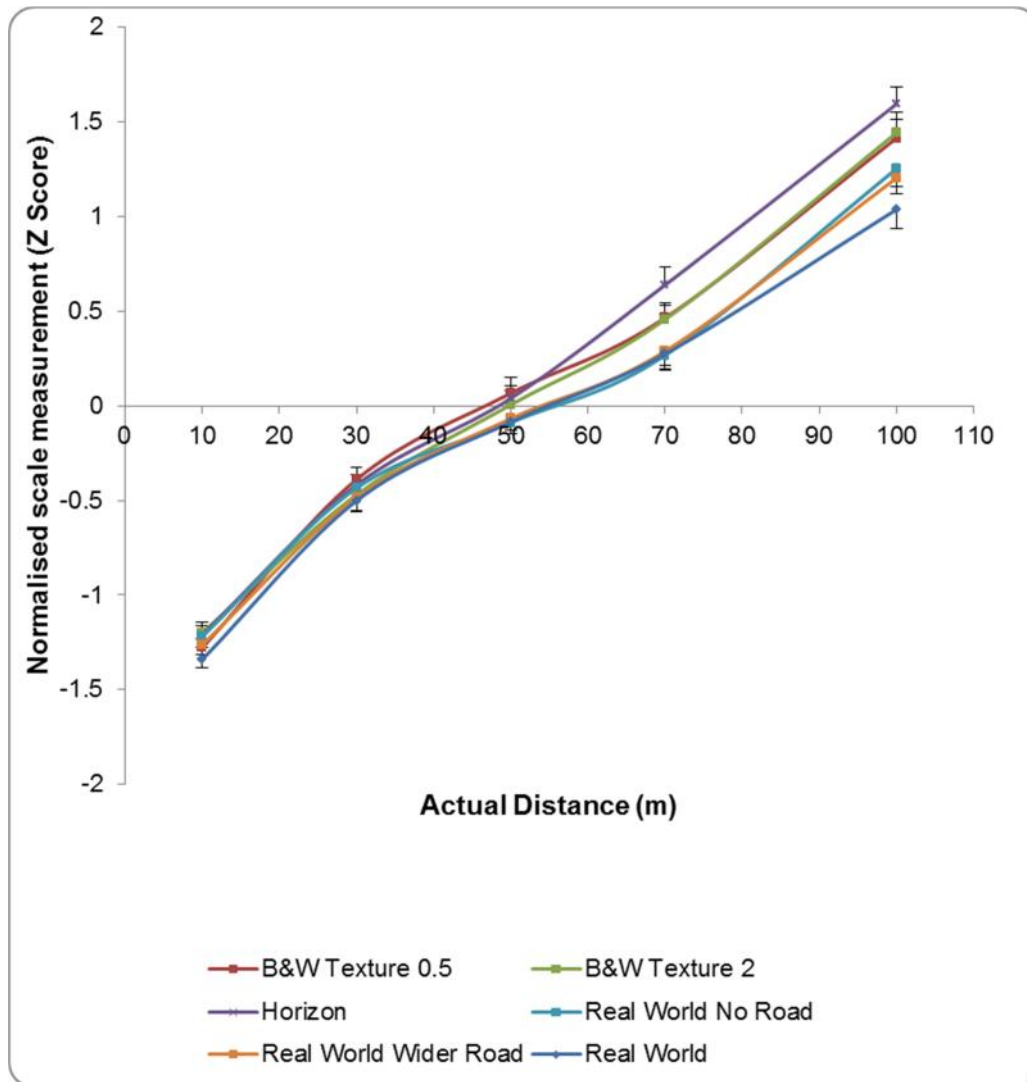


Figure 14. The normalised scale measurements of distances for different backgrounds averaged across all but participants 023 and 028. Error bars represent the 95% confidence interval (CI) of the mean.

For verbal judgements, pairwise comparison of the main effect of backgrounds showed a significant difference between the Horizon-only condition (Background 6) and the Real World condition (Background 1) ( $p=.041$ ), between the Horizon-only condition (Background 6) and the Real World Wider Road condition (Background 2) ( $p=.01$ ) and between the

Horizon-only condition (Background 6) and the Real World No Road condition (Background 3) ( $p=.02$ ). The targets were perceived as being closer in the simulated “real world” (Background 1, 2 and 3) than in the simulated simplified Horizon-only condition (Background 6). There was no significant difference between the other conditions.

For scale judgements, pairwise comparison of the main effect of backgrounds showed significant differences between the Horizon-only condition (Background 6) and the Real World condition (Background 1) ( $p<.001$ ), between the Horizon-only condition (Background 6) and the Real World Wider Road condition (Background 2) ( $p<.001$ ) and between the Horizon-only condition (Background 6) and the Real World No Road condition (Background 3) ( $p<.001$ ). As with the verbal judgements, the cars were perceived as being closer in the simulated “real world” (Background 1, 2 and 3) than in the simplified Horizon-only condition (Background 6).

Significant differences were also found between the B&W Texture 0.5 condition (Background 5) and the Real World condition (Background 1) ( $p<.001$ ), between the B&W Texture 0.5 condition (Background 5) and the Real World Wider Road condition (Background 2) ( $p=.002$ ), between the B&W Texture 0.5 condition (Background 5) and the Real World No Road condition (Background 3) ( $p=.024$ ), between the B&W Texture 2 condition

(Background 4) and the Real World condition (Background 1) ( $p < .001$ ), between the B&W Texture 2 condition (Background 4) and the Real World Wider Road condition (Background 2) ( $p = .004$ ) and between the B&W Texture 2 condition (Background 4) and the Real World No Road condition (Background 3) ( $p = .014$ ). The car targets were perceived as being closer in the simulated “real world” (Background 1, 2 and 3) than in the simulated simplified conditions (Background 4 and 5).

Furthermore, there were significant differences between the Real World No Road condition (Background 3) and the Real World condition (Background 1) ( $p = .019$ ), between the B&W Texture 2 condition (Background 4) and the Horizon condition (Background 6) ( $p = .011$ ). There was no significant difference between the other conditions tested.

### **6.1.3 Discussion**

One of the purposes of this experiment was to investigate the effect of the size of the ground texture on egocentric distance estimation. No significant difference was found between Background 4 (large textures) and Background 5 (small textures). This suggests that the size of the texture on the ground had a limited effect on the participants' distance estimation. This is consistent with Witmer and Kline (1998)'s findings. They investigated the effect of depth cues on distance estimation and found that floor texture had

no significant effect on participants' performance. Combined with the Expt. 2 results it is reasonable to conclude that in VEs, the size of the ground texture patterns has little or no effect on distance estimation within both action and vista space.

In contrast to the texture patterns used in the conditions for Background 4 and 5, the roads presented in Background 1 (wide road) and Background 2 (narrow road) are more relevant to driving and could have been used to determine the relative size of the target vehicle. One would expect that the width of the road could have an effect on the perceived size of the car and hence on its perceived distance away. However, it was found that there was no significant difference between Background 1 and 2, thus suggesting that the width of the road had no effect. This may not be such a surprising result given that people often drive on roads of varying width (e.g., highways versus urban roads) and may be adapted to the difference.

Again, somewhat counter-intuitively, participants performed better in the simplified VE conditions in this experiment compared to the "real world" condition ("full-cue"), especially in the Horizon-only case. As suggested above, in the simplified VE conditions the limited availability of various depth cues may have forced participants to adopt any available visual cues in vista space. Only three visual cues were available in the Horizon-only

condition: angular declination from the horizon, familiar size and visual contrast. Participants therefore had no choice but to attend to these cues. Messing and Durgin (2005) investigated the use of angular declination from the horizon in VEs and found it to be an effective egocentric distance cue. The familiar size cue can specify egocentric distance even when the target is far away from observers. However, Predebon and Woolley (1994) suggested that familiar size is not a major determinant of distance estimation. Non-perceptual factors mediate the effects of familiar size when using direct measurement (e.g., verbal reports) of perceived distance. Alternatively participants might have been influenced by the visual contrast of the target when estimating distance. The simplified VE conditions all had a dark sky as opposed to the brighter blue sky in the real world conditions. The contrast between the car and the background sky was very different between the simplified conditions and the real world conditions (see Fig. 11). There was less contrast in the simplified condition. Low contrast is often used as a cue to large distances (e.g., aerial perspective). By using visual contrast as a distance cue participants may have been inclined to judge the car in the simple VE conditions as being further away than in the real world conditions.

In Expt. 1, reliable distance compression was found in all conditions for all

but one participant. Participants performed better in the simplified VE. Expt. 2 further investigated the effect of environmental context on distance estimation. Compared with Expt. 1, the percentage of participants consistently underestimating distance in all conditions dropped from 95% to just over 60%. Two participants grossly overestimated the distance. It was found that participants performed better in Expt 2 than in the Expt 1. As discussed above the participants tended to make more accurate estimation of distance in the Horizon-only condition. Therefore one possibility is that the introduction of the Horizon-only condition (Background 6) somehow affected the participants' estimation in other conditions and improved their overall performance. Two previous studies have found that the presence of one environmental context can affect participants' distance estimation in other environmental contexts. Witt et al., (2007) found that the environmental context had a significant effect on participants' distance estimation when participants viewed the targets and performed the tasks in the opposite end of the environment (e.g., at two different ends of a hallway). However, when participants performed blind walking tasks in order to estimate distance in the same end of the hallway as the targets, environmental context had no significant effect. Witt et al., (2007) suggested that this could be attributed to the absence of a comparison between the two ends of the hallway. Ziemer et al. (2009) found that a

carry-over effect can confound experimental results (i.e., distance estimation in other environmental contexts). It is possible therefore that in this experiment the participants compared stimuli across conditions when estimating distances. Compared with the Horizon-only condition, participants had a greater degree of underestimation in all other conditions. The Horizon-only cars were judged to be the furthest away. Therefore the introduction of the Horizon-only condition might have contributed to the overall improvement of distance estimation in Expt. 2 compared with Expt. 1. One other possibility is that the apparent improvement is due to individual differences and the limited sample size. As mentioned previously, verbal estimation of distance in the real world tends to be more variable than action based measures of distance (Pagano & Bingham, 1998; Pagano et al., 2001; Kelly et al., 2004; Andre & Rogers, 2006). Inter-individual differences have also been found in verbal estimation of distance in VEs (Armbrüster et al., 2005).

In both Expt. 1 and 2, three CRT monitors were used to display stimuli. CRT and LCD monitors cannot display life size virtual objects; neither can they block out visual information from the real world (Brooks, 1999). Thus they have limited ability to create the illusion of immersion. Another issue with using a CRT or an LCD monitor is that potentially it can cause visual cue



conflicts that can affect distance estimation. Accommodation and convergence are often considered to be weak cues for absolute distance (Beall et al., 1995) as they do not directly provide information about absolute distance beyond a few metres. However, it is possible that depth perception of nearby locations obtained from accommodation and convergence is combined with other distance information to scale space, thus impacting on distance estimation. For example, Bingham et al. (2001) found that the discrepancy between accommodative distance of HMD and the target distances led to overreaching to near targets. They have suggested that it is possible that a discrepancy in the opposite direction could result in underestimation of distances.

Another problem with using a CRT or LCD monitor is the restricted FOV. In Expt. 1, it was found that HFOV had no effect on participants' distance estimation in VEs displayed on CRT monitors. However, it is still possible that the limited vertical FOV of the CRT monitors could have produced the distance underestimation found in the study. Kline and Witmer (1996) and Wu et al. (2004) suggested that when combined with restrictions on head movement, vertical FOV restrictions resulted in a significant underestimation of distance. However, it was found that a restricted vertical FOV did not affect distance estimation when head movement was allowed

(Knapp & Loomis, 2004). Free head movement enables participants to see the entire environment even under restricted FOV. However, as CRT or LCD monitor cannot block out visual information from the surrounding environment, even with unrestricted head movement, people will not be able to gather more relevant visual information other than that presented on screen.

Finally, observers may not be able to use absolute eye-height scaling effectively in VEs displayed on CRT and LCD monitors, as the use of these monitors could lead to a dissociation between the horizon and one's own eye height (Dixon et al. 2000). Eby and Braunstein (1995) found that a visible frame surrounding CRT and LCD screens reduced perceived depth of the 3D scene. Dixon et al. (2000) investigated the eye-height scaling of absolute size in comparable immersive (presented in a HMD) and non-immersive (presented on TV screen) conditions. Dixon et al. (2000) found that participants made more accurate size judgements in immersive viewing conditions than in non-immersive conditions. Furthermore, more participants perceived that they were a part of the environment in immersive viewing conditions than in non-immersive conditions. The underestimation of distance among some participants and the significant differences between backgrounds found in the previous two experiments might be

attributed to the parameters of the CRT displays, altering spatial depth cues such as accommodation and familiar size, and their inability to create the illusion of immersion. This was investigated in the next experiment where participants estimated distance in a VE displayed using an immersive environment. In addition, the effect of contrast on distance estimation was also examined in more detail.

## **Chapter 7 Immersion**

### **7.1 Expt. 3 Distance Estimation Using an Immersive Display**

This experiment was carried out using the University of Waikato's driving simulator consisting of a complete automobile (BMW 314i) positioned in front of three angled projection surfaces (shown in Fig. 15). It compared participants' distance estimation performance in five different environments (i.e., the target car's background scene was varied as per Fig. 16). In the last two experiments, participants performed better in the simplified VE conditions, especially in the Horizon-only condition. This might be attributable to the parameters of the CRT displays and the fact that the participants were viewing the displays from relatively close up. The driving simulator uses display screens that are more than 2m away from the

observer and so depth cues such as accommodation should be minimised. In Expt. 3, four conditions from Expt. 2 were used in order to compare the different display types and to test the effect of display distance and properties on the target distance estimates. Additionally, a daylight condition was incorporated into the design to examine the effect of background contrast on distance estimation.

The driving simulator used in this experiment provided more realistic and consistent visual information (as opposed to conflicting depth cues). It has been suggested that the peripheral scenery provided by the CAVE VR system (similar to the driving simulator used here) contributed to the relatively accurate distance estimation found by Klein et al. (2006). Using a large screen also improves spatial knowledge of the targets in VEs and this can be attributed to the more immersive nature of large screens (Bakdash et al., 2006). The purpose of Expt. 3 was to examine whether the underestimation of distance and the significant differences between backgrounds found in the previous two experiments remain the same in a more immersive environment where cue conflicts have been minimised.



Figure 15. The University of Waikato's driving simulator.

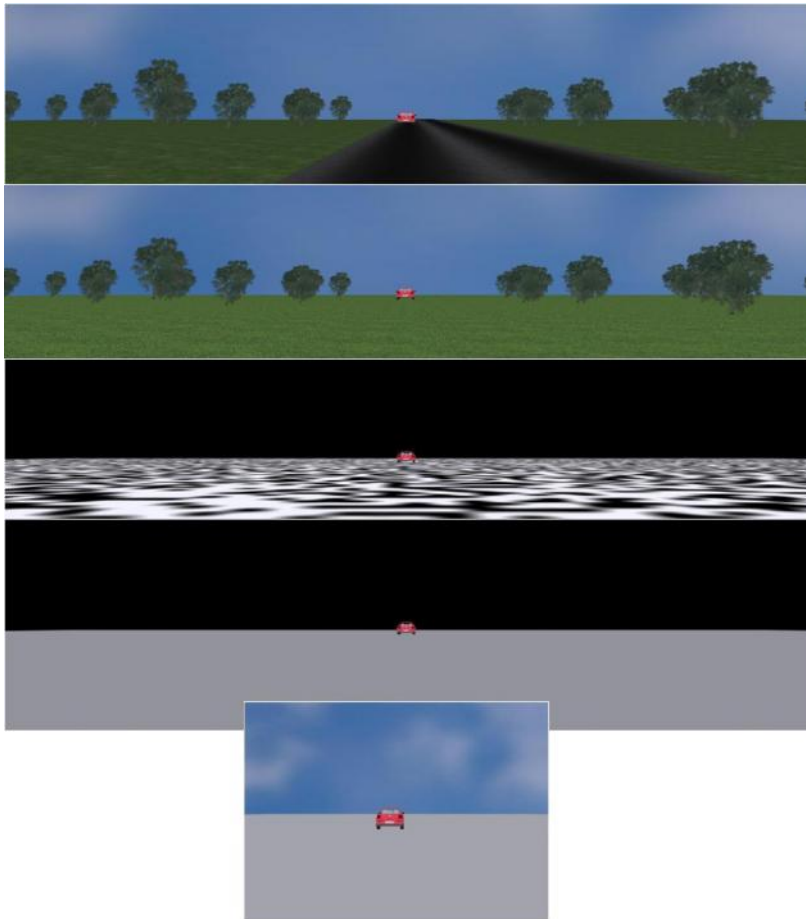


Figure 16. Examples of stimuli used in Expt. 3.

*Note.* From the top down: Background 1 (Real World): the simulated “real world” scenario; Background 2 (Real World No Road); Background 3 (B&W Texture); Background 4 (Horizon-only): the simulated simplified environment consisted of a grey ground surface and dark sky; Background 5 (Daylight Horizon): the simulated simplified environment consisted of a grey ground surface and blue sky. (The picture is only a screen-shot of the condition displayed on the centre projection screen. It is not intended to indicate a narrow field of view).

### **7.1.1 Methodology**

#### **7.1.1.1 Participants**

Nineteen new participants were recruited, aged between 19 and 52 years old with an average age of 31 years ( $SD=10.16$ ). Ten were female and nine were male. The recruitment procedure and criteria were the same as that of Expt. 2. Ethics approval for this experiment was granted by the Waikato University Ethics Committees and written informed consent was obtained from all participants prior to the experiment.

#### **7.1.1.2 Design**

The experiment used a within-subject design. The independent variables were (a) the simulated backgrounds (b) simulated distance of an object

from the participants - 10, 30, 50, 70 and 100 metres. Participants were presented with six replications of 25 conditions (5 backgrounds x 5 distances) within three experiment sessions; that is each participant undertook 150 trials. Trials within each session were presented in a predefined randomised order. Participants were given five practice trials at the beginning of the experiment.

### **7.1.1.3 Stimuli and Apparatus**

The experimental apparatus was the University of Waikato's driving simulator consisting of a complete automobile (BMW 314i) positioned in front of three angled projection surfaces (shown in Fig. 15). The centre projection surface was located 2.42 m in front of the driver's seat with two peripheral surfaces connected to the central surface at 62° angles. The entire projection surface was angled back away from the driver at 14° (from the bottom to the top of the projection surface) and produced a 175° (horizontal) by 41° (vertical) forward view of the simulated roadway from the driver's position. The image projected on the central surface measured 2.64 m wide by 2.10 m high (at a resolution of 1280 by 1024 pixels) and each of the two peripheral images measured approximately 2.65 m by 2.00 m (at resolutions of 1024 by 768 pixels). The object used in the experiment was once again a red VW Golf.

