Effects of Field of View on Performance with Head-Mounted Displays

by

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ABSTRACT

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Effects of Field of View on Performance with Head-Mounted Displays
(Under the direction of Frederick P. Brooks, Jr.)

The field of view (FOV) in most head-mounted displays (HMDs) is no more than 60 degrees wide – far narrower than our normal FOV of about 200° wide. This mismatch arises mostly from the difficulty and expense of building wide-FOV HMDs. Restricting a person's FOV, however, has been shown in real environments to affect people's behavior and degrade task performance. Previous work in virtual reality too has shown that restricting FOV to 50° or less in an HMD can degrade performance.

I conducted experiments with a custom, wide-FOV HMD and found that performance is degraded even at the relatively high FOV of 112°, and further at 48°. The experiments used a prototype tiled wide-FOV HMD to measure performance in VR at up to 176° total horizontal FOV, and a custom large-area tracking system to establish new findings on performance while walking about a large virtual environment.

FOV was significant in predicting performance of two tasks: searching for and locating a target by turning one's head, and walking through a simple maze-like environment while avoiding walls. Wide FOV (112° or greater) was especially important for the walking task; for it, performance at 112° was 23% less than at 176°. At 48°, performance was 31% less than at 176°. For the search task, performance at 112° was 12% less than at 176°. At 48°, performance was 24% less than at 176°.

Additional analyses of the data show trends that suggest future investigation. Restricting FOV appears to decrease the user's sense of presence, as measured by a questionnaire. VR sickness, also measured by questionnaire, increased with successive exposures to our system within an hour-long session, but stayed at relatively low levels. FOV appears to alter the occurrence of some sickness symptoms, but the data are inconclusive on whether FOV predicts total sickness. I performed additional measures and analyses, including tests of postural instability, distance memory, spatial memory, head-movement behavior, and comparisons with other HMDs and with real-world performance.

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Introduction

1.1 Introduction

The human field of view (FOV) spans approximately 200 degrees horizontally, taking into account both eyes, and 135 degrees vertically (Gibson, 1979; Werner, 1991; Barfield et al., 1995). (Figure 1-1 shows the typical human FOV for one eye.) Virtual reality (VR) systems replace that view with a simulated one, generated in our case by a head-mounted display and a computer graphics system (Sutherland, 1965; Ellis et al., 1993; Brooks, 1999). In VR, to the extent that the technology affords it, we can perform tasks and feel "present" in the virtual environment the same way we feel present in the real world. For VR to be effective, the design or choice of system needs to take into account the characteristics of human perception and performance. A key design variable for a head-mounted display (HMD) is the FOV size. Most HMDs offer limited FOV, often only 40° to 60° horizontally and 30° to 45° vertically. This work reports on studies to determine how such restrictions of FOV affect performance in VR.

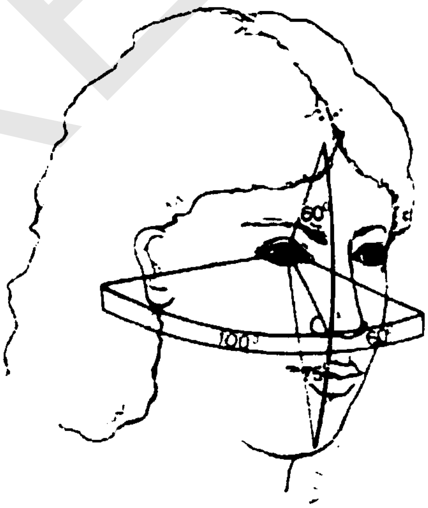

Figure 1-1. Normal human field of view. From Werner (1991).

The effects of FOV on performance have been studied in other contexts. Scientists have tested peoples' behavior while viewing the real world through FOV-restricting goggles (blinders).

Narrow FOV has been shown to degrade performance on locomotion, visual search, and spatial awareness tasks; it causes longer task completion times, disrupted eye- and head-movement coordination, and misperception of size, space, and ego-center (Dolezal, 1982a; Alfano and Michel, 1990). Limited studies have shown some similar effects to occur in VR or flight simulators, in locomotion by flying (Kenyon and Kneller, 1993; de Vries and Padmos, 1997) and in searching tasks (Wells and Venturino, 1990; Piantanida et al., 1992; Cunningham et al., 1996).

Too wide a FOV in VR may also degrade performance; it may cause VR sickness. Researchers have hypothesized that wide FOV in VR will aggravate sickness due to vection and visual-vestibular mismatch (Kolasinski, 1995), which can occur when there are lags in the VR system or other sources of mismatch. Results to date, including those from the present study, have neither confirmed nor refuted this hypothesis, but given how low the levels of VR sickness are that we see with current systems it appears unlikely that wide FOV will cause serious VR sickness under typical circumstances. It may, however, aggravate VR sickness in unusual circumstances with high vection; moving backgrounds, travel by flying, or rotating-scene stimuli (Stern et al., 1990; So and Lo, 1999) may be such cases.

Too wide a FOV may of course be unnecessary for tasks where the 3D region of interest is small, and therefore inefficient given the engineering costs. Thus FOV choice depends on the task as well as on considerations of performance and sickness.

1.2 New approaches

This document presents research investigating the effects of FOV on task performance, sickness, and other factors in VR. In particular I studied the following:

- Performance with a wide-FOV head-mounted display. Previous work comparing FOV sizes in VR has used HMDs with FOV of approximately 120° or less[1]. For the present work I used a 176° tiled display from Kaiser Electro-Optics – the widest FOV available in a HMD at the time of the study.

[1] In studies where *total* FOV was the variable, as it is in the present study, the highest FOV tested in VR is 90° (Piantanida et al., 1992). Piantanida et al. compared performance at total FOV of 90°, 53°, and smaller. They used a VPL EyePhone HMD and reported its FOV as "approximately 100°"; Robinett and Rolland (1992), however, have measured its actual FOV to be 90°. In a different type of FOV study, where total FOV remained constant but stimulus FOV varied, the largest FOV tested in an HMD is 120°, by Wells et al. (1990) using the VCASS HMD for a flight simulator. Total FOV remained constant at 120° and the size of an inner region containing target stimuli was reduced.

- Performance when walking about a large environment. I used the UNC-CH optical ceiling tracker to allow subjects to walk about a 10 m by 4 m environment. This allowed for measuring the effects of FOV on locomotion in VR by real walking, which has not been tested previously.

- Performance of generic spatial tasks chosen to be representative of the tasks typically performed in virtual environments. These generic tasks are: a search task, a walking task, a distance judgment task (distance from observer to object), and a spatial memory task (arrangement of objects with respect to each other).

- Health effects of FOV. VR sickness was measured by questionnaire and by postural instability measures.

These tasks were performed with three different FOV sizes (48°, 112°, and 176° horizontal by 47° vertical, as calibrated in the Kaiser HMD). For comparison, some tasks were tested in the Virtual Research V8 HMD (48° by 36°) and in a real-world blindered condition (48° by 36°).

The following thesis statement summarizes the hypotheses that were verified by the studies.

1.3 Thesis statement

Restricting FOV in a head-mounted display degrades human performance. Performance is degraded even at the moderately high FOV of 112° horizontal. The severity of the effect depends on the task: it affects locomotion (or travel) performance most.

1.4 Summary of findings

I tested task performance at three levels of horizontal FOV: 48°, 112°, and 176° and found the following statistically significant results ($p < .0125$). In all cases the percent-performance comparison is to 176° FOV.

Restricting FOV degrades performance on searching and walking tasks at both 48° and 112°. Gains can be had beyond 112°, which is wider than the FOV available in most commercially available HMDs.

Searching: restricting FOV degrades performance by 12% at 112° and by 24% at 48°. For a headcentric search task with targets whose initial position was outside the visual field, performance decreased by the same amount between the two levels (12% decrease in performance for each drop of 64°). If we consider performance at 176° to be 100%, then restricting FOV to 112° decreased performance to 88%; restricting further to 48° decreased performance to 76%.

Walking: restricting FOV degrades performance by 23% at 112° and by 31% at 48°. For a task of walking through a simple maze-like environment while avoiding walls, performance decreased most in the drop from 176° to 112°, suggesting that a wide FOV benefits locomotion (travel) most. If performance at 176° is 100%, then we saw performance at 112° of 77% (a drop of 23%) and performance at 48° of 69% (a further drop of 8%).

Sickness and FOV. The data were not statistically significant on FOV predicting sickness or not. Opposing (and non-significant) trends were seen, however, on the nausea and disorientation subscores of the SSQ. The levels of sickness seen were low in all conditions.

Visual quality is still important. The vastly better visual quality, the lower weight, and the lower display latency available with the V8 HMD and in the real-world with blinders may have been enough to overcome the performance losses due to restricted FOV for the tasks I tested. Performance in those conditions was slightly better than with the Kaiser HMD at 176°. Practice effects may also have caused some of this improvement.