#### **7.1.1.4 Procedure**

The procedure was the same as that of Expt. 1 and 2.

#### **7.1.1.5 Data Analysis**

The analysis process was the same as that used for Expt. 2. For verbal judgements a between-subjects analysis was conducted to compare estimations between Expt. 1 and Expt. 2 and between Expt. 2 and Expt. 3 for two conditions, Real World and B&W Texture.

#### **7.1.2 Results**

Figure 17 shows the scatter plot of estimated distances against actual distances and the fitted regression line for five backgrounds from a typical participant (Participant 015). See Appendix D for R squared values, F and P values for all participants. In Expt. 3, 13 out of 19 (68%) participants underestimated distance consistently across all conditions; the slopes of the regression line were less than one (for more details see Table 6). The slopes ranged from 0.10 to 2.49, again indicating large individual differences.



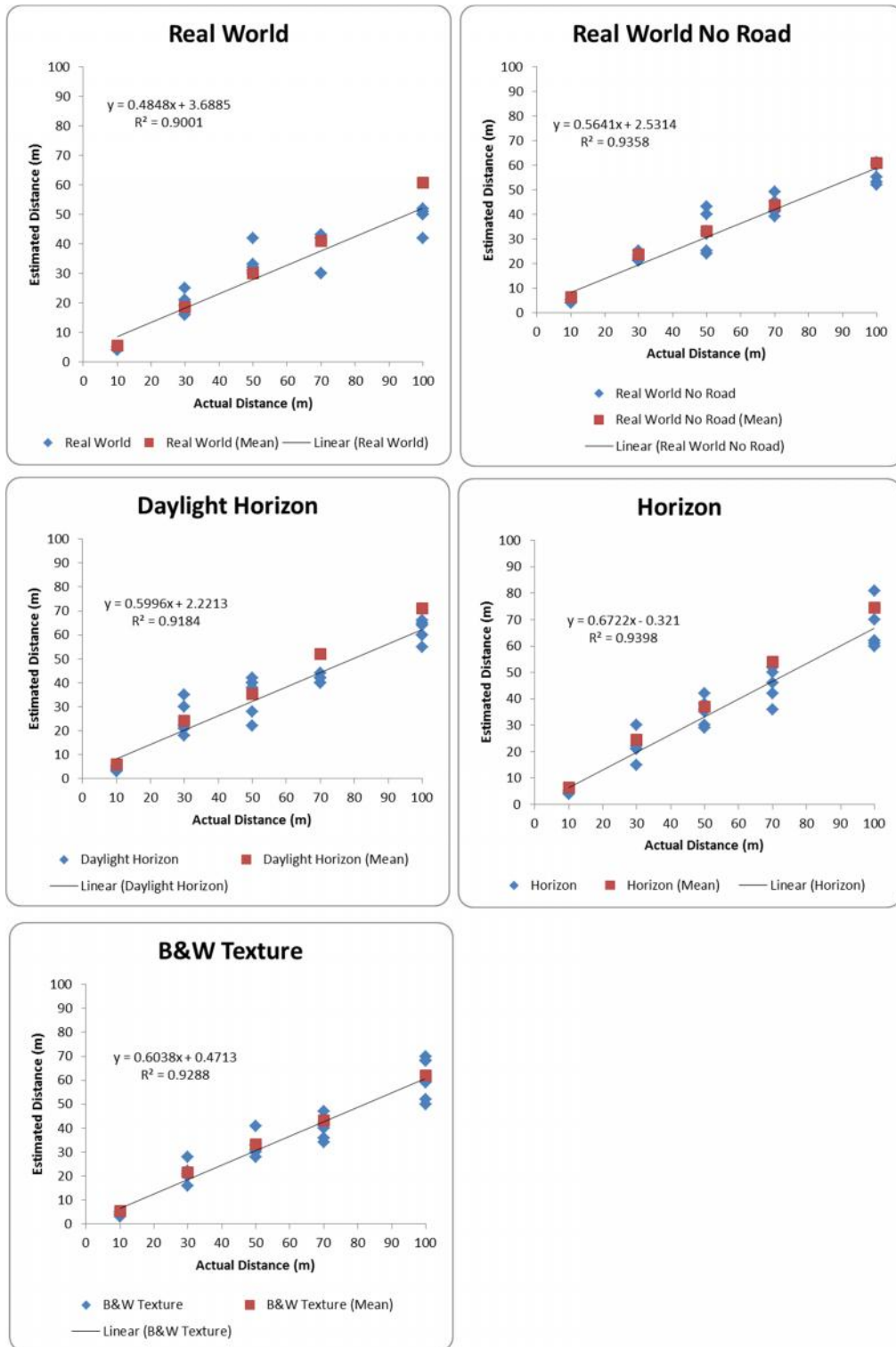


Figure 17. Scatter plot of estimated distances against actual distances and the fitted regression line for five backgrounds from a typical participant (Participant 015) and the group mean (red).

Table 6 Regression Coefficients between Estimated Distance and Actual

Distance

| Par# | Real World | Real World No Road | Daylight Horizon | Horizon-only | B&W Texture |
|------|------------|--------------------|------------------|--------------|-------------|
| 1    | 0.16       | 0.23               | 0.21             | 0.17         | 0.19        |
| 2    | 0.33       | 0.44               | 0.43             | 0.56         | 0.4         |
| 3    | 0.15       | 0.1                | 0.14             | 0.14         | 0.15        |
| 4    | 0.7        | 0.83               | 0.98             | 1.12         | 1           |
| 5    | 0.36       | 0.34               | 0.98             | 0.62         | 0.45        |
| 6    | 1.48       | 1.24               | 1.21             | 1.4          | 1.44        |
| 7    | 0.72       | 0.72               | 1                | 0.87         | 0.76        |
| 8    | 0.38       | 0.4                | 0.48             | 0.5          | 0.42        |
| 9    | 0.65       | 0.63               | 0.63             | 0.74         | 0.69        |
| 10   | 0.32       | 0.45               | 0.39             | 0.46         | 0.57        |
| 11   | 0.17       | 0.16               | 0.19             | 0.27         | 0.2         |
| 12   | 1.28       | 0.91               | 1.15             | 1.3          | 1.17        |
| 13   | 1.9        | 1.57               | 2.4              | 2.49         | 1.19        |
| 14   | 0.13       | 0.13               | 0.15             | 0.15         | 0.13        |
| 15   | 0.48       | 0.56               | 0.6              | 0.67         | 0.6         |
| 16   | 0.28       | 0.33               | 0.4              | 0.37         | 0.36        |
| 17   | 1.02       | 0.99               | 1.06             | 1.08         | 1.02        |
| 18   | 0.62       | 0.66               | 0.57             | 0.67         | 0.53        |
| 19   | 1.24       | 1.24               | 1.31             | 1.34         | 1.19        |
| Mean | 0.65       | 0.63               | 0.75             | 0.79         | 0.66        |

The estimated distances for different backgrounds are shown as averages across all participants in Figure 18. The normalised scale measurements of distances for different backgrounds are shown as an average across all participants in Figure 19. For both types of judgement (verbal and scale), significant main effects were found for the backgrounds ( $F(4, 14) = 13.16, p < .001, \eta_p^2 = 0.790$  for verbal;  $F(4, 14) = 13.31, p < .001, \eta_p^2 = 0.792$  for scale), and the distances ( $F(4, 14) = 11.44, p < .001, \eta_p^2 = 0.766$  for verbal;  $F(4, 14) = 11.39, p < .001, \eta_p^2 = 0.765$  for scale). There was no significant interaction between background and target distance for verbal judgements ( $F(16, 2) = 1.29, p = .524, \eta_p^2 = 0.911$ ) nor for the scale judgement ( $F(16, 2) = 1.43, p = .4888, \eta_p^2 = 0.920$ ). The large Partial Eta Squared values suggest that this could be due to the limited sample size. Furthermore, significant main effects were not found for replication order for either verbal ( $F(5, 13) = 1.42, p = .281, \eta_p^2 = 0.353$ ) or scale judgements ( $F(5, 13) = 1.44, p = .276, \eta_p^2 = 0.356$ ), which again may be attributed to the limited sample size. Finally, it was found that between-subjects factors had no significant effect on participants' estimation; there were no differences in the estimations between Expt. 1 and Expt. 3 ( $F(1, 36) = .95, p = .336, \eta_p^2 = 0.026$ ) and between Expt. 2 and Expt. 3 ( $F(1, 48) = 1.77, p = .181, \eta_p^2 = 0.069$ ) for two of the conditions, Real World and B&W Texture.

For both judgement types a pairwise comparison of the main effect of backgrounds showed:

1. A significant difference between the Real World condition (Background 1) and the Real World No Road condition (Background 2) ( $p < .001$  for verbal and  $p < .001$  for scale judgements).
2. A significant difference between the Real World condition (Background 1) and the Daylight Horizon condition (Background 5) ( $p = .001$  for verbal and  $p = .001$  for scale judgements).
3. A significant difference between the Real World condition (Background 1) and the Horizon-only condition (Background 4) ( $p = .001$  for verbal and  $p = .001$  for scale judgements),
4. A significant difference between the Real World No Road condition (Background 2) and the Daylight Horizon (Background 5) condition ( $p = .037$  for verbal judgements and  $p = .037$  for scale judgements),
5. A significant difference between the Real World No Road condition (Background 2) and the Horizon-only (Background 4) condition ( $p = .01$  for verbal and  $p = .01$  for scale judgements).

The targets were perceived as being closer (greater underestimation) in the simulated “real world” (Background 1 and 2) than in the simulated simplified conditions (Background 4 and 5). Finally, targets were perceived as being

further away in the Background 2 condition than in the simulated “real world” scenario consisting of a vehicle, a stretch of road, blue sky and roadside areas (Background 1). There was no significant difference between the other conditions.

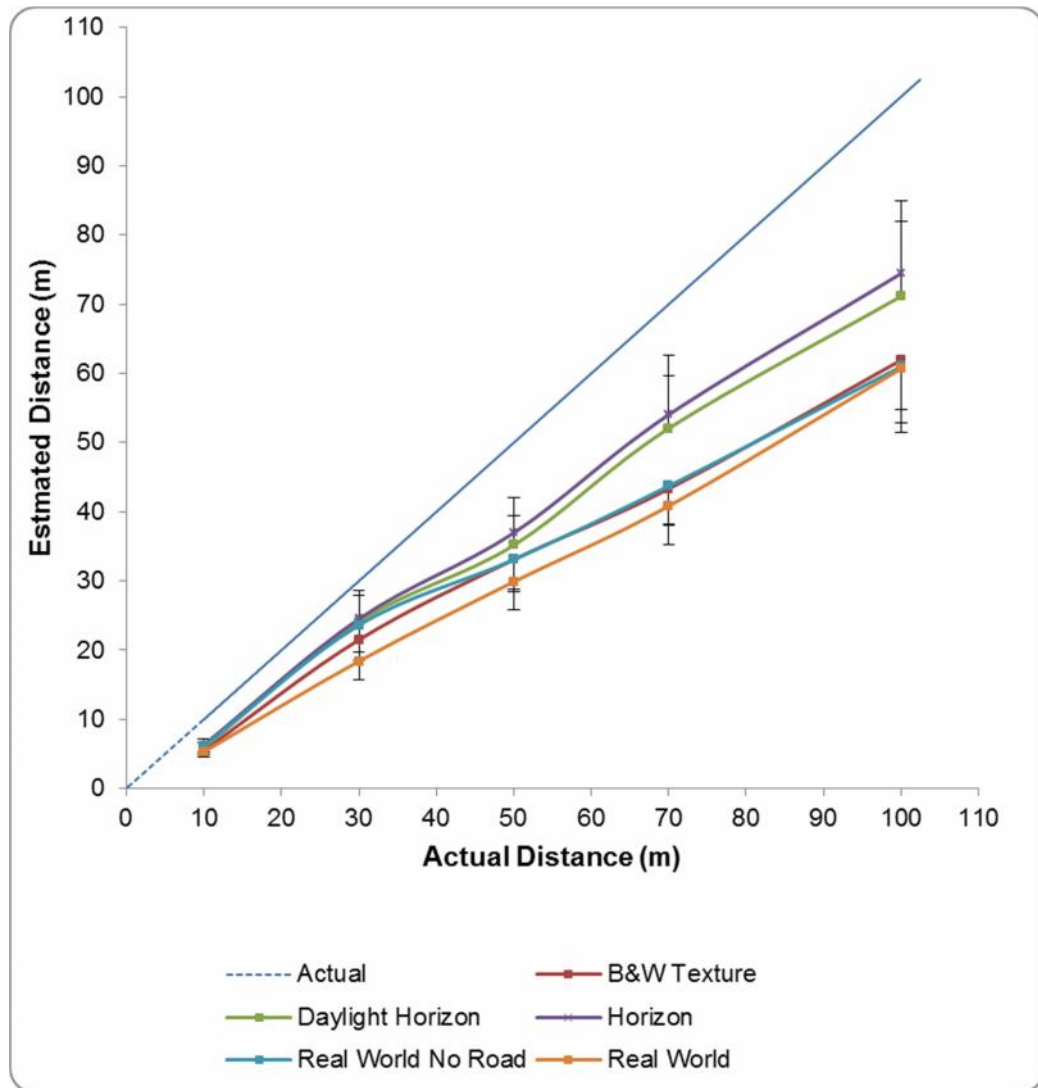


Figure 18. The estimated distances for different backgrounds are shown as an average across all participants. Error bars represent the 95% confidence interval (CI) of the mean.

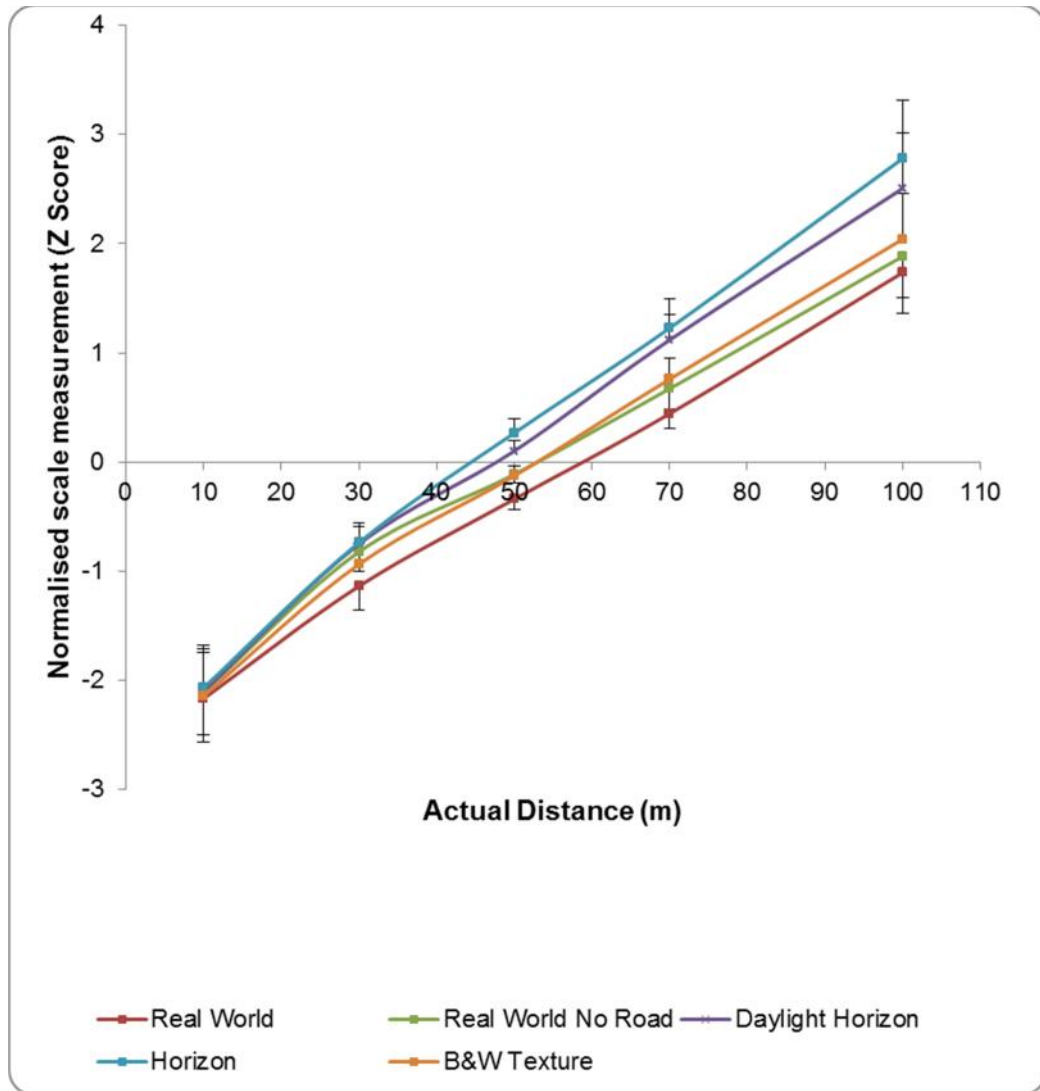


Figure 19. The normalised scale measurements of distances for different backgrounds are shown as an average across all participants. Error bars represent the 95% confidence interval (CI) of the mean.

### 7.1.3 Discussion

In Expt. 1, reliable distance compression was found in all conditions for all

but one participant. Participants seemed to perform better (less underestimation of the car distance) in Expt. 2 compared to Expt. 1. In both Expt. 1 and 2, participants performed better in the simplified, minimal cue VE. In this latest experiment the focus was on whether the underestimation of distance and the significant differences between backgrounds found in the previous two experiments would remain the same in a more immersive environment where cue conflicts (such as accommodation and convergence) have been minimised.

Surprisingly the cue conflict reduction did not have a large effect on performance. It was found in Expt. 3 that 68% of the participants underestimated the car's distance consistently across all conditions. It was suggested above that the introduction of the Horizon-only condition could have improved participants' performance in Expt. 2 compared to Expt. 1. However, in this latest experiment, the between-subjects analysis revealed that there were no significant differences in distance estimations between Expt.1 and Expt. 3, and between Expt. 2 and Expt. 3. A Horizon-only condition was also one of the conditions tested in Expt. 3, yet the distance judgements did not increase relative to Expt. 1 where the Horizon-only condition was not included. Therefore this suggests that the apparent improvement of estimations found in Expt. 2 was not due to the introduction

of the Horizon-only condition, but more likely individual differences and the limited sample size.