Future work. Areas for future research are discussed, including the following.

- Augmented HMDs. New HMD designs that use add-on ambient peripheral displays may be the best route towards balancing the trade-offs between FOV and rendering speed. Studies are needed to measure their effectiveness and to choose the best design parameters.

- FOV and presence. The present study found a trend in presence scores, that presence was lower with restricted FOV. Further studies are recommended to establish statistical significance for this hypothesis, using more samples and better measures of presence.

- VR sickness and postural instability. The present study found low sickness levels in general, and found no trend of higher total sickness or postural instability with wider FOV as had been hypothesized. There was a trend of disorientation subscores increasing with wider FOV and nausea subscores decreasing with wider FOV. Finer measures, longer exposure times, and more statistical power would be needed to prove or disprove this trend. It's possible that in practice sickness will not be significant enough that FOV size will change it. The same may be true of postural instability in VR.

1.5 Definition of terms

Field of view (FOV). The angular extent subtended by a display in front of the eyes. The typical human FOV is about 200° horizontal by 135° vertical (Werner, 1991), though it varies with the person. More specifically, this is the **total binocular FOV** – the angular extent seen by both eyes. The **monocular FOV** is the angular extent seen by one eye. The **binocular overlap (or stereo overlap)** is the central region of the two monocular FOVs that overlaps. In this work I varied horizontal FOV only, and therefore in this document I usually write FOV for short, meaning total binocular horizontal FOV size.

Head-mounted display (HMD). A display worn on the head to provide a view of a computer-generated scene. I assume stereoscopic binocular HMDs with appropriate perspective projections, though non-stereoscopic HMDs also exist – monocular HMDs that show one image to one eye, or biocular HMDs that show one image to both eyes.

Virtual reality (VR). The illusion or state of being present and visually immersed in a simulated three-dimensional environment, evoked in our case through use of a head-tracked HMD. I assume that graphics and tracking systems are used to provide dynamic, geometrically correct perspective views from arbitrary viewpoints, and that the user can move his or her head and body to change the view. I will occasionally use the term **virtual environment (VE)**, and take it to mean the same as VR.

VR Sickness. Any sickness arising from exposure to a virtual reality system. VR sickness includes symptoms such as nausea, headache, and disorientation, which are commonly measured by the **simulator sickness questionnaire (SSQ)** (Kennedy et al., 1993). Another VR sickness symptom is **postural instability** (or ataxia), which is an impaired ability to stand up straight, analogous to effects produced by alcohol (Kennedy and Lilienthal, 1995). VR sickness is related to, but is not equivalent to, simulator sickness, which is related to motion sickness (Kennedy et al., 1993; Stanney et al., 1997). VR sickness has also been called cybersickness or VE sickness.

I will use the following terms frequently in describing the experiments:

- **Session** – a visit to the laboratory to perform several tasks during multiple VR exposures. Each session took place on a different day.

- **VR exposure** – one "go" in the VR system, usually lasting 5 or 6 minutes. Subjects had three VR exposures in each session.
- **Task** – there was typically one main task per VR exposure.
- **Trial** – a single instance of the task. Trials were grouped into blocks with breaks between.

1.6 Overview

Chapter 2 reviews the literature on human factors in VR, FOV options for HMDs, VR sickness, and known effects of FOV on performance. Chapter 3 describes the methods and research questions. Chapter 4 presents results and analysis of the main hypotheses. Chapter 5 presents results and analyses on exploratory hypotheses. Chapter 6 discusses areas for future work. The Appendices present additional data summaries and documents.

Chapter 2
Review of the literature

2.1 Human factors of virtual reality from a task-level standpoint

Several researchers have classified and outlined human factors issues of VR. Stanney et al. (1998) review human factors issues for VR from three perspectives: human performance efficiency, health and safety, and social impact. Barfield et al. (1995) take a lower-level approach and review the mismatches between human sensory capabilities and the display capabilities of VR equipment. Melzer and Moffitt (1997) review the issues and relate them specifically to HMD design and selection requirements. They categorize the issues as: visual requirements (derived from understanding of the human visual system), physical requirements (derived from anthropometry and ergonomics knowledge), environmental requirements (according to the physical environment the HMD is to be worn in – requirements for comfort, etc.), and interface requirements (the ease and appropriateness of controls on the HMD).