In Expt. 3 the VE was presented in a driving simulator (Fig. 15). The driving simulator provided more realistic and consistent visual information, with improved spatial knowledge of the target's location in the VE and it also provided peripheral scenery. In addition it provided a more immersive environment where cue conflicts (accommodation and convergence) have been minimised. Finally, using a life-sized driving simulator provided a larger vertical FOV ( $41^\circ$  versus  $27^\circ$  in Expt. 1 and 2), yet the distance underestimation did not change that much. Others have found that reducing the vertical FOV can increase distance underestimation (Kline and Witmer, 1996; Wu et al. 2004) but it does not seem to have had a large effect in Expt. 3.

It is somewhat surprising that a similar level of accuracy was found when the VE was displayed on the CRT monitors (Expt. 1 and 2) and in the driving simulator (Expt. 3). This result suggests that the ample differences between the two display systems did not lead to differences in distance estimation, at least as measured by verbal estimation and the perceptual matching protocol (scale). It is particularly striking in light of the fact that the CRT monitors used in the first two experiments are significantly smaller and



display smaller images; neither can they create the illusion of immersion, something that occurs in the driving simulator. On the other hand, these results agree well with Willemsen et al. (2008)'s finding that minimising accommodation-convergence cue conflicts do not affect the accuracy of distance judgements.

At the time that this experiment was run (in 2007), the author was not aware of any other studies that compared distance estimation in the VE displayed on CRT monitors and on a large-screen immersive display (LSID) or a CAVE system. Since then a number of studies have found that the use of a large screen projection or a CAVE system did not improve distance estimation in VE. For example, Sciarini et al. (2008) compared distance estimation (27, 60, 105, 158 and 200 feet) using a laptop, a projection system and in a live environment, and found that participants had greater distance estimation in VE than in the live environment. On the other hand, there was no difference between the two VE environments. Additionally, Grechkin et al. (2010) compared three types of VE displays: HMD, LSID and AR, and found similar levels of distance compression in all three VE displays. These findings are consistent with the results from Expt. 2 and 3. This has implications for the selection of display hardware to be used in driver training or testing that requires distance estimation (e.g., overtaking

manoeuvres). If the perceived distance is underestimated as much using a small desktop display as it is when using a large CAVE system then the added expense of the large system is not justified in this context.

Once again, and somewhat counter-intuitively, participants had the greatest amount of distance underestimation in the simulated real world scenario consisting of a vehicle, a stretch of road, blue sky and roadside areas than other conditions apart from Background 3, the B&W Texture condition.

These results therefore indicate that the differences between conditions cannot be attributed to the display system. Realistic scenes lead to more distance underestimation no matter what type of display system they are presented on.

In Expt. 3, a new condition (Background 5, Daylight Horizon) was added to examine the effect of background contrast on distance estimation. There was a dark and light sky condition in the design which provided different levels of contrast for the target car. It was found that there were no significant differences between these two conditions. Therefore background contrast alone cannot explain the difference between the “real world” conditions and the simplified conditions.

A number of studies have been conducted to test the “ground theory” originally proposed by Gibson in both VEs and in the real world (Sinai et al.,

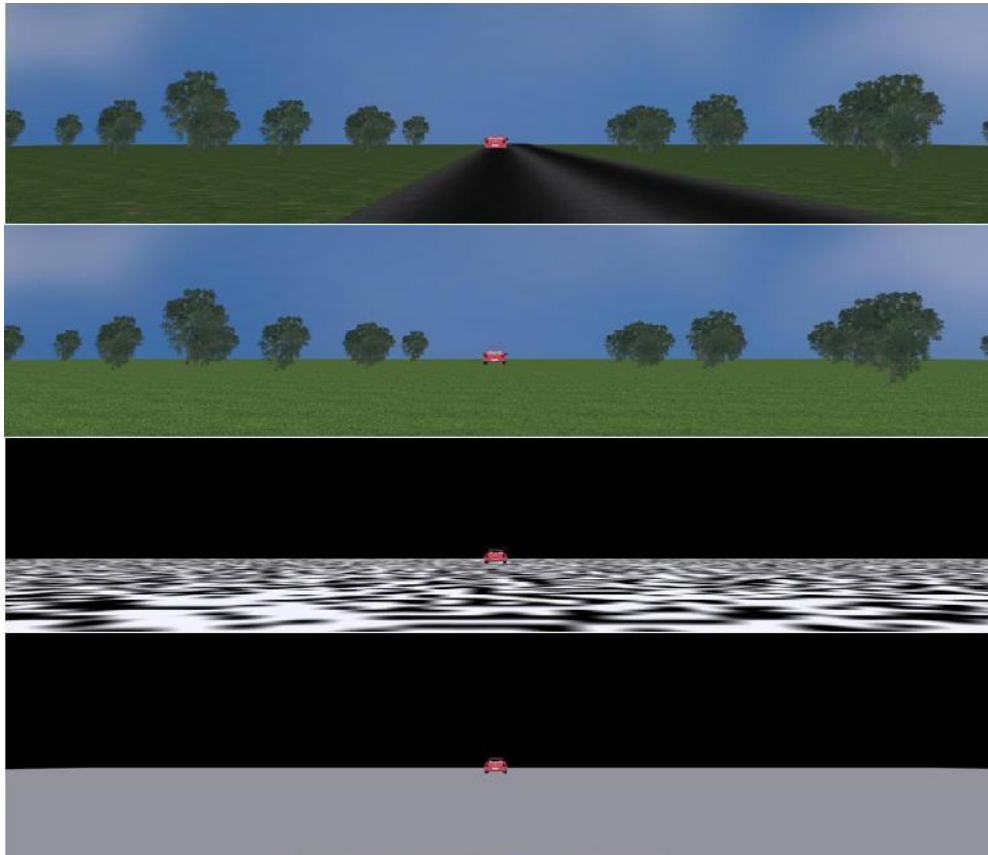
1998, He et al., 2004; Wu et al., 2004). They have found that the ground surface is an essential reference for judging distance. The ground surface close to the observer can be used as a reference frame to extrapolate ground surfaces in the distance. It has been shown that observers make more localisation errors when the near ground surface is disrupted by either a gap or a block, and when their view of the ground surface around the target is restricted. In all three experiments (Expt. 1 – 3), the near ground surface between the participants and the virtual ground was always disrupted by either a gap between the participants and the CRT monitor or by the windshield frame and hood of the BMW. This may have contributed to the distance underestimation found in these three experiments.

## **Chapter 8 Distance Estimation in the Presence of Image Motion**

In the previous chapters, three experiments were described that investigated distance estimation of a vehicle in a VE that simulated a static observer. The effect of the horizontal field of view (HFOV), environmental context and the effect of contrast on distance estimation were examined. In addition, in the first two experiments a “desktop” driving simulator consisting of three CRT monitors was used to display the stimuli. Expt. 3 repeated parts of the previous two experiments but used an immersive virtual

environment. Next, Expt. 4 looks at the effect of observer motion on the distance estimation task and attempts to answer the third question raised at the beginning of the thesis (Does motion affect distance judgements?). The results from the previous experiments suggest that the basic experimental design used in the previous three experiments can also be employed to examine distance estimation during simulated observer motion.

An experiment was carried out that investigates the effect of background movement on distance estimation in a VE presented using an immersive driving simulator (the same one used for Expt. 3). This experiment also compared participants' distance estimation performance in four different environments (the same as the ones used in the previous experiments and depicted in Fig. 20). In Expt. 4, the targets and the simulated observers were set to move at the same speed (and as in the pilot study, the distance between them was constant). The backgrounds (excluding Background 4) provided participants with the necessary visual cues consistent with forward motion of a car following the target vehicle.



*Figure 20.* Examples of stimuli used in Expt. 4.

*Note.* From the top down: Background 1 (Real World): the simulated “real world” scenario consisted of a vehicle, a stretch of road, blue sky and roadside areas; Background 2 (Real World No Road): the simulated “real world” scenario consisted of a vehicle, blue sky and grass areas; Background 3 (B&W Texture): the simulated simplified environment consisted of a textured ground surface and dark sky; Background 4 (Horizon-only): the simulated simplified environment consisted of a grey ground surface and dark sky; background.

## **8.1 Methodology**

### **8.1.1 Participants**

Nineteen new participants were recruited, aged between 18 and 40 years old with an average age of 23 years ( $SD=7.08$ ). Fifteen were female and four were male. The recruitment procedure and criteria were the same as that of Expt. 2. Ethics approval for this experiment was granted by the Waikato University Ethics Committees and written informed consent was obtained from all participants prior to the experiment.

### **8.1.2 Design**

The experiment used a within-subjects design. The independent variables were (a) the simulated backgrounds, (b) simulated distance of an object from the participants - 10, 30, 50, 70 and 100 metres, and (c) speed – 0 km/h or 100 km/h. Participants 001 and 002 were presented with six replications of 30 conditions (2 speeds x 3 backgrounds (background 1-3) x 5 distances) for a total of three experiment sessions. Other participants were presented with an additional four replications of the five conditions (1 speed (static) x 1 background (Background 4) x 5 distances) in the last experiment session. These additional trials provided the opportunity to compare results with the previous experiment. Since Background 4 does

not provide any visual cues for motion perception, motion was not involved in the additional trials. Trials within each session were presented in a predefined randomised order. Participants were given five practice trials at the beginning of the experiment.

### **8.1.3 Stimuli and Apparatus**

Except for the motion, the stimulus parameters and the apparatus were the same as those used for Expt. 3.

### **8.1.4 Procedure**

The procedure was the same as that used in Expt.1, 2 and 3.

### **8.1.5 Data Analysis**

For the verbal judgements, each participant's slope of the regression line fit to a scatter plot of estimated distance versus actual distance was calculated for all 35 conditions (3 backgrounds (Background 1-3) x 2 speeds x 5 distances, and Background 4 x 5 distances). The mean estimated distance was calculated for each participant for 30 conditions (3 backgrounds (Background 1-3) x 2 speeds x 5 distances) and analysed in an analysis of variance (ANOVA).

The scale responses produced numbers from 1-10. Data was normalized

by Z score transformation for each participant for all conditions and all distances. The mean value of the scale judgements was also calculated for each participant for 30 conditions (3 backgrounds (Background 1-3) x 2 speeds x 5 distances) and analysed in an analysis of variance (ANOVA). In addition (for both measurement types), the mean value was calculated for each participant for the 20 static conditions (4 backgrounds x 5 distances) and analysed in an ANOVA. A pairwise comparison of the main effect of backgrounds was also conducted using a Bonferroni correction for P value adjustments.

## **8.2 Results**

Figure 21 shows the scatter plot of estimated distances against actual distances and the fitted regression line for four static backgrounds and three motion backgrounds from a typical participant (Participant 006). See Appendix E for R squared values, F and P values for all participants.



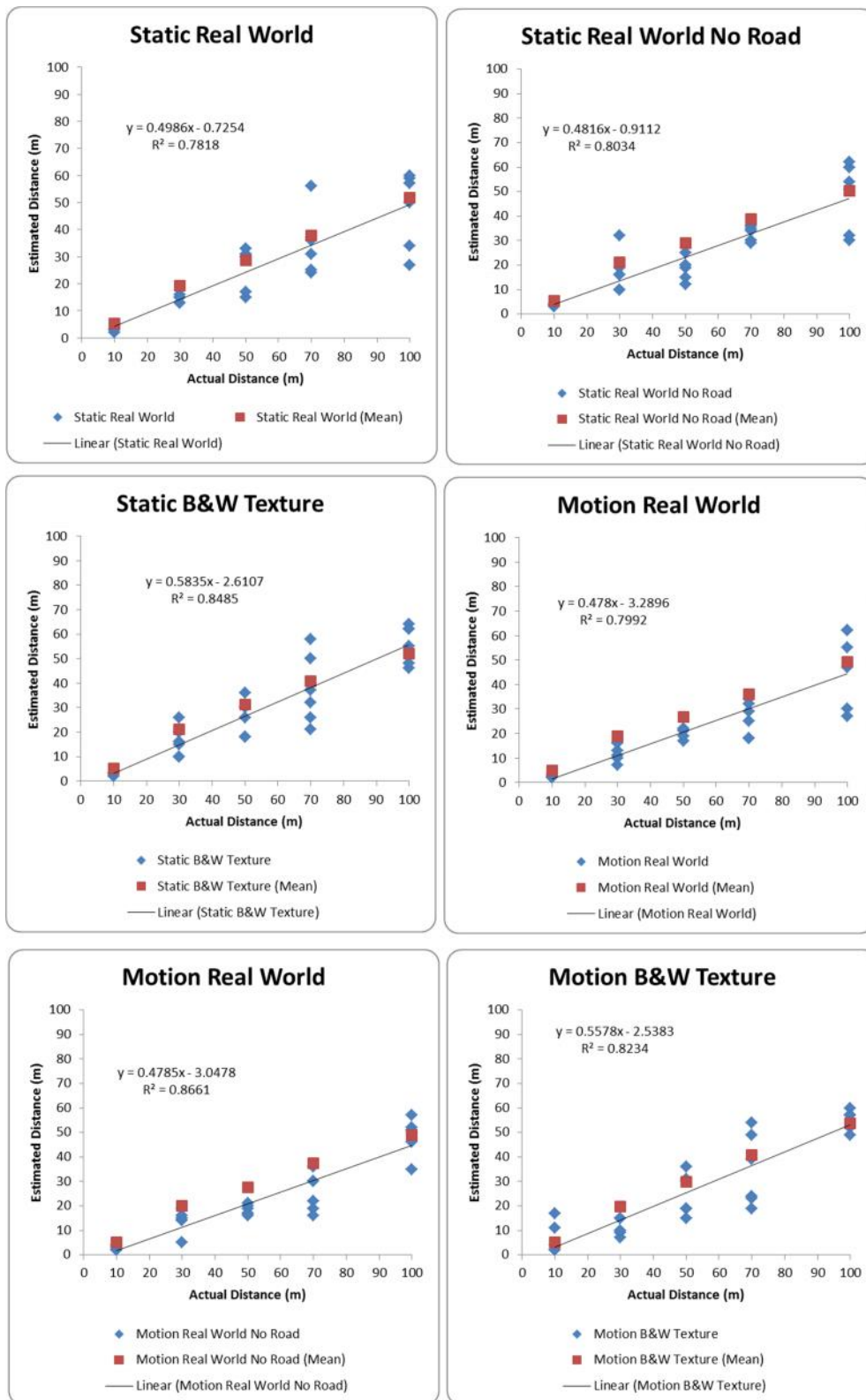


Figure 21. Scatter plots of estimated distances against actual distances and the fitted regression line from Participant 006 and the group mean (red).

In Expt. 4, 17 out of 19 (89%) participants underestimated the target car distance consistently across all conditions; the slopes of the regression line were less than one (for more details see Table 7). The slopes ranged from 0.06 to 2.73 again indicating large individual differences. Notably, compared with the last experiment there was a lower percentage of participants, who had relatively accurate estimation.

Table 7 Regression Coefficients between Estimated Distance and Actual Distance

| Par# | Static Real World | Motion Real World | Static Real World No Road | Motion Real World No Road | Static B&W Texture | Motion B&W Texture | Static Horizon |
|------|-------------------|-------------------|---------------------------|---------------------------|--------------------|--------------------|----------------|
| 1    | 0.69              | 0.69              | 0.55                      | 0.5                       | 0.57               | 0.7                | N/A            |
| 2    | 0.65              | 0.59              | 0.57                      | 0.62                      | 0.54               | 0.6                | N/A            |
| 3    | 0.34              | 0.31              | 0.27                      | 0.32                      | 0.36               | 0.36               | 0.3            |
| 4    | 0.36              | 0.33              | 0.46                      | 0.37                      | 0.42               | 0.38               | 0.58           |
| 5    | 0.29              | 0.29              | 0.28                      | 0.27                      | 0.34               | 0.32               | 0.27           |
| 6    | 0.5               | 0.48              | 0.48                      | 0.48                      | 0.58               | 0.56               | 0.57           |
| 7    | 0.11              | 0.11              | 0.11                      | 0.11                      | 0.11               | 0.1                | 0.12           |
| 8    | 0.5               | 0.51              | 0.5                       | 0.54                      | 0.55               | 0.52               | 0.52           |
| 9    | 0.44              | 0.47              | 0.41                      | 0.38                      | 0.54               | 0.46               | 0.46           |
| 10   | 0.4               | 0.26              | 0.34                      | 0.35                      | 0.35               | 0.39               | 0.88           |
| 11   | 0.06              | 0.08              | 0.08                      | 0.07                      | 0.06               | 0.07               | 0.07           |
| 12   | 0.87              | 0.93              | 0.73                      | 0.95                      | 1.03               | 0.91               | 1.14           |
| 13   | 0.07              | 0.08              | 0.06                      | 0.07                      | 0.09               | 0.08               | 0.08           |
| 14   | 0.33              | 0.32              | 0.32                      | 0.36                      | 0.37               | 0.35               | 0.26           |
| 15   | 0.71              | 0.81              | 0.81                      | 0.8                       | 0.95               | 0.96               | 0.89           |
| 16   | 2.59              | 2.17              | 2.58                      | 2.22                      | 2.2                | 2.6                | 2.73           |
| 17   | 0.15              | 0.17              | 0.21                      | 0.17                      | 0.23               | 0.17               | 0.26           |
| 18   | 0.17              | 0.17              | 0.15                      | 0.15                      | 0.18               | 0.16               | 0.16           |
| 19   | 0.37              | 0.33              | 0.27                      | 0.27                      | 0.3                | 0.43               | 0.3            |
| Mean | 0.51              | 0.48              | 0.48                      | 0.47                      | 0.51               | 0.53               | 0.56           |

The main effect of background was significant for both judgements ( $F(2, 13) = 6.58, p = .011, \eta_p^2 = 0.503$  for verbal judgement;  $F(2, 13) = 6.54, p = .011, \eta_p^2 = 0.501$  for scale judgement). The main effect of speed was also significant for both judgement types ( $F(1, 14) = 10.26, p = .006, \eta_p^2 =$

0.423 for verbal judgement;  $F(1, 14) = 10.17, p = .007, \eta_p^2 \approx 0.421$  for scale judgements). The car was perceived as being closer when the car and the observer were moving at a speed of 100 km/h. For both types of judgement, significant effects were found for the distances ( $F(4, 11) = 8.62, p = .002, \eta_p^2 \approx 0.758$  for verbal judgement;  $F(4, 11) = 8.74, p = .002, \eta_p^2 \approx 0.761$  for scale judgement). For both measures there was no significant interaction between background and target distance. However, the large effect size ( $\eta_p^2 \approx 0.592$  for verbal judgement,  $\eta_p^2 \approx 0.583$  for scale judgement) does suggest that this could be due to the limited sample size. In addition, no significant main effects were found for replication orders ( $\eta_p^2 \approx 0.369$  for verbal judgement,  $\eta_p^2 \approx 0.372$  for scale judgement), which again may be attributed to the limited sample size.

For both measures, a pairwise comparison of the main effect of backgrounds showed a significant difference between the simulated simplified environment which consisted of a textured ground surface with a dark sky (Background 3) and the Real World condition (Background 1), ( $p = .008$  for verbal judgement and  $p = .008$  for scale judgements). There was a significant difference between the simplified environment (Background 3) and Real World No Road condition (Background 2) ( $p = .009$  for verbal judgement and  $p = .009$  for scale judgement).

The target cars were perceived as being closer in the simulated “real world” that consisted of a stretch of road, blue sky and roadside areas (Background 1) compared to when the car was in the simulated simplified environment consisting of a textured ground surface and dark sky (Background 3). However, there was no difference between Background 1 and Background 2, suggesting that in this experiment the road had a limited effect on the participants’ distance perception. The estimated distances for different backgrounds are shown averaged across all participants in Figure 22 (motion: 100 km/h) and Figure 23 (static: 0 km/h). The estimated distances for different backgrounds averaged across all participants are shown in Figure 24 (motion: 100 km/h) and Figure 25 (static: 0 km/h). It is evident that again participants made more accurate judgements in the static, Horizon-only condition (Fig. 23).

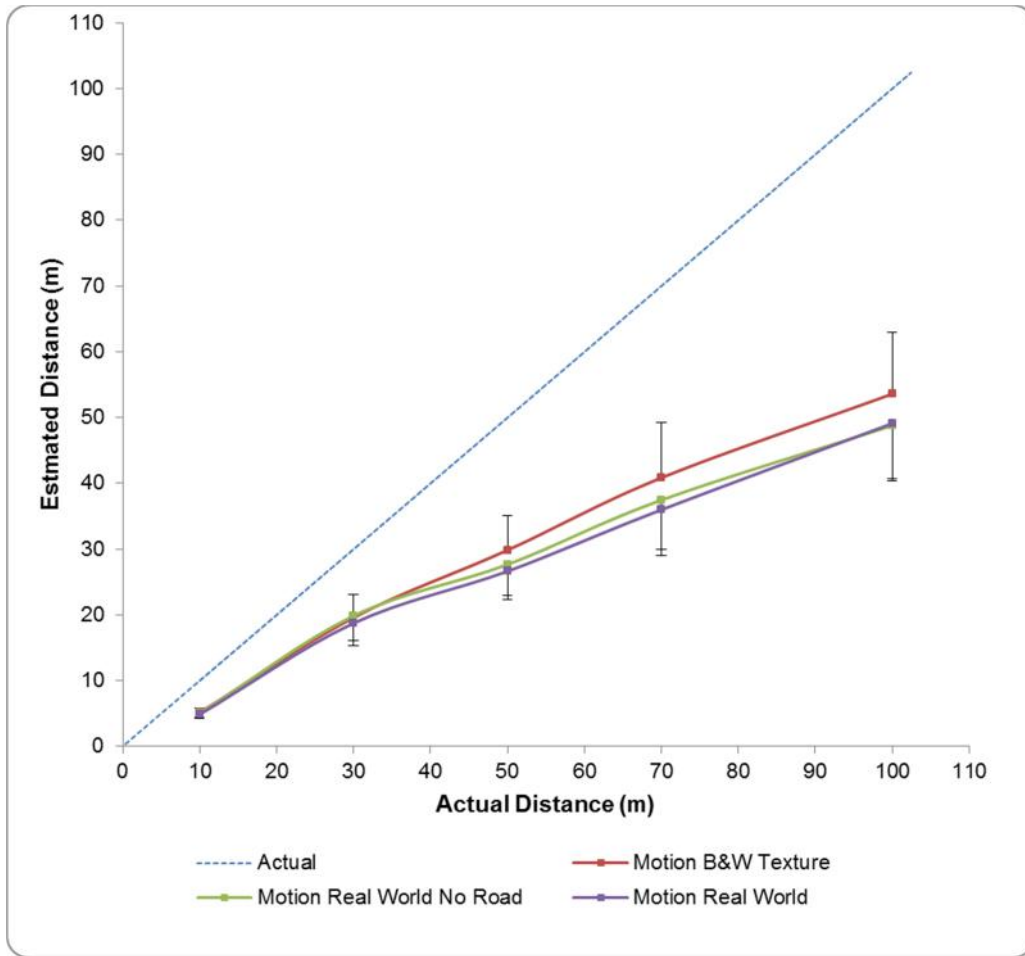


Figure 22. The estimated distances for different backgrounds (motion) averaged across all participants. Error bars represent the 95% confidence interval (CI) of the mean.

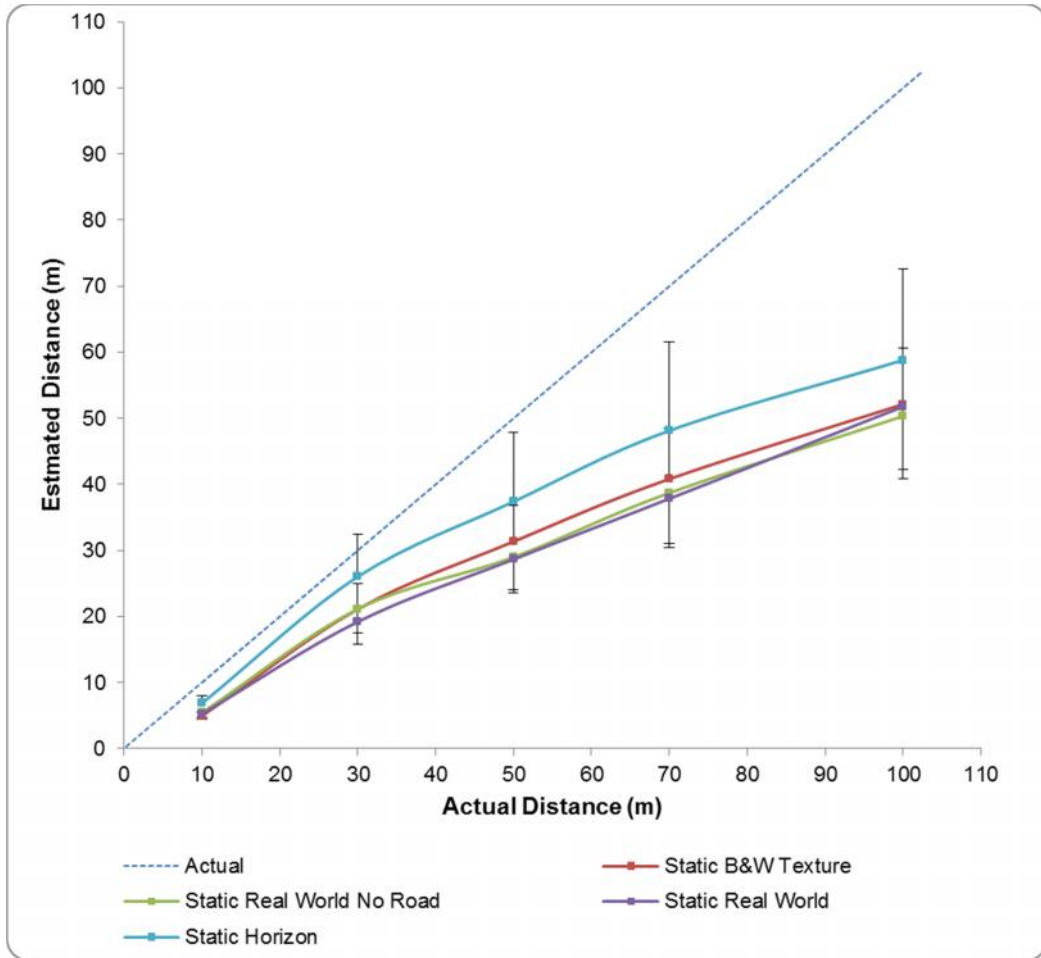


Figure 23. The estimated distances for different backgrounds (static) averaged across all participants. Error bars represent the 95% confidence interval (CI) of the mean.

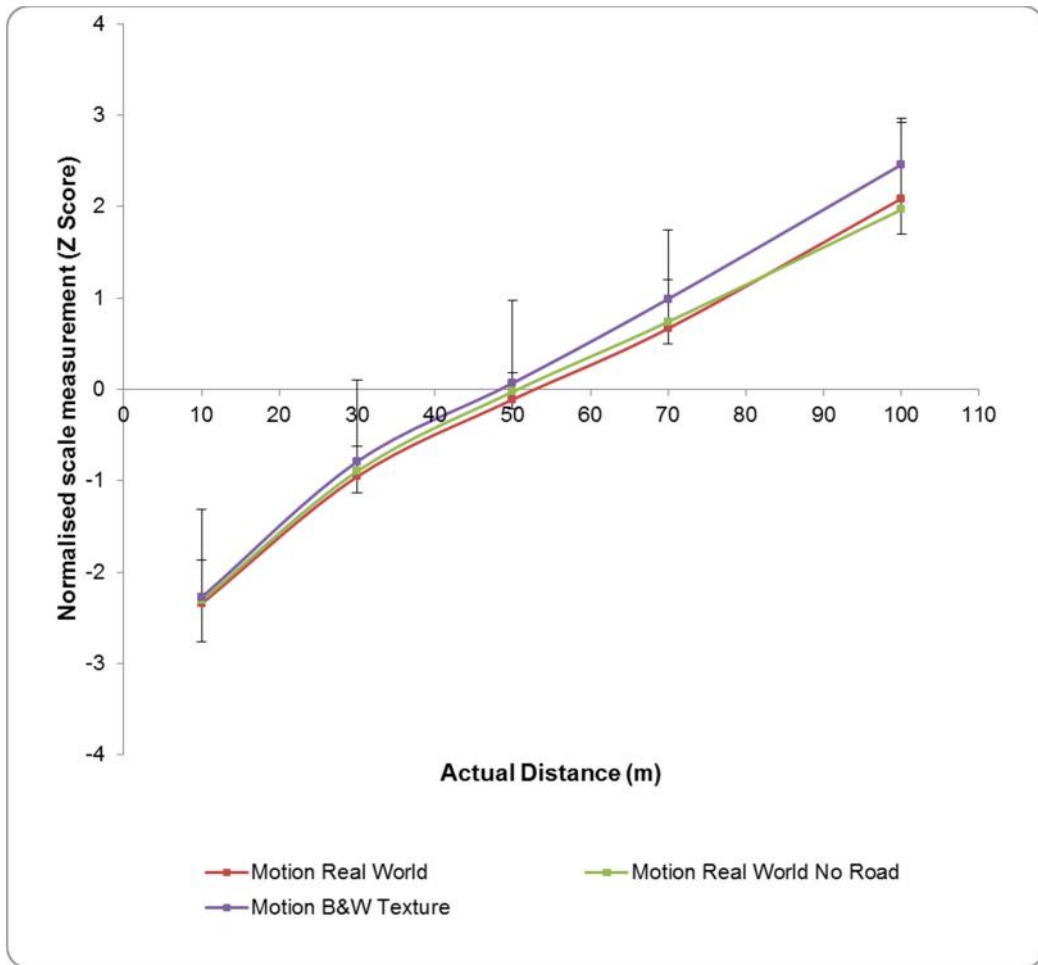


Figure 24. The normalised scale measurements of distances for different backgrounds (motion) averaged across all participants. Error bars represent the 95% confidence interval (CI) of the mean.



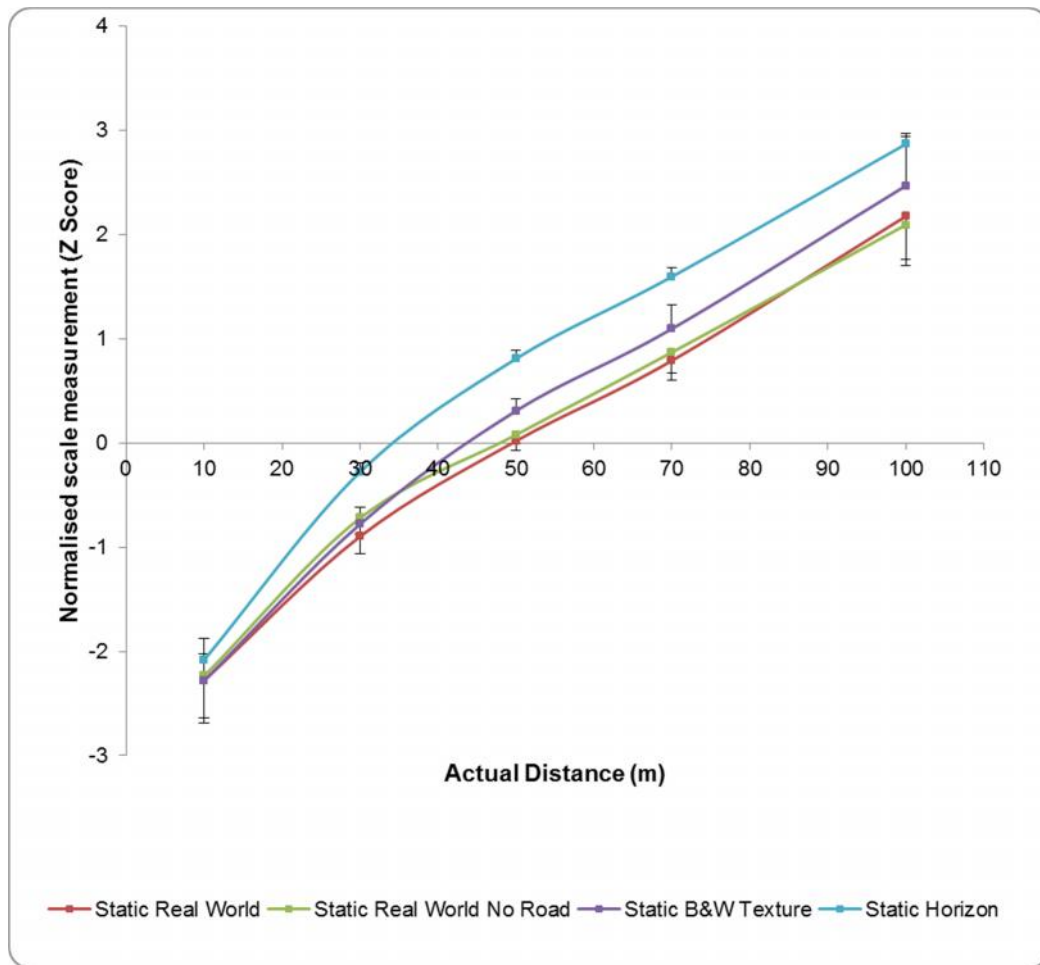


Figure 25. The normalised scale measurements of distances for different backgrounds (static) averaged across all participants. Error bars represent the 95% confidence interval (CI) of the mean.

### 8.3 Discussion

This experiment investigated the effect of simulated observer movement on distance estimation of a car in front, presented using an immersive driving simulator. It was found that speed had a significant effect on distance estimation for both response protocols (verbal and scale judgement). The

distances to the car ahead were judged as being closer when the target and the observer were set to move at a simulated speed of 100 km/h. This indicates that background motion leads to a greater amount of distance underestimation in vista space. Additionally, this effect of background motion exists in both the simplified and realistic VE conditions. The Expt. 4 results add to the small body of work indicating that the perception of distance, both egocentric and relative distance, is generally compressed while moving forwards through the world (Hiro, 1996; Panerai et al., 2001; Baumberger & Fluckiger, 2004; Baumberger et al. 2005). The original Hiro (1996) data can no longer be considered an anomaly and this non-intuitive result (more realism leads to greater distance estimation errors) seems to be a robust property of two-dimensional VE displays.

## **Chapter 9 Distance Estimation in Natural Environments**

In the previous chapters, five experiments were presented that investigated distance perception of a vehicle in VEs. Overall there is clear evidence of distance underestimation among a large proportion of participants in all of these experiments. One of the surprising aspects of the results is that

participants performed better in the simplified (reduced-cue) VE compared to the more detailed scenes. The previous experiments were conducted using a simulated environment. For a number of reasons participants may have behaved differently in the simulated environment than they would have in reality. Is it the lack of realism in the simulated displays that is causing the distance underestimation or simply that the participants are sitting in front of screens? The fact that the reduced-cue conditions in the previous experiments produced less underestimation suggests that it is not an issue of display fidelity but something about the 2D nature of the displays. Therefore, in the experiment introduced in this chapter field testing was carried out using actual cars. Two conditions were used in this experiment: Background 1, Daytime scenario and Background 2, Nighttime scenario. (Fig. 26). These two conditions were selected to replicate the real world and simplified environments used in the previous experiments, as many distance cues (e.g., linear perspective, texture gradients) are ineffective in a dark environment. This experiment also focused on distance estimation in far vista space and on the effect of the near ground surface on distance estimation.

A number of studies have found that perception of distance within action space in the real environment is quite accurate (Witmer & Sadowski, 1998;

Knapp, 1999; Durgin, Fox, Lewis, & Walley, 2002; Willemsen & Gooch, 2002). On the other hand, others have found that participants overestimated distance in far vista space, above 75 m (Daum & Hecht, 2009). Daum and Hecht (2009) suggested that some simple heuristics might be at work when large distances are estimated. In vista space, a number of monocular distance cues are likely to contribute to the participants' distance estimates. Daum and Hecht (2009) suggested that the crossover between compression and dilation could be the result of a re-weighting of cues.

A number of studies have also been conducted to test the “ground theory” originally proposed by Gibson (1953) in both VEs and the real world (Sinai et al., 1998, He, Wu et al., 2004; Wu et al., 2004). They have found that the ground surface is an essential reference for judging distance. In all of the previous experiments reported in this thesis, the near ground surface between the participants and the virtual ground was always disrupted by the bottom edge of the CRT monitor or by the front of the BMW car. This could have contributed to the distance underestimation found in all of the experiments. If this is true then it is expected that a similar level of distance underestimation will be found in this “real world” experiment as well, since the ground will again be disrupted by the windscreen frame and front of the

vehicle.

## **9.1 Methodology**

### **9.1.1 Participants**

Fourteen new participants were recruited, aged between 18 and 40 years old with an average age of 27 years ( $SD= 6.08$ ). Nine were female and five were male. Two participants were excluded as they were unable to complete the experiment sessions. The recruitment procedure and criteria were the same as that of Expt. 2. Ethics approval for this experiment was granted by the Waikato University Ethics Committees and written informed consent was obtained from all participants prior to the experiment.