Recent years have also seen an increase in research activity aimed at quantifying the sense of "presence" in virtual environments (Barfield and Weghorst, 1993; Slater and Usoh, 1993a) and studies to compare human performance with and without HMDs (Henry and Furness, 1993; Pausch et al., 1993).

2.1.1 Tasks for human factors studies in virtual reality

Key to understanding human performance in virtual environments is identifying the tasks that will be performed in them. Lampton et al. (1994) describe a set of tasks (the "Virtual Environment Performance Assessment Battery" or VEPAB) developed for testing training applications of virtual environments. Their primary goal was to develop tasks that "produce cost-effective transfer of training from VE practice to real-world performance." Gerth (1997) discusses task issues in performance-based testing of HMDs.

I consider below tasks in terms of a "frames of reference" system that has been used previously to characterize human task performance (Lee, 1977; Feldman, 1985; Howard, 1993). The following sections describe four common classes of tasks: search, locomotion, judgments of distance and space, and manipulation (reaching and grasping). These are shown in Table 2-1 with reference to the appropriate frames of reference according to Howard's system (1993).

Table 2-1. Classes of tasks in VR and frames of reference.

Task	Frame of Reference
Search	Headcentric
Locomotion (Travel)	Bodycentric
Judgments of distance and space	Egocentric or exocentric
Reaching	Handcentric

In the following sections I describe theses classes of tasks and their previous use in VR studies. Later, in Section 2.4 I revisit these tasks and discuss implications of FOV.

2.1.1.1 Search

To some extent, everything to be done in a virtual environment involves visual search – locating a target visually. To travel we need to find the place we wish to move to; to reach for something we usually need to locate it visually; to "take in" an environment and form a mental model of it we need to scan it visually. Visual search is a task that has been widely studied outside of VR (Stark et al., 1992), and has been used in VR studies of field of view (Piantanida et al., 1992) and degradation of the periphery in HMDs (Watson et al., 1997), and comparison of HMD performance with "desktop" (non-tracked) performance (Pausch et al., 1997).

2.1.1.2 Locomotion

Many virtual environments are large enough that the user needs a way to move about them (beyond just moving his or her head). For this reason it is important to provide an effective method for the user to get to where he wants to be – through actual walking, virtual flying (Robinett and Holloway, 1992), walking in place (Slater et al., 1995), or other methods. The effectiveness of a method of navigation, and the suitability of that method for a given display technology, can be evaluated by giving the user a task such as "walk along the path marked on the floor without stepping outside of it" (Alfano and Michel, 1990), or "fly through the tunnel without hitting the walls" (Ware and Osborne, 1990). Recently, Jorgensen et al. (1997) described studies in progress to compare performance and physiological responses when navigating through randomly generated maze scenes.

2.1.1.3 Judgments of distance and space

The issue here is how accurately subjects perceive the spatial layout of a virtual environment, including the distances to and between objects. Correct perception of space and distance is vital for applications such as architectural walkthrough (Brooks, 1986) and medical visualization. I use the term "distance judgments" here to mean judgments of the distance from oneself to an object (an egocentric judgment). By "spatial judgments" I mean judgments of distance between objects, external to oneself (exocentric judgments) (Howard, 1993).

Spatial memory can be evaluated using a task such as that used by Alfano and Michel (1990) in real-world studies, where subjects were asked to look around an office for 60 seconds and were then removed from the room and asked to indicate the positions of objects by positioning icons onto a 2D map.

Dinh et al. (1999) measured spatial memory in VR as a function of multisensory inputs. They added tactile, olfactory and auditory cues to a virtual environment (of an office) and measured presence and memory. They questioned people on their memory of where different objects were located in the environment, and found that with olfactory and tactile cues, subjects performed significantly better in recalling the location of objects. Additional studies have compared memory performance in VR to memory performance in the real world (Billinghurst and Weghorst, 1995; Hoffman et al., 1995).

2.1.1.4 Manipulation (Reaching and grasping)

These are tasks that involve manual manipulation, using one or both hands. Such hand movements can be considered as having two phases: reaching (rapidly moving the hand to the vicinity of a target for manipulation) and grasping (using the fingers and thumb to have an effect on the object) (Sivak and MacKenzie, 1992). Most VR applications involve some type of hand-based interaction, and thus it is important that reaching and grasping can be performed adequately. Various 3D reaching tasks have been applied to study 3D interaction in head-tracked displays (non-HMD) (McKenna, 1992; Ware and Balakrishnan, 1994).