### **9.1.2 Design**

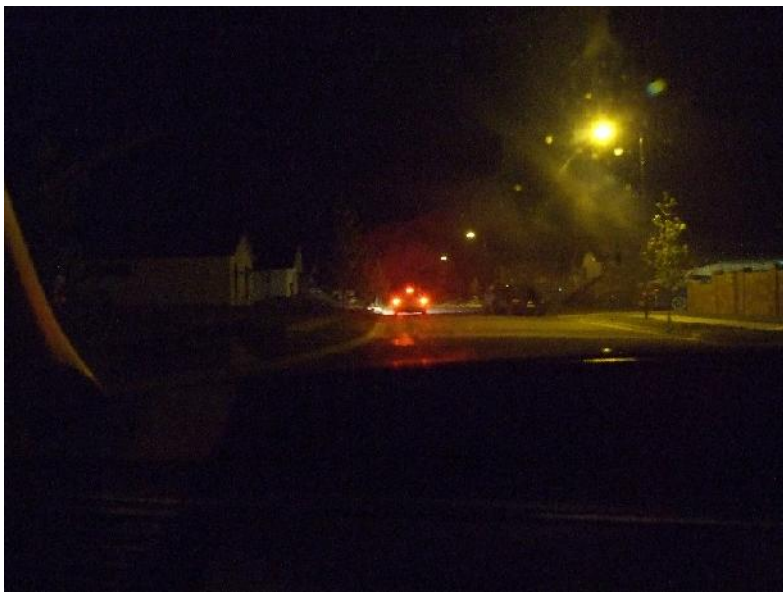
As in the previous experiments, Expt. 5 used a within-subjects design. The independent variables were (a) the day and night environment and (b) distance of the target from the participants (five different locations).

Participants 002 and 004 were presented with six replications of five conditions (1 background (Daytime scenario) x 5 distances) in total of one experiment session. Other participants were presented with 10 conditions (2 backgrounds (day and night) x 5 distances) in a total of two experiment sessions. Participants were given two practice trials at the beginning of the

experiment.

### **9.1.3 Stimuli and Apparatus**

The real environment was a stretch of road in Hamilton (Fig. 26). The target used in the experiment was a grey VW Golf. While judging distance, participants were sitting in their own vehicle (in the driver's seat, with the experimenter sitting in the passenger seat). The use of participants' vehicles was to create a comfortable and familiar natural environment. As the vehicles used in this experiment were either a family sedan or station wagon, the bonnet lengths were not hugely different from the bonnet length of the BMW in the lab.



*Figure 26.* Photographs of the real environments used in Expt. 5.

*Note.* From the top down: Background 1, Daytime scenario and Background 2, Nighttime scenario.

#### **9.1.4 Procedure**

At the beginning of the experiment, instructions and consent forms were given to the participants and experiment procedures were fully explained to them. They were then given two practice trials. Participants were instructed to close their eyes and the driver of the target vehicle moved the target to one of the five locations. Participants were then instructed to open their eyes and estimate the distance of the car from themselves. They recorded their estimations on a recording sheet and closed their eyes again. In the meantime the actual distance of the target was measured using a “speed gun” (Marksman LTI 20.20). As in the previous experiments, for each trial two judgements were collected. One involved a report of target distance in metres (verbal judgement), and the other involved the use of a ruler-like scale adapted for use on paper rather than on a computer screen (Fig. 27). Seven out of the 13 participants started the experiment with the verbal (numerical) judgement (i.e., trial one: verbal and scale; trial two: scale and verbal) and the others started with the scale judgement (trial one: scale and verbal; trial two: verbal and scale). The daytime session was conducted in the afternoon and the nighttime session at night (after 8:30pm). At the end of the experiment, three questions were asked to gather data on participants’ age, ethnicity and driving experience.



**Recording Sheet**

*Task A:*

\_\_\_\_\_

Very Close                      Very Far

*Task B:*

\_\_\_\_\_ Meters

1

---

**Recording Sheet**

*Task A:*

\_\_\_\_\_ Meters

*Task B:*

\_\_\_\_\_

Very Close                      Very Far

2

Figure 27. Recoding sheet for Expt. 5.

Before the experiment, the driver of the target vehicle was instructed to move the target vehicle and park it at five locations in each trial. The target was to stop at each location six times in each experiment session. The five locations were to be as close as possible to 15, 35, 50, 70 and 100 metres from participants. The driver decided the exact locations of the target and the order in which each location was presented on the day. The experimenter and participants had no prior knowledge of either the exact location or the trial order. During the experiment the driver and the experimenter communicated through a walkie-talkie set.

### **9.1.5 Data Analysis**

The analysis process was similar to that of Expt. 3, except that a pairwise comparison of backgrounds was not required as there were only two backgrounds in the experiment. Power law exponents (Stevens, 1986) for distance estimation were calculated for both conditions. Daum and Hecht

(2009) found non-linear trends within vista space: distances less than 70 m were underestimated, whereas distances greater than 70 m were overestimated. The power fit was used to test if the same non-linear trends could be found in this experiment. An exponent of 1.0 indicates that the distance judgements were exactly proportional to the true distance and the relationship is linear.

## **9.2 Results**

Figure 28 shows the scatter plot of estimated distances against actual distances and the fitted regression line for two conditions from a typical participant (Participant 000). See Appendix F for R squared values, F and P values for all participants. In Expt. 5, seven out of 12 (58%) participants underestimated the distance consistently across all conditions; the slopes of the regression line were less than one (for more details see Table 8). The slopes ranged from 0.12 to 1.89 again indicating large individual differences.

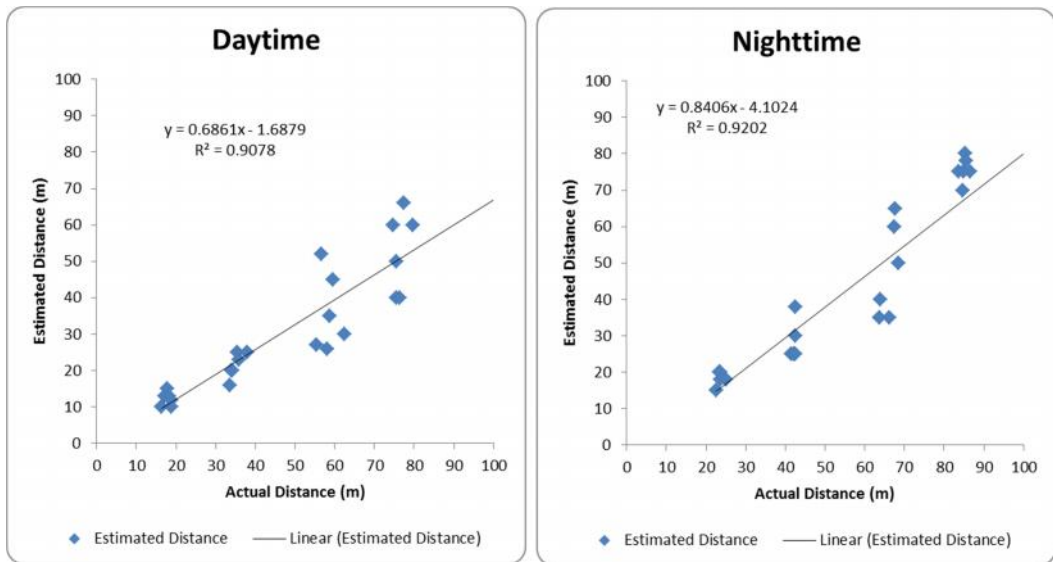


Figure 28. Scatter plot of estimated distances against actual distances and the fitted regression line from Participant 000.

Table 8 *Regression Coefficients between Estimated Distance and Actual*

*Distance*

| <b>Par #</b> | <b>Night</b> | <b>Day</b> |
|--------------|--------------|------------|
| 0            | 0.84         | 0.69       |
| 1            | 0.93         | 1.2        |
| 3            | 0.15         | 0.12       |
| 5            | 1.77         | 1.89       |
| 6            | 1.41         | 1.55       |
| 7            | 0.92         | 1.18       |
| 8            | 0.72         | 0.87       |
| 9            | 0.48         | 0.43       |
| 10           | 0.78         | 0.63       |
| 11           | 0.91         | 1.28       |
| 12           | 0.82         | 0.84       |
| 13           | 0.85         | 0.85       |
| Mean         | 0.88         | 0.96       |

The estimated distances for the different backgrounds are shown as averages across all participants in Figure 29. The effect of conditions (Daytime or Nighttime) was not significant for either judgement ( $F(1, 11) = 0.77$  for verbal;  $F(1, 11) = 0.76$  for scale judgements). There was no significant effect of distance and no significant interaction between background and target distance. Additionally, it was found that between-subjects factors had no significant effect on the participants' estimation. Finally the power law exponents for distance estimation were

1.07 for the Daytime condition and 0.99 for the Nighttime condition indicating almost veridical performance in the judgement of the car distances.

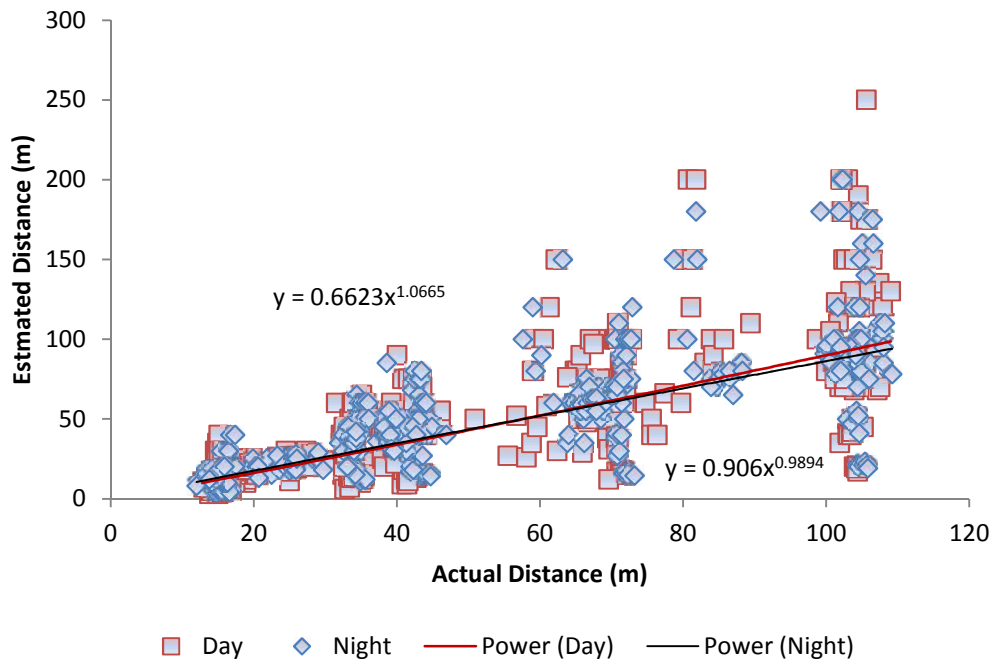


Figure 29. The estimated distances for different backgrounds are shown across all Expt. 5 participants.

### 9.3 Discussion

Although 58% of the participants were found to underestimate distance consistently across all conditions, their estimations were much closer to the target distance compared with the previous experiments, especially during the day. A number of studies have found that perception of distance within action space in the real environment is quite accurate (Witmer & Sadowski,

1998; Knapp, 1999; Durginet al., 2002; Willemsen & Gooch, 2002). On the other hand, Daum and Hecht (2009) found that participants overestimated distance in far vista space, above 75 m. The results from this experiment did not support Daum and Hecht (2009)'s findings. Instead of overestimating distance, a number of participants underestimated the distance when the car was further than 75 m away. Most importantly, a close examination of individual data shows that for most participants there was no clear indication of an estimation pattern change (under to overestimation) at around 70 m of target distance. Two participants did exhibit a pattern change at around 70 m, however, this was in the direction of underestimation rather than overestimation. Additionally, the power law exponents for distance estimation were 1.07 for the Daytime condition and 0.99 for the Nighttime condition, indicating that the estimated distances were proportional to the true distances. Estimations increased linearly with distance in all conditions and there was no systematic pattern of changes at any distance.

There were a number of differences between this experiment and the Daum and Hecht (2009) study that could have potentially contributed to the different results found in the two studies. Firstly Daum and Hecht (2009) conducted their study in a large open field which had no salient landmarks

or points to aid orientation. In contrast, Expt. 5 was conducted on a stretch of road with houses and cars on both sides of the road (Fig. 26). These features provided participants with extra visual and cognitive information about distance and may have contributed to the more accurate estimation. Secondly, in the Daum and Hecht (2009) study the targets were square wooden boards scaled to three different sizes. Thus participants had no knowledge of the size of the target. The target used in Expt. 5 was a grey VW Golf, which provided the participant with familiar size information, and might have contributed to the more accurate estimation compared to the Daum and Hecht (2009) data. Additionally, in Expt. 5 the near ground surface was disrupted by the vehicle that the participant was sitting in, as opposed to the Daum and Hecht (2009) experiments where the near ground surface was visible. A number of studies have found that the ground surface is an essential reference for judging distance (Sinai et al., 1998, He et al., 2004; Wu et al., 2004). The ground surface close to the observer can be used as a reference frame to extrapolate ground surfaces in the distance. It is, however, possible that the ground surface is not a very effective cue for distance estimation in far vista space. In Expt. 5, since the near ground surface was disrupted, participants had to attend to other cues that might be more effective for distance estimation in far vista space. Finally, participants had a different eye height in this experiment compared to those

in the Daum and Hecht (2009) study; the estimates of distance were made while sitting in a car in Expt. 5. This could have affected the use of angular declination from the horizon as a distance cue, thus producing the difference between this experiment's results and those in the Daum and Hecht (2009) study. Overall this experiment indicated that the findings of Daum and Hecht (2009) cannot be generalised to distance estimation in far vista space in general. As demonstrated here, a number of factors could potentially affect distance estimation in far vista space.

In the previous experiments (Expt. 1-4) participants displayed a greater degree of distance underestimation in the simulated real world scenario (with many features such as trees and a road) compared to the reduced-cue conditions (the Horizon-only condition and the B&W Texture condition). This is counterintuitive and suggests that there is something about the VE situation and the use of screens that is producing this result. Expt. 5 was conducted to investigate distance estimation during day and night conditions in the real environment. The results indicate that underestimation of the distance to the target car is greatly diminished in the real world. There was also no difference between the day and night conditions although there were fewer cues available in the Nighttime condition. In the simulator (VE) experiments there was a difference in



distance estimation performance between the full-cue and the reduced-cue conditions. The absence or presence of cues does not seem to be as important in the real world situation.

Although the distance estimation performance in the real world trials was different from what was found in the previous VE experiments, it may not be too surprising. All of the experiment trials in the Nighttime conditions were conducted after the Daytime conditions. Thus the results could have been affected by a carry-over effect from the daytime trials. Ziemer et al. (2009) found that the order in which the conditions were presented affected participants' distance estimation, thus suggesting that carry-over effects can confound distance experiment results. In Expt. 5 all of the Nighttime trials were conducted three to four hours after the Daytime conditions but it is unclear whether this prevented any carry-over effects.

The experiment was conducted on a stretch of road with houses and cars on both sides of the road (see Fig. 26). These features provided participants with extra visual and cognitive information on distance, especially during the day as all of these features were clearly visible. In the previous VE-based experiments these features were not present. Therefore participants had to attend to other visual cues, which may have resulted in the difference between the full-cue versus reduced-cue conditions in these earlier

experiments.

Many distance cues (e.g., linear perspective, texture gradients) are ineffective in a dark environment. Conducting experiments on distance estimation in the dark effectively diminishes these cues and creates a reduced-cue condition. Early research (e.g., Gogel & Tietz, 1973, 1979, Foley, 1977) suggested that distance cue reduction leads to inaccurate verbal estimation of distance. Philbeck and Loomis (1997) investigated distance estimation in a dark room and found that participants underestimated distance when the target was farther than 3 m. No such differences were observed in the real world in Expt. 5, and both the night and day conditions produced similar distance estimates.

A number of participants made more accurate distance estimates at night compared to during the day. Therefore, the main effect of the reduced-cue conditions on distance estimation found in the previous VE experiments is also apparent in the real world, at least for some people. Future studies need to be conducted in order to replicate the current experiment in an open field without any landmarks using a balanced presentation order of conditions (day versus night). This type of design will eliminate the additional visual and cognitive information provided by the surrounding environment and any carry-over effect, and would help reveal any real

differences between the night and day conditions.

A number of studies have found that the ground surface is an essential reference for judging distance in both VEs and in the real world (Sinai et al., 1998, He et al., 2004; Wu et al., 2004). Creem-regehr et al. (2005), however, found that the view of one's body and feet on the floor had no effect on distance estimation. In the previous experiments (Expt. 1-4) the near-ground surface between the participants and the virtual ground was always disrupted by the bottom of the CRT monitor or by the front of the BMW car the participants were seated in. Based on the earlier work on occluded ground surfaces (Sinai et al., 1998, He et al., 2004; Wu et al., 2004) it is feasible that this occlusion may have contributed to the distance underestimation found in the previous VE-based experiments. However, in the Expt. 5 real world case, the near ground surface was also disrupted by the vehicle that the participants were sitting in. Although 58% of participants underestimated distance consistently across all conditions, their estimations were much closer to the actual target car distance compared with the previous experiments, especially during the day. A number of participants also overestimated the distance. This suggests that the disruption of the near ground surface alone cannot explain the distance underestimation found in the previous experiments. While driving a car, the

near ground surface is nearly always blocked by the front of the car. It is possible that people have adapted to this situation and learned to navigate through the environment without visual information from the near ground surface.

## **Chapter 10 General Discussion**

It is well established that people are generally quite accurate at estimating distance within action space in the real environment, but underestimate distance in virtual environments, relative to the real world (Loomis et al., 1996; Witmer & Sadowski, 1998; Sahm et al., 2005; Creem-Regehr et al., 2005; Loomis & Knapp, 2003; Messing & Durgin, 2005; Richardson & Waller, 2007; Thompson et al., 2004; Willemsen & Gooch, 2002). A number of investigations have attempted to explain this bias in behaviour by examining technical aspects of VEs (Knapp and Loomis 2004; Thompson et al., 2004; Bingham et al., 2001; Creem-Regehr et al., 2005). However, because of the wide range of techniques/methodologies used and the diversity of findings, it is difficult to make a general conclusion about distance estimation in VEs.

The research reported in this thesis investigated how people estimate distance between themselves and a virtual car in front of them, within a

number of differing environmental contexts. It attempted to replicate part of Hiro's (1996) experiment in a computer generated VE and address two main issues: distance estimation in a static VE and distance estimation in the presence of simulated forward motion.

It was found that there was clear evidence of distance underestimation among a large proportion of participants in the VE (static and motion), even when familiar objects such as cars were used as the targets. The findings are consistent with other studies of distance estimation in VEs (Witmer & Kline, 1997; Witmer & Kline, 1998; Witmer & Sadowski, 1998; Sinai et al., 1999; Knapp, 1999; Willemsen & Gooch, 2002; Loomis & Knapp, 2003; Thompson et al., 2004; Creem-Regehr et al., 2005; Messing & Durgin, 2005; Richardson & Waller, 2007; Sahm et al., 2005). Furthermore, it was found that there was a significant effect of speed on distance estimation. Background motion leads to distance underestimation in vista space. This effect of background motion exists in both simplified and realistic VE. The current findings add to the small body of work suggesting that the perception of distance, both egocentric and relative distance, is generally compressed while moving forwards through the world (Hiro, 1996; Panerai et al., 2001; Baumberger & Fluckiger, 2004; Baumberger et al. 2005).

One of the subtle surprising aspects of the results is that participants

performed better in the simplified VE. As participants may have behaved differently in the simulated environment than they would have in reality, a subsequent field test was conducted comparing distance estimation during the day and at night. These two conditions were selected to replicate the Real World condition and simplified environments used in the simulated environment. The field test did not find significant difference between the two conditions (day versus night). One would expect that distance estimation during the day should have been more accurate than at night because there are more cues in the daylight condition. However, the participants performed just as well in the reduced-cue situation. Therefore, the main effect of conditions on distance estimation found in the VE in the previous thesis experiments is valid in the real world at least for some people.

One explanation for this effect is that the limited availability of the usual full complement of depth cues in a simplified VE forces participants to focus on and adopt a different pattern of visual cues in vista space. To explain how individuals perceive the combination of visual cues, a number of visual cue combination models have been proposed ranging from modular to multiplicative (Macredie & Morar, 2000), including the three strategies for cue combination proposed by Bruno and Cutting (1988). The fundamental

aspect of these strategies is that the more effective the visual cue is, the more likely it will have an impact on perception. Distance estimation in a VE can be seen as two tasks. Firstly one needs to be able to perceive 3D dimensionality, and then they are required to judge distance. In theory the combination of all cues available should provide information for both tasks. However, it is also possible that visual cues for perceiving 3D dimensionality are not effective cues for distance estimation, especially in vista space. Individuals rely upon these visual cues to perceive 3D dimensionality and then use them to judge distance. Removing this cue from the VE reduces the VE's ability to create the illusion of immersion, which then forces the individual to adopt different visual cues in vista space which produce more accurate distance estimation performance compared to when a greater range of cues are available.

This raises the question, how useful are VEs for tasks such as driver training? After all virtual environments (VEs) are "interactive, virtual image displays enhanced by special processing and by non-visual display modalities, such as auditory and haptic, to convince users that they are immersed in a synthetic space" (Ellis, 1994, p.17). Traditionally, the core focus of a VE is to create the illusion of immersion. It is a problem in some situations if such displays cannot provide the cues for accurate distance

judgement.

In this thesis a number of issues have also been investigated in an attempt to explain the compressed spatial judgements in a static VE. There were four main findings that added to the literature investigating distance estimation in a simulated environment: ground texture characteristics, target characteristics, disruption of the ground surface, and display characteristics. Firstly, it was found that the size of the texture on the ground had a limited effect on participants' estimation. This is consistent with Witmer and Kline (1998)'s findings. In Expt. 2 and in the first Witmer and Kline (1998) experiment, the estimation of distance ranged from 3 m to 100 m in both virtual indoor and outdoor environments. Three different ground texture patterns were investigated using verbal estimation, magnitude estimation and perceptual matching protocols. Additionally, two targets were used across these two experiments: one with (a VW Golf) and one without (a cylinder) relative size information. It is reasonable to conclude that in a VE the size of the ground texture patterns has no effect on distance estimation within both action and vista space.

Secondly, the parameters of the CRT displays and viewing conditions such as accommodation and familiar size, did not lead to differences in distance estimation. Both a desktop display and an immersive driving simulator



produced similar levels of distance underestimation, at least as measured by verbal estimation and the perceptual matching protocol (scale). More recent studies have also found that the use of a large screen projection or a CAVE system does not improve distance estimation in VE (Sciarini et al., 2008, Grechkin et al., 2010), consistent with the results described here. This finding has implications for the selection of display hardware to be used in driver training or testing that requires distance estimation (e.g., overtaking manoeuvres). If the perceived distance is underestimated as much using a small desktop display as it is when using a large CAVE system, then the added expense of the large system is not justified in this context.

Thirdly, it was found that the disruption of the near ground surface alone cannot explain the distance underestimation found in VEs. While driving a car the near ground surface is always blocked by the car. It is possible that people adapt to the environment and learn to navigate through the environment without visual information from the near ground surface.

Furthermore, it was found that the width of the road had limited effect on distance estimation in a static VE. This is, however, not a very surprising result as people often drive on roads varying in width (e.g., highways versus urban roads) and may have adapted to the difference. Finally, in this study,

the main effect of FOV was not significant for either form of judgement. This result agrees with the suggestion that a restricted horizontal FOV alone cannot explain the distance underestimation found in Ves .

In addition this research also investigated distance estimation in far vista space, contributing to the literature in this area. Daum and Hecht (2009) found that participants overestimated distance in far vista space, above 75 m. Results from Expt. 5 did not support the findings of Daum and Hecht (2009). Overall, it seems that the Daum and Hecht (2009) findings cannot be generalised to all distance estimation in far vista space. A number of factors, such as eye height or extra visual and cognitive information, could potentially affect distance estimation in far vista space.

## **10.1 Future Work**

The review and findings concerning distance estimation issues in this thesis have highlighted options for prospective areas of future research. Relevant areas that contribute to furthering the understanding of distance estimation have been identified and are briefly discussed in this section. Firstly, in this study it was found that speed had a significant effect on distance estimation. This study is the first that the author is aware of that examined the effect of speed on egocentric distance estimation in VEs using traditional distance estimation protocols (i.e., verbal reporting and perceptual matching).

Furthermore, the question of why and how speed impacts on distance estimation has yet to be answered. When moving at a high speed, people may lose the ability to track the objects around them with their eyes. Furthermore, in such a situation an observer's central "field of clear vision" may get smaller and smaller such that they tend to focus on one point corresponding to the direction they are heading. These two mechanisms may help elaborate on Hiro's (1996) theory that distance underestimation is due to a reduced degree of stimulation during high speed driving. To test this idea it would be useful to measure people's ability to track moving objects during driving and to assess people's visual field changes during high speed movement. Finally, it would also be useful to find out how the combination of optic flow and other cues such as edge rate, motion parallax or vestibular system inputs affect distance perception and how these cues are integrated. These can be investigated in the future using similar stimuli and apparatus to that employed in this thesis.

The most surprising aspect of the thesis results is that participants performed better in the simplified VE. One explanation of this effect is that the limited availability of various depth cues in a simplified VE forces the participants to adopt potentially more effective visual cues in vista space. Future experiments could be conducted to isolate and test the effectiveness

of the three visual cues presented in the Horizon-only condition in Expt. 2 and 3, including angular declination from the horizon, familiar size and visual contrast. An attempt could be made to isolate the preferred but ineffective distance cues by manipulating the cues in the real world conditions, and then comparing the distance estimation in the real world condition with estimations made in the simplified VE world.

Further research could also be conducted to replicate Expt. 5 in an open field without any landmarks and using a count-balanced presentation order of conditions (day versus night). This design would eliminate the additional visual and cognitive information provided by the surrounding environment and any potential carry-over effect that occurred in Expt. 5. This design is also a step closer to the Daum and Hecht (2009) study and would be more suitable for investigating whether participants overestimate distance in far vista space, above 75 m.

Finally, the design of Expt. 5 provided a good opportunity to test ground theory (Gibson, 1950) in a real world situation. While driving a car the near ground surface is always blocked by the car. It is possible that people adapt to the environment and learn to navigate through the environment without visual information from the near ground surface. This raises several interesting questions. How do observers navigate through the environment

without visual information from the near ground surface? What other cues do they focus on to compensate for the lack of visual information from the near ground surface? Is it a learned behaviour or are individuals able to adjust and adapt quickly?

Overall the thesis has added to the body of work investigating distance estimation in a simulated environment. The findings of this research should help the designers of driver-training simulators and testing equipment to better understand the types of distance estimation errors that can potentially occur when humans view two-dimensional virtual environment displays.

## References

- Andre, J., & Rogers, S. (2006). Using verbal and blind-walking distance estimates to investigate the two visual systems hypothesis. *Perception & Psychophysics*, *68*(3), 353-361.
- Armbrüster, C., Heber, I. A., Valvoda, J. T., Kuhlen, T., Fimm, B., & Spijkers, W. (2005). Distance Estimation in a VR application: interindividual differences and intra-individual stabilities from a psychological point of view. In *Proceedings of the 11th International Conference on Human-Computer Interaction* (pp. 642-0285).
- Armbrüster, C., Wolter, M., Kuhlen, T., Spijkers, W., & Fimm, B. (2008). Depth perception in virtual reality: distance estimations in peri- and extrapersonal space. *Cyberpsychology & Behavior*, *11*(1), 9-15.
- Bakdash, J. Z., Augustyn, J. S., & Proffitt, D. R. (2006, July). Large displays enhance spatial knowledge of a virtual environment. In *Proceedings of the 3rd symposium on Applied perception in graphics and visualization* (pp. 59-62). ACM.
- Baumberger, B., & Flückiger, M. (2004). The development of distance estimation in optic flow. *Perception*, *33*(9), 1081-1099.
- Baumberger, B., Isableu, B., & Flückiger, M. (2004). The visual control of stability in children and adults: postural readjustments in a ground optical flow. *Experimental Brain Research*, *159*(1), 33-46.

- Baumberger, B., Flückiger, M., Paquette, M., Bergeron, J., & Delorme, A. (2005). Perception of relative distance in a driving simulator. *Japanese Psychological Research*, 47(3), 230-237.
- Beall, A. C., Loomis, J. M., Philbeck, J. W., & Fikes, T. G. (1995, April). Absolute motion parallax weakly determines visual scale in real and virtual environments. In *IS&T/SPIE's Symposium on Electronic Imaging: Science & Technology* (pp. 288-297). International Society for Optics and Photonics.
- Bingham, G. P., Bradley, A., Bailey, M., & Vinner, R. (2001). Accommodation, occlusion, and disparity matching are used to guide reaching: A comparison of actual versus virtual environments. *Journal of Experimental Psychology: Human Perception and Performance*, 27(6), 1314.
- Bodenheimer, B., Meng, J., Wu, H., Narasimham, G., Rump, B., McNamara, T. P., ... & Rieser, J. J. (2007, July). Distance estimation in virtual and real environments using bisection. In *Proceedings of the 4th symposium on Applied perception in graphics and visualization* (pp. 35-40). ACM.
- Brooks Jr, F. P. (1999). What's real about virtual reality?. *Computer Graphics and Applications, IEEE*, 19(6), 16-27.
- Bruno, N., & Cutting, J. E. (1988). Minimodularity and the perception of layout. *Journal of Experimental Psychology: General*, 117(2), 161.

- Cardinali, L., Brozzoli, C., & Farnè, A. (2009). Peripersonal space and body schema: two labels for the same concept?. *Brain topography*, 21(3-4), 252-260.
- Creem, S. H., & Proffitt, D. R. (1998). Two memories for geographical slant: Separation and interdependence of action and awareness. *Psychonomic Bulletin & Review*, 5(1), 22-36.
- Creem-Regehr, S. H., Willemsen, P., Gooch, A. A., & Thompson, W. B. (2005). The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual indoor environments. *Perception*, 34(2), 191-204.
- Cutting, J. E., & Vishton, P. M. (1995). Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In W. Epstein & S. J. Rogers (Eds.), *Perception of space and motion* (pp. 69-117). San Diego: Academic Press.
- Daum, S. O., & Hecht, H. (2009). Distance estimation in vista space. *Attention, Perception, & Psychophysics*, 71(5), 1127-1137.
- Dixon, M. W., Wraga, M., Proffitt, D. R., & Williams, G. C. (2000). Eye height scaling of absolute size in immersive and nonimmersive displays. *Journal of Experimental Psychology: Human Perception and Performance*, 26(2), 582.
- Durgin, F. H., Fox, L. F., Lewis, J., & Walley, K. A. (2002). Perceptuomotor adaptation: More than meets the eye. *Psychonomic Society*, 7, 103-104.



- Eby, D. W., & Braunstein, M. L. (1995). The perceptual flattening of three-dimensional scenes enclosed by a frame. *PERCEPTION-LONDON-*, 24, 981-981.
- Elliott, D. (1987). The influence of walking speed and prior practice on locomotor distance estimation. *Journal of Motor Behavior*, 19(4), 476-485.
- Ellis, S. R. (1994). What are virtual environments?. *Computer Graphics and Applications, IEEE*, 14(1), 17-22.
- Ellis, S. R., & Menges, B. M. (1997). Judgments of the distance to nearby virtual objects: interaction of viewing conditions and accommodative demand. *Presence (Cambridge, Mass.)*, 6(4), 452.
- Foley, J. M. (1977). Effect of distance information and range on two indices of visually perceived distance. *Perception*, 6(4), 449-460.
- Foley, J. M. (1980). Binocular distance perception. *Psychological Review*, 87(5), 411-434.
- Fukushima, S. S., Loomis, J. M., & Da Silva, J. A. (1997). Visual perception of egocentric distance as assessed by triangulation. *Journal of Experimental Psychology: Human Perception & Performance*, 23(1), 86-100.
- Gibson, J. J. (1950). *The perception of the visual world*. Greenwood Press, Westport, Conn.
- Gogel, W. C. (1961). Convergence as a cue to absolute distance. *The Journal of Psychology*, 52(2), 287-301.

- Gogel, W. C., & Tietz, J. D. (1973). Absolute motion parallax and the specific distance tendency. *Perception & Psychophysics*, 13(2), 284-292.
- Gogel, W. C. (1976). An indirect method of measuring perceived distance from familiar size. *Perception & Psychophysics*, 20(6), 419-429.
- Gogel, W. C., & Tietz, J. D. (1979). A comparison of oculomotor and motion parallax cues of egocentric distance. *Vision Research*, 19(10), 1161-1170.
- Grechkin, T. Y., Nguyen, T. D., Plumert, J. M., Cremer, J. F., & Kearney, J. K. (2010). How does presentation method and measurement protocol affect distance estimation in real and virtual environments?. *ACM Transactions on Applied Perception (TAP)*, 7(4), 26.
- Grüsser, O. J. Grundlagen der neuronalen Informationsverarbeitung in den Sinnesorganen und im Gehirn. In S. Schindler & W. K. Giloi (Eds.), *Informatik-Fachberichte* (Vol. 16). Berlin: Springer, 1978, pp. 234–273.
- Grüsser, O. J. (1983). Multimodal structure of the extrapersonal space. In *Spatially oriented behavior* (pp. 327-352). Springer New York.

- He, Z. J., Wu, B., Ooi, T. L., Yarbrough, G., & Wu, J. (2004). Judging egocentric distance on the ground: Occlusion and surface integration. *PERCEPTION-LONDON-*, 33(7), 789-806.
- Hiro, O. (1996). Distance perception in driving. *Tohoku Psychologica Folia*, 55, 92-100.
- Interrante, V., Ries, B., & Anderson, L. (2006, March). Distance perception in immersive virtual environments, revisited. In *Virtual Reality Conference, 2006* (pp. 3-10). IEEE.
- Jones, J. A., Swan II, J. E., Singh, G., Kolstad, E., & Ellis, S. R. (2008, August). The effects of virtual reality, augmented reality, and motion parallax on egocentric depth perception. In *Proceedings of the 5th symposium on Applied perception in graphics and visualization* (pp. 9-14). ACM.
- Kelly, J. W., Loomis, J. M., & Beall, A. C. (2005). The importance of perceived relative motion in the control of posture. *Experimental Brain Research*, 161(3), 285-292.
- Klein, E., Stadt, O. G., Swan II, J. E., Schmidt, G., & Livingston, M. A. (2006, July). Egocentric medium-field distance perception in projection environments. In *ACM SIGGRAPH 2006 Research posters* (p. 181). ACM.

- Kline, P. B., & Witmer, B. G. (1996, October). Distance perception in virtual environments: Effects of field of view and surface texture at near distances. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 40, No. 22, pp. 1112-1116). SAGE Publications.
- Knapp, J. M. (1999). *The visual perception of egocentric distance in virtual environments*. (Doctoral dissertation). Retrieved from ProQuest. (UMI Number: 9987005)
- Knapp, J. M., & Loomis, J. M. (2004). Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence: Teleoperators and Virtual Environments*, 13(5), 572-577.
- Kuhl, S. A., Thompson, W. B., & Creem-Regehr, S. H. (2006, July). Minification influences spatial judgments in virtual environments. In *Proceedings of the 3rd symposium on Applied perception in graphics and visualization* (pp. 15-19). ACM.
- Kuhl, S. A., Thompson, W. B., & Creem-Regehr, S. H. (2009). HMD calibration and its effects on distance judgments. *ACM Transactions on Applied Perception (TAP)*, 6(3), 19.
- Kunz, B. R., Creem-Regehr, S. H., & Thompson, W. B. (2009). Evidence for motor simulation in imagined locomotion. *Journal of Experimental Psychology: Human Perception and Performance*, 35(5), 1458.

- Lappin, J. S., Shelton, A. L., & Rieser, J. J. (2006). Environmental context influences visually perceived distance. *Perception & Psychophysics*, 68(4), 571-581.
- Sciarini, W. L., Kemper, D., Guay, L., & Nicholson, D. (2008, September). Performance of Egocentric Range Estimation in a Laptop Based Virtual Environment. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 52, No. 27, pp. 2122-2126). SAGE Publications.
- Loomis, J. M., Da Silva, J. A., Fujita, N., & Fukusima, S. S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception & Performance*, 18(4), 906-921.
- Loomis, J. M., & Knapp, J. M. (2003). Visual perception of egocentric distance in real and virtual environments. In L. J. Hettinger & M. W. Haas (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp. 21-46). Mahwah, NJ: Erlbaum.
- Loomis, J. M., & Philbeck, J. W. (2008). *Measuring spatial perception with spatial updating and action* (pp. 1-43). Taylor & Francis, New York.
- Macredie, R. D., & Morar, S. S. (2000). Cognitive Issues in the Perception of Desktop Virtual Environments. *Journal of Intelligent Systems*, 10(5-6), 421-450.
- Messing, R., & Durgin, F. H. (2005). Distance perception and the visual horizon in head-mounted displays. *ACM Transactions on Applied Perception (TAP)*, 2(3), 234-250.

- Murgia, A., & Sharkey, P. M. (2009). Estimation of distances in virtual environments using size constancy. *International Journal of Virtual Reality*, 8(1), 67-74.
- Ohtsuka, S., Ujike, H. I. R. O. Y. A. S. U., & Saida, S. (1999). Scaling of motion parallax and absolute distance perception. *Japanese Journal of Psychonomic Science*, 17(2), 100-110.
- Ooi, T. L., Wu, B., & He, Z. J. (2001). Distance determined by the angular declination below the horizon. *Nature*, 414(6860), 197-200.
- Pagano, C. C., & Bingham, G. P. (1998). Comparing measures of monocular distance perception: Verbal and reaching errors are not correlated. *Journal of Experimental Psychology-Human Perception and Performance*, 24(4), 1037-1051.
- Pagano, C. C., Grutzmacher, R. P., & Jenkins, J. C. (2001). Comparing verbal and reaching responses to visually perceived egocentric distances. *Ecological Psychology*, 13(3), 197-226.
- Panerai, F., Droulez, J., Kelada, J. M., Kemeny, A., Balligand, E., & Favre, B. (2001, September). Speed and safety distance control in truck driving: comparison of simulation and real-world environment. In *Proceedings of driving simulation conference* (pp. 91-107).
- Pagano, C. C., & Isenhower, R. W. (2008). Expectation affects verbal judgments but not reaches to visually perceived egocentric distances. *Psychonomic bulletin & review*, 15(2), 437-442.
- Palmer, S. E. (1999). *Vision science: Photons to phenomenology* (Vol. 1). Cambridge, MA: MIT press.

- Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. *Journal of Experimental Psychology: Human Perception & Performance*, 23(1), 72-85.
- Plumert, J. M., Kearney, J. K., Cremer, J. F., & Recker, K. (2005). Distance perception in real and virtual environments. *ACM Transactions on Applied Perception (TAP)*, 2(3), 216-233.
- Predebon, J., & Woolley, J. S. (1994). The familiar-size cue to depth under reduced-cue viewing conditions. *PERCEPTION-LONDON-*, 23, 1301-1301.
- Proffitt, D. R. (2006). Distance perception. *Current Directions in Psychological Science*, 15(3), 131-135.
- Richardson, A. R., & Waller, D. (2007). Interaction with an immersive virtual environment corrects users' distance estimates. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(3), 507-517.
- Rizzolatti, G., Fadiga, L., Fogassi, L., & Gallese, V. (1997). The space around us. *Science*, 277(5323), 190-191.
- Rohaly, A. M., & Wilson, H. R. (1999). The effects of contrast on perceived depth and depth discrimination. *Vision Research*, 39(1), 9-18.
- Roumes, C., Meehan, J. W., Plantier, J., & Menu, J. P. (2001). Distance estimation in a 3-D imaging display. *The International Journal of Aviation Psychology*, 11(4), 381-396.

- Sahm, C. S., Creem-Regehr, S. H., Thompson, W. B., & Willemsen, P. (2005). Throwing versus walking as indicators of distance perception in similar real and virtual environments. *ACM Transactions on Applied Perception (TAP)*, 2(1), 35-45.
- Saracini, C., Franke, R., Blümel, E., & Belardinelli, M. O. (2009). Comparing distance perception in different virtual environments. *Cognitive processing*, 10, 294-296.
- Sinai, M. J., Ooi, T. L., & He, Z. J. (1998). Terrain influences the accurate judgement of distance. *Nature*, 395(6701), 497-500.
- Sinai, M. J., Krebs, W. K., Darken, R. P., Rowland, J. H., & McCarley, J. S. (1999, September). Egocentric Distance Perception in a Virtual Environment Using a Perceptual Matching Task. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 43, No. 22, pp. 1256-1260). SAGE Publications.
- Steenhuis, R. E., & Goodale, M. A. (1988). The effects of time and distance on accuracy of target-directed locomotion: Does an accurate short-term memory for spatial location exist?. *Journal of Motor Behavior*, 20(4), 399.
- Surdick, R. T., Davis, E. T., King, R. A., & Hodges, L. F. (1997). The perception of distance in simulated visual displays- A comparison of the effectiveness and accuracy of multiple depth cues across viewing distances. *Presence: Teleoperators and Virtual Environments*, 6(5), 513-531.



- Swan, J. E., Jones, A., Kolstad, E., Livingston, M. A., & Smallman, H. S. (2007). Egocentric depth judgments in optical, see-through augmented reality. *Visualization and Computer Graphics, IEEE Transactions on*, 13(3), 429-442.
- Thompson, W. B., Willemsen, P., Gooch, A. A., Creem-Regehr, S. H., Loomis, J. M., & Beall, A. C. (2004). Does the quality of the computer graphics matter when judging distance in visually immersive environments? *Presence: Teleoperators & Virtual Environments*, 13(5), 560-571.
- Thompson, W. B., Dilda, V., & Creem-Regehr, S. H. (2007). Absolute distance perception to locations off the ground plane. *PERCEPTION-LONDON-*, 36(11), 1559.
- Vianin, P., Baumberger, B., & Fluckiger, M. (2004). Distance estimation in a dynamic simulated environment: A visual field dependence problem?. *PERCEPTION-LONDON-*, 33, 561-568.
- Willemsen, P., & Gooch, A. A. (2002). Perceived egocentric distances in real, image-based, and traditional virtual environments. *In Proceedings of IEEE Virtual Reality Conference 2002* (p. 275). Washington, DC: IEEE Computer Society.
- Willemsen, P., Gooch, A. A., Thompson, W. B., & Creem-Regehr, S. H. (2008). Effects of stereo viewing conditions on distance perception in virtual environments. *Presence: Teleoperators & Virtual Environments*, 17, 91-101.

- Willemsen, P., Colton, M. B., Creem-Regehr, S. H., & Thompson, W. B. (2009). The effects of head-mounted display mechanical properties and field-of-view on distance judgments in virtual environments. *ACM Transactions on Applied Perception (TAP)*, 6(2).
- Witmer, B. G., & Kline, P. B. (1997). *Training efficiently in virtual environments: Determinants of distance perception of stationary observers viewing stationary objects* (No. ARI-RN-97-36). Army research inst for the behavioral and social Sciences alexandria va.
- Witmer, B. G., & Kline, P. B. (1998). Judging perceived and traversed distance in virtual environments. *Presence*, 7(2), 144-167.
- Witmer, B. G., & Sadowski, W. J. (1998). Nonvisually guided locomotion to a previously viewed target in real and virtual environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 40(3), 478-488.
- Witt, J. K., Stefanucci, J. K., Riener, C. R., & Proffitt, D. R. (2007). Seeing beyond the target: Environmental context affects distance perception. *PERCEPTION-LONDON-*, 36(12), 1752.
- Wu, B., Ooi, T. L., & He, Z. J. (2004). Perceiving distance accurately by a directional process of integrating ground information. *Nature*, 428(6978), 73-77.
- Ziemer, C. J., Plumert, J. M., Cremer, J. F., & Kearney, J. K. (2009). Estimating distance in real and virtual environments: Does order make a difference?. *Attention, Perception, & Psychophysics*, 71(5), 1095-1106.

## Appendices

### Appendix A

R squared values, F and P values for each participant for Expt. 1.

| Participants | Real World WHFOV |         |      | Real World NHFOV |        |      | Simplified World WHFOV |         |      | Simplified World NHFOV |        |      |
|--------------|------------------|---------|------|------------------|--------|------|------------------------|---------|------|------------------------|--------|------|
|              | R2               | F       | P    | R2               | F      | P    | R2                     | F       | P    | R2                     | F      | P    |
| 1            | 0.90             | 439.67  | 0.00 | 0.89             | 378.37 | 0.00 | 0.90                   | 416.43  | 0.00 | 0.90                   | 422.41 | 0.00 |
| 2            | 0.84             | 255.61  | 0.00 | 0.78             | 169.14 | 0.00 | 0.92                   | 530.97  | 0.00 | 0.81                   | 207.82 | 0.00 |
| 3            | 0.79             | 181.22  | 0.00 | 0.93             | 686.73 | 0.00 | 0.87                   | 319.03  | 0.00 | 0.93                   | 669.08 | 0.00 |
| 4            | 0.81             | 204.62  | 0.00 | 0.80             | 190.79 | 0.00 | 0.79                   | 183.93  | 0.00 | 0.78                   | 171.06 | 0.00 |
| 5            | 0.76             | 152.26  | 0.00 | 0.91             | 499.56 | 0.00 | 0.79                   | 184.17  | 0.00 | 0.92                   | 522.18 | 0.00 |
| 6            | 0.83             | 233.93  | 0.00 | 0.78             | 165.54 | 0.00 | 0.84                   | 252.82  | 0.00 | 0.85                   | 266.52 | 0.00 |
| 7            | 0.85             | 273.23  | 0.00 | 0.88             | 349.50 | 0.00 | 0.90                   | 424.17  | 0.00 | 0.91                   | 465.81 | 0.00 |
| 8            | 0.94             | 793.49  | 0.00 | 0.87             | 313.94 | 0.00 | 0.96                   | 1274.34 | 0.00 | 0.85                   | 280.97 | 0.00 |
| 9            | 0.62             | 77.04   | 0.00 | 0.59             | 69.01  | 0.00 | 0.66                   | 91.95   | 0.00 | 0.66                   | 93.71  | 0.00 |
| 10           | 0.97             | 1733.81 | 0.00 | 0.93             | 668.92 | 0.00 | 0.95                   | 978.03  | 0.00 | 0.91                   | 501.97 | 0.00 |
| 11           | 0.85             | 268.77  | 0.00 | 0.93             | 690.11 | 0.00 | 0.83                   | 230.45  | 0.00 | 0.88                   | 347.16 | 0.00 |
| 12           | 0.89             | 386.19  | 0.00 | 0.91             | 458.02 | 0.00 | 0.90                   | 434.65  | 0.00 | 0.90                   | 420.02 | 0.00 |
| 13           | 0.83             | 227.75  | 0.00 | 0.87             | 314.94 | 0.00 | 0.79                   | 181.88  | 0.00 | 0.87                   | 322.56 | 0.00 |
| 14           | 0.69             | 109.02  | 0.00 | 0.77             | 165.24 | 0.00 | 0.82                   | 216.00  | 0.00 | 0.74                   | 138.53 | 0.00 |
| 15           | 0.86             | 292.04  | 0.00 | 0.89             | 387.96 | 0.00 | 0.68                   | 102.07  | 0.00 | 0.87                   | 322.46 | 0.00 |
| 16           | 0.93             | 611.49  | 0.00 | 0.89             | 399.59 | 0.00 | 0.94                   | 779.32  | 0.00 | 0.91                   | 467.47 | 0.00 |
| 17           | 0.91             | 510.47  | 0.00 | 0.93             | 667.08 | 0.00 | 0.90                   | 409.66  | 0.00 | 0.95                   | 985.94 | 0.00 |
| 18           | 0.86             | 301.85  | 0.00 | 0.92             | 520.48 | 0.00 | 0.90                   | 423.79  | 0.00 | 0.88                   | 345.53 | 0.00 |
| 19           | 0.81             | 198.31  | 0.00 | 0.94             | 703.79 | 0.00 | 0.91                   | 506.16  | 0.00 | 0.92                   | 537.77 | 0.00 |
| 20           | 0.88             | 362.88  | 0.00 | 0.92             | 533.62 | 0.00 | 0.86                   | 306.68  | 0.00 | 0.88                   | 368.23 | 0.00 |

## Appendix B

R squared values, F and P values for each participant for Expt. 2.

| Participants | B&W Texture 0.5 |        |      | B&W Texture 2 |        |      | Horizon |        |      | Real World |        |      | Real World No Road |        |      | Real World Wider Road |        |      |
|--------------|-----------------|--------|------|---------------|--------|------|---------|--------|------|------------|--------|------|--------------------|--------|------|-----------------------|--------|------|
|              | R2              | F      | P    | R2            | F      | P    | R2      | F      | P    | R2         | F      | P    | R2                 | F      | P    | R2                    | F      | P    |
| 1            | 0.82            | 127.86 | 0.00 | 0.77          | 93.38  | 0.00 | 0.75    | 82.07  | 0.00 | 0.83       | 133.68 | 0.00 | 0.84               | 145.21 | 0.00 | 0.92                  | 315.84 | 0.00 |
| 2            | 0.71            | 68.35  | 0.00 | 0.77          | 96.16  | 0.00 | 0.91    | 293.46 | 0.00 | 0.86       | 167.46 | 0.00 | 0.92               | 309.15 | 0.00 | 0.84                  | 143.30 | 0.00 |
| 3            | 0.90            | 240.44 | 0.00 | 0.66          | 54.67  | 0.00 | 0.86    | 173.51 | 0.00 | 0.70       | 65.17  | 0.00 | 0.77               | 94.94  | 0.00 | 0.82                  | 124.19 | 0.00 |
| 4            | 0.83            | 139.37 | 0.00 | 0.75          | 84.84  | 0.00 | 0.88    | 207.44 | 0.00 | 0.59       | 39.53  | 0.00 | 0.85               | 154.52 | 0.00 | 0.83                  | 136.66 | 0.00 |
| 5            | 0.84            | 145.64 | 0.00 | 0.88          | 201.61 | 0.00 | 0.86    | 165.15 | 0.00 | 0.75       | 84.78  | 0.00 | 0.86               | 176.29 | 0.00 | 0.79                  | 107.60 | 0.00 |
| 6            | 0.80            | 109.51 | 0.00 | 0.70          | 65.96  | 0.00 | 0.78    | 97.91  | 0.00 | 0.73       | 74.96  | 0.00 | 0.75               | 85.34  | 0.00 | 0.30                  | 11.75  | 0.00 |
| 7            | 0.89            | 235.67 | 0.00 | 0.88          | 198.59 | 0.00 | 0.91    | 270.56 | 0.00 | 0.90       | 263.22 | 0.00 | 0.89               | 233.71 | 0.00 | 0.79                  | 105.73 | 0.00 |
| 8            | 0.81            | 122.10 | 0.00 | 0.84          | 150.08 | 0.00 | 0.90    | 258.31 | 0.00 | 0.89       | 220.57 | 0.00 | 0.89               | 225.04 | 0.00 | 0.86                  | 174.02 | 0.00 |
| 9            | 0.78            | 99.72  | 0.00 | 0.71          | 68.88  | 0.00 | 0.58    | 38.40  | 0.00 | 0.73       | 74.34  | 0.00 | 0.72               | 70.58  | 0.00 | 0.74                  | 78.93  | 0.00 |
| 10           | 0.89            | 218.69 | 0.00 | 0.86          | 174.76 | 0.00 | 0.89    | 233.10 | 0.00 | 0.91       | 283.17 | 0.00 | 0.89               | 216.48 | 0.00 | 0.79                  | 106.01 | 0.00 |
| 11           | 0.66            | 54.69  | 0.00 | 0.71          | 70.12  | 0.00 | 0.79    | 102.59 | 0.00 | 0.75       | 84.43  | 0.00 | 0.79               | 105.22 | 0.00 | 0.74                  | 80.09  | 0.00 |
| 12           | 0.56            | 36.23  | 0.00 | 0.77          | 96.02  | 0.00 | 0.78    | 101.55 | 0.00 | 0.65       | 52.26  | 0.00 | 0.86               | 172.74 | 0.00 | 0.85                  | 153.57 | 0.00 |
| 13           | 0.91            | 282.06 | 0.00 | 0.85          | 162.81 | 0.00 | 0.88    | 206.79 | 0.00 | 0.93       | 346.37 | 0.00 | 0.84               | 143.34 | 0.00 | 0.89                  | 227.94 | 0.00 |
| 14           | 0.64            | 49.07  | 0.00 | 0.71          | 68.72  | 0.00 | 0.80    | 109.61 | 0.00 | 0.62       | 45.12  | 0.00 | 0.84               | 145.60 | 0.00 | 0.73                  | 75.94  | 0.00 |
| 15           | 0.79            | 103.14 | 0.00 | 0.83          | 132.90 | 0.00 | 0.89    | 215.56 | 0.00 | 0.87       | 181.29 | 0.00 | 0.84               | 151.88 | 0.00 | 0.90                  | 262.08 | 0.00 |
| 16           | 0.93            | 390.47 | 0.00 | 0.96          | 610.09 | 0.00 | 0.91    | 288.24 | 0.00 | 0.13       | 4.02   | 0.05 | 0.94               | 443.15 | 0.00 | 0.87                  | 194.26 | 0.00 |
| 17           | 0.83            | 136.25 | 0.00 | 0.79          | 107.54 | 0.00 | 0.78    | 101.55 | 0.00 | 0.74       | 81.63  | 0.00 | 0.77               | 93.76  | 0.00 | 0.80                  | 112.28 | 0.00 |
| 18           | 0.76            | 91.01  | 0.00 | 0.77          | 95.91  | 0.00 | 0.82    | 126.83 | 0.00 | 0.90       | 252.75 | 0.00 | 0.75               | 84.33  | 0.00 | 0.78                  | 100.20 | 0.00 |
| 19           | 0.71            | 69.72  | 0.00 | 0.63          | 47.43  | 0.00 | 0.79    | 102.68 | 0.00 | 0.58       | 38.87  | 0.00 | 0.73               | 77.32  | 0.00 | 0.48                  | 26.07  | 0.00 |
| 20           | 0.88            | 209.11 | 0.00 | 0.77          | 95.67  | 0.00 | 0.85    | 154.76 | 0.00 | 0.77       | 96.33  | 0.00 | 0.77               | 95.70  | 0.00 | 0.70                  | 65.55  | 0.00 |
| 22           | 0.87            | 182.28 | 0.00 | 0.79          | 106.04 | 0.00 | 0.88    | 212.01 | 0.00 | 0.82       | 127.95 | 0.00 | 0.85               | 161.06 | 0.00 | 0.76                  | 90.70  | 0.00 |
| 23           | 0.64            | 50.86  | 0.00 | 0.67          | 57.34  | 0.00 | 0.77    | 95.72  | 0.00 | 0.73       | 74.97  | 0.00 | 0.81               | 115.83 | 0.00 | 0.74                  | 80.95  | 0.00 |
| 24           | 0.84            | 149.00 | 0.00 | 0.81          | 121.57 | 0.00 | 0.87    | 187.54 | 0.00 | 0.79       | 103.34 | 0.00 | 0.86               | 166.94 | 0.00 | 0.88                  | 206.29 | 0.00 |
| 25           | 0.87            | 180.06 | 0.00 | 0.81          | 122.75 | 0.00 | 0.83    | 136.16 | 0.00 | 0.88       | 211.99 | 0.00 | 0.89               | 226.15 | 0.00 | 0.88                  | 206.20 | 0.00 |
| 26           | 0.89            | 222.21 | 0.00 | 0.81          | 117.57 | 0.00 | 0.89    | 234.11 | 0.00 | 0.83       | 137.03 | 0.00 | 0.84               | 144.03 | 0.00 | 0.79                  | 107.06 | 0.00 |
| 27           | 0.96            | 696.92 | 0.00 | 0.95          | 501.02 | 0.00 | 0.86    | 167.70 | 0.00 | 0.87       | 190.10 | 0.00 | 0.88               | 196.90 | 0.00 | 0.83                  | 133.74 | 0.00 |
| 28           | 0.74            | 79.49  | 0.00 | 0.66          | 54.90  | 0.00 | 0.65    | 52.72  | 0.00 | 0.62       | 45.88  | 0.00 | 0.62               | 45.52  | 0.00 | 0.74                  | 81.64  | 0.00 |
| 29           | 0.54            | 33.42  | 0.00 | 0.66          | 55.07  | 0.00 | 0.58    | 37.95  | 0.00 | 0.54       | 33.03  | 0.00 | 0.65               | 51.77  | 0.00 | 0.40                  | 19.04  | 0.00 |
| 30           | 0.54            | 32.79  | 0.00 | 0.61          | 43.72  | 0.00 | 0.39    | 17.73  | 0.00 | 0.69       | 61.39  | 0.00 | 0.71               | 67.48  | 0.00 | 0.72                  | 71.82  | 0.00 |
| 31           | 0.86            | 165.99 | 0.00 | 0.92          | 317.23 | 0.00 | 0.90    | 257.48 | 0.00 | 0.82       | 123.57 | 0.00 | 0.89               | 232.35 | 0.00 | 0.90                  | 254.80 | 0.00 |

## Appendix C

The slope of regression fit to a scatter plot of estimated distance versus actual distance for each participant for Expt. 2.

| Participant # | B&W Texture 0.5 | B&W Texture 2 | Horizon    | Real World | Real World No Road | Real World Wider Road |
|---------------|-----------------|---------------|------------|------------|--------------------|-----------------------|
| 1             | 0.72            | 0.75          | 0.78       | 0.68       | 0.62               | 0.66                  |
| 2             | 0.32            | 0.36          | 0.54       | 0.36       | 0.32               | 0.31                  |
| 3             | 0.85            | 1.18          | 0.96       | 1.09       | 0.9                | 0.86                  |
| 4             | 0.71            | 0.65          | 0.74       | 0.5        | 0.64               | 0.64                  |
| 5             | 1.61            | 1.53          | 1.7        | 1.28       | 1.4                | 1.23                  |
| 6             | 0.64            | 0.47          | 0.61       | 0.51       | 0.42               | 0.37                  |
| 7             | 0.18            | 0.17          | 0.17       | 0.18       | 0.17               | 0.16                  |
| 8             | 0.59            | 0.64          | 0.72       | 0.59       | 0.67               | 0.61                  |
| 9             | 1.84            | 1.36          | 1.43       | 1.52       | 1.34               | 1.57                  |
| 10            | 0.68            | 0.59          | 0.73       | 0.47       | 0.57               | 0.52                  |
| 11            | 0.47            | 0.39          | 0.6        | 0.33       | 0.34               | 0.25                  |
| 12            | 0.28            | 0.44          | 0.41       | 0.37       | 0.42               | 0.38                  |
| 13            | 0.64            | 0.61          | 0.68       | 0.61       | 0.62               | 0.63                  |
| 14            | 0.59            | 0.59          | 0.67       | 0.44       | 0.63               | 0.56                  |
| 15            | 1.04            | 1.11          | 1.22       | 1.19       | 1.12               | 1.26                  |
| 16            | 0.42            | 0.43          | 0.43       | 0.43       | 0.42               | 0.38                  |
| 18            | 0.25            | 0.27          | 0.32       | 0.29       | 0.24               | 0.28                  |
| 19            | 0.92            | 0.79          | 0.9        | 0.71       | 0.81               | 0.66                  |
| 20            | 0.91            | 0.86          | 0.94       | 0.71       | 0.62               | 0.53                  |
| 22            | 1.01            | 0.91          | 1.12       | 0.92       | 0.85               | 0.92                  |
| 23            | 8.4             | 8.96          | 10.5       | 8.5        | 10.83              | 10.21                 |
| 24            | 0.23            | 0.26          | 0.28       | 0.28       | 0.28               | 0.26                  |
| 25            | 1.13            | 1.08          | 1.27       | 0.89       | 1.01               | 0.94                  |
| 26            | 0.79            | 0.7           | 0.8        | 0.6        | 0.66               | 0.63                  |
| 27            | 0.96            | 1.04          | 0.94       | 0.75       | 0.87               | 0.71                  |
| 28            | 3.76            | 4.52          | 5.41       | 2.7        | 3.03               | 2.55                  |
| 29            | 1.58            | 1.72          | 1.69       | 0.89       | 1.02               | 1.47                  |
| 30            | 0.53            | 0.64          | 0.47       | 0.62       | 0.63               | 0.57                  |
| 31            | 0.64            | 0.68          | 0.7        | 0.62       | 0.67               | 0.65                  |
| <b>Mean</b>   | <b>1.13</b>     | <b>1.16</b>   | <b>1.3</b> | <b>1</b>   | <b>1.11</b>        | <b>1.06</b>           |

## Appendix D

R squared values, F and P values for each participant for Expt. 3.

| Participants | B&W Texture |        |      | Daylight Horizon |        |      | Horizon |        |      | Real World |        |      | Real World No Road |        |      |
|--------------|-------------|--------|------|------------------|--------|------|---------|--------|------|------------|--------|------|--------------------|--------|------|
|              | R2          | F      | P    | R2               | F      | P    | R2      | F      | P    | R2         | F      | P    | R2                 | F      | P    |
| 1            | 0.61        | 43.78  | 0.00 | 0.65             | 51.41  | 0.00 | 0.60    | 41.62  | 0.00 | 0.47       | 24.54  | 0.00 | 0.48               | 26.11  | 0.00 |
| 2            | 0.88        | 197.96 | 0.00 | 0.78             | 96.89  | 0.00 | 0.85    | 155.24 | 0.00 | 0.77       | 96.35  | 0.00 | 0.68               | 58.21  | 0.00 |
| 3            | 0.80        | 111.90 | 0.00 | 0.88             | 205.47 | 0.00 | 0.74    | 78.71  | 0.00 | 0.78       | 98.61  | 0.00 | 0.79               | 106.81 | 0.00 |
| 4            | 0.92        | 324.33 | 0.00 | 0.67             | 57.85  | 0.00 | 0.94    | 468.43 | 0.00 | 0.91       | 295.29 | 0.00 | 0.90               | 254.15 | 0.00 |
| 5            | 0.83        | 132.14 | 0.00 | 0.31             | 12.65  | 0.00 | 0.60    | 41.29  | 0.00 | 0.87       | 188.71 | 0.00 | 0.56               | 35.35  | 0.00 |
| 7            | 0.82        | 130.70 | 0.00 | 0.94             | 439.00 | 0.00 | 0.81    | 116.86 | 0.00 | 0.89       | 235.63 | 0.00 | 0.84               | 149.33 | 0.00 |
| 8            | 0.70        | 64.72  | 0.00 | 0.77             | 92.53  | 0.00 | 0.71    | 69.16  | 0.00 | 0.84       | 148.90 | 0.00 | 0.75               | 85.33  | 0.00 |
| 9            | 0.84        | 149.35 | 0.00 | 0.82             | 126.42 | 0.00 | 0.89    | 230.16 | 0.00 | 0.92       | 325.73 | 0.00 | 0.84               | 143.12 | 0.00 |
| 10           | 0.68        | 58.26  | 0.00 | 0.64             | 50.06  | 0.00 | 0.56    | 35.40  | 0.00 | 0.59       | 40.41  | 0.00 | 0.59               | 39.68  | 0.00 |
| 11           | 0.76        | 90.03  | 0.00 | 0.76             | 90.57  | 0.00 | 0.84    | 151.82 | 0.00 | 0.67       | 56.91  | 0.00 | 0.74               | 80.20  | 0.00 |
| 12           | 0.74        | 79.47  | 0.00 | 0.72             | 70.71  | 0.00 | 0.76    | 89.58  | 0.00 | 0.80       | 110.78 | 0.00 | 0.61               | 43.12  | 0.00 |
| 13           | 0.72        | 73.11  | 0.00 | 0.82             | 125.08 | 0.00 | 0.71    | 69.78  | 0.00 | 0.73       | 74.05  | 0.00 | 0.76               | 90.63  | 0.00 |
| 14           | 0.46        | 24.20  | 0.00 | 0.85             | 157.64 | 0.00 | 0.85    | 155.14 | 0.00 | 0.89       | 233.84 | 0.00 | 0.88               | 199.06 | 0.00 |
| 15           | 0.93        | 365.23 | 0.00 | 0.92             | 315.30 | 0.00 | 0.94    | 437.50 | 0.00 | 0.90       | 252.26 | 0.00 | 0.94               | 408.31 | 0.00 |
| 16           | 0.84        | 145.23 | 0.00 | 0.87             | 185.63 | 0.00 | 0.84    | 149.85 | 0.00 | 0.88       | 199.64 | 0.00 | 0.75               | 82.78  | 0.00 |
| 17           | 0.84        | 144.24 | 0.00 | 0.82             | 130.66 | 0.00 | 0.86    | 168.45 | 0.00 | 0.86       | 174.03 | 0.00 | 0.89               | 233.83 | 0.00 |
| 18           | 0.80        | 112.41 | 0.00 | 0.86             | 177.27 | 0.00 | 0.88    | 198.13 | 0.00 | 0.80       | 113.16 | 0.00 | 0.82               | 131.42 | 0.00 |
| 19           | 0.96        | 733.87 | 0.00 | 0.96             | 635.90 | 0.00 | 0.90    | 250.14 | 0.00 | 0.95       | 558.30 | 0.00 | 0.89               | 230.16 | 0.00 |

## Appendix E

R squared values, F and P values for each participant for Expt. 4.

| Participants | Motion B&W Texture |        |      |  | Motion Real World |        |      |  | Motion Real World No Road |        |      |  | Static B&W Texture |        |      |  | Static Horizon |        |      | Static Real World |        |      |    | Static Real World No Road |        |      |
|--------------|--------------------|--------|------|--|-------------------|--------|------|--|---------------------------|--------|------|--|--------------------|--------|------|--|----------------|--------|------|-------------------|--------|------|----|---------------------------|--------|------|
|              | R2                 | F      | P    |  | R2                | F      | P    |  | R2                        | F      | P    |  | R2                 | F      | P    |  | R2             | F      | P    | R2                | F      | P    | R2 | F                         | P      |      |
| 1            | 0.85               | 154.45 | 0.00 |  | 0.68              | 58.87  | 0.00 |  | 0.60                      | 41.67  | 0.00 |  | 0.69               | 61.63  | 0.00 |  |                |        |      | 0.74              | 81.57  | 0.00 |    | 0.72                      | 70.61  | 0.00 |
| 2            | 0.82               | 131.43 | 0.00 |  | 0.87              | 191.84 | 0.00 |  | 0.83                      | 135.33 | 0.00 |  | 0.79               | 106.92 | 0.00 |  |                |        |      | 0.88              | 196.50 | 0.00 |    | 0.81                      | 120.80 | 0.00 |
| 3            | 0.90               | 240.07 | 0.00 |  | 0.96              | 607.82 | 0.00 |  | 0.92                      | 321.71 | 0.00 |  | 0.90               | 242.44 | 0.00 |  | 0.94           | 283.32 | 0.00 | 0.97              | 877.15 | 0.00 |    | 0.94                      | 403.27 | 0.00 |
| 4            | 0.67               | 57.19  | 0.00 |  | 0.60              | 41.65  | 0.00 |  | 0.64                      | 50.82  | 0.00 |  | 0.70               | 64.17  | 0.00 |  | 0.91           | 172.17 | 0.00 | 0.62              | 45.46  | 0.00 |    | 0.72                      | 71.97  | 0.00 |
| 5            | 0.91               | 272.06 | 0.00 |  | 0.88              | 197.01 | 0.00 |  | 0.90                      | 247.39 | 0.00 |  | 0.91               | 296.87 | 0.00 |  | 0.90           | 162.81 | 0.00 | 0.88              | 207.10 | 0.00 |    | 0.90                      | 254.12 | 0.00 |
| 6            | 0.82               | 130.56 | 0.00 |  | 0.80              | 111.42 | 0.00 |  | 0.87                      | 181.07 | 0.00 |  | 0.85               | 156.88 | 0.00 |  | 0.94           | 300.97 | 0.00 | 0.78              | 100.35 | 0.00 |    | 0.80                      | 114.45 | 0.00 |
| 7            | 0.87               | 184.28 | 0.00 |  | 0.88              | 199.45 | 0.00 |  | 0.89                      | 216.63 | 0.00 |  | 0.89               | 224.28 | 0.00 |  | 0.94           | 284.36 | 0.00 | 0.89              | 229.51 | 0.00 |    | 0.88                      | 197.62 | 0.00 |
| 8            | 0.82               | 127.04 | 0.00 |  | 0.86              | 169.69 | 0.00 |  | 0.85                      | 161.76 | 0.00 |  | 0.77               | 95.75  | 0.00 |  | 0.76           | 58.04  | 0.00 | 0.80              | 111.61 | 0.00 |    | 0.78                      | 99.52  | 0.00 |
| 9            | 0.92               | 323.77 | 0.00 |  | 0.94              | 444.40 | 0.00 |  | 0.92                      | 309.09 | 0.00 |  | 0.94               | 417.28 | 0.00 |  | 0.98           | 731.58 | 0.00 | 0.90              | 251.27 | 0.00 |    | 0.93                      | 394.98 | 0.00 |
| 10           | 0.44               | 21.93  | 0.00 |  | 0.33              | 13.72  | 0.00 |  | 0.47                      | 25.20  | 0.00 |  | 0.44               | 21.97  | 0.00 |  | 0.81           | 74.52  | 0.00 | 0.60              | 42.30  | 0.00 |    | 0.39                      | 18.21  | 0.00 |
| 11           | 0.63               | 47.28  | 0.00 |  | 0.78              | 100.86 | 0.00 |  | 0.65                      | 52.59  | 0.00 |  | 0.69               | 63.63  | 0.00 |  | 0.63           | 30.51  | 0.00 | 0.55              | 33.80  | 0.00 |    | 0.78                      | 102.10 | 0.00 |
| 12           | 0.88               | 213.08 | 0.00 |  | 0.90              | 244.88 | 0.00 |  | 0.91                      | 288.72 | 0.00 |  | 0.96               | 625.38 | 0.00 |  | 0.93           | 233.30 | 0.00 | 0.86              | 172.71 | 0.00 |    | 0.80                      | 111.77 | 0.00 |
| 13           | 0.81               | 122.97 | 0.00 |  | 0.85              | 153.20 | 0.00 |  | 0.83                      | 137.76 | 0.00 |  | 0.83               | 138.38 | 0.00 |  | 0.86           | 109.78 | 0.00 | 0.71              | 70.25  | 0.00 |    | 0.83                      | 134.51 | 0.00 |
| 14           | 0.84               | 148.11 | 0.00 |  | 0.85              | 162.39 | 0.00 |  | 0.91                      | 296.87 | 0.00 |  | 0.89               | 237.95 | 0.00 |  | 0.87           | 115.89 | 0.00 | 0.86              | 171.13 | 0.00 |    | 0.90                      | 250.94 | 0.00 |
| 15           | 0.77               | 91.88  | 0.00 |  | 0.91              | 277.14 | 0.00 |  | 0.88                      | 213.88 | 0.00 |  | 0.84               | 150.03 | 0.00 |  | 0.86           | 107.50 | 0.00 | 0.81              | 118.63 | 0.00 |    | 0.80                      | 112.87 | 0.00 |
| 16           | 0.85               | 161.15 | 0.00 |  | 0.86              | 167.72 | 0.00 |  | 0.83                      | 139.98 | 0.00 |  | 0.82               | 126.08 | 0.00 |  | 0.85           | 101.03 | 0.00 | 0.90              | 255.28 | 0.00 |    | 0.93                      | 363.07 | 0.00 |
| 17           | 0.86               | 166.37 | 0.00 |  | 0.69              | 61.36  | 0.00 |  | 0.76                      | 86.97  | 0.00 |  | 0.79               | 102.51 | 0.00 |  | 0.91           | 179.83 | 0.00 | 0.71              | 68.88  | 0.00 |    | 0.83                      | 137.35 | 0.00 |
| 18           | 0.90               | 249.44 | 0.00 |  | 0.83              | 132.26 | 0.00 |  | 0.89                      | 228.09 | 0.00 |  | 0.80               | 113.03 | 0.00 |  | 0.95           | 356.27 | 0.00 | 0.78              | 97.90  | 0.00 |    | 0.86                      | 173.09 | 0.00 |
| 19           | 0.77               | 91.21  | 0.00 |  | 0.80              | 114.32 | 0.00 |  | 0.75                      | 84.81  | 0.00 |  | 0.49               | 26.94  | 0.00 |  | 0.47           | 15.94  | 0.00 | 0.73              | 75.76  | 0.00 |    | 0.60                      | 42.09  | 0.00 |

## Appendix F

R squared values, F and P values for each participant for Expt. 5.

| Participants | Daytime |        |      | Nighttime |         |      |
|--------------|---------|--------|------|-----------|---------|------|
|              | R2      | F      | P    | R2        | F       | P    |
| 0            | 0.91    | 275.81 | 0.00 | 0.92      | 322.92  | 0.00 |
| 1            | 0.97    | 858.05 | 0.00 | 0.96      | 676.32  | 0.00 |
| 3            | 0.75    | 74.77  | 0.00 | 0.83      | 138.51  | 0.00 |
| 5            | 0.74    | 80.29  | 0.00 | 0.78      | 99.13   | 0.00 |
| 6            | 0.91    | 269.01 | 0.00 | 0.90      | 254.44  | 0.00 |
| 7            | 0.63    | 39.12  | 0.00 | 0.97      | 752.61  | 0.00 |
| 8            | 0.94    | 342.04 | 0.00 | 0.87      | 158.48  | 0.00 |
| 9            | 0.87    | 181.62 | 0.00 | 0.85      | 164.64  | 0.00 |
| 10           | 0.82    | 126.85 | 0.00 | 0.90      | 238.94  | 0.00 |
| 11           | 0.93    | 398.87 | 0.00 | 0.86      | 167.54  | 0.00 |
| 12           | 0.94    | 442.10 | 0.00 | 0.95      | 520.41  | 0.00 |
| 13           | 0.96    | 697.09 | 0.00 | 0.98      | 1364.94 | 0.00 |