Simulated and Virtual Realities

Elements of Perception

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Head-coupled virtual environment with display lag

Richard H. Y. So and Michael J. Griffin

5.1 Introduction

5.1.1 Head-coupled VR systems and their benefits

A typical virtual reality (VR) system that can present head-slaved images will contain: (i) a helmet-mounted display, (ii) a head position sensor, and (iii) an image generator. The image generator will consist of a computer, or a head-slaved camera, or both a computer and a head-slaved camera (Figure 5.1). Such a system will be referred to as a 'head-coupled VR system' and the entire visual field will be called 'head-coupled virtual environment'.

Many benefits of such systems have already been mentioned in Chapter 2. For example, the ability to change the orientation of computer-generated images according to head position enables three-dimensional medical imagery to be viewed. Video captured by a head-slaved camera mounted on a remote controlled vehicle may provide the 'telepresence experience' (see section 2.2.4). In these applications, images may be presented in three-dimensional perspective and have constant coordinates with respect to the Earth. These images will be called 'space stationary images'.

Most images within a head-coupled environment will be space stationary. Two-dimensional text and symbols, however, can be projected along the operator's head-pointing angle. This enables information to be presented to an operator regardless of head orientation. Examples of such information include control parameters with 'telerobotics' applications and on-line instructions. In the field of aviation, pilots will be able to access flight control information through a head-coupled VR system without referring to conventional instrument panels (Gibson and Furness, 1987). This could be of great benefit during target searching or dog-fighting when the time during which the pilots take their eyes off targets is to be minimized.

5.1.2 Problems with head movements

5.1.2.1 Vibration problems and solutions (image blurring)

Head-coupled VR systems are subjected to movements, whether they are generated voluntarily or by external vibration. In applications where an image is presented at a fixed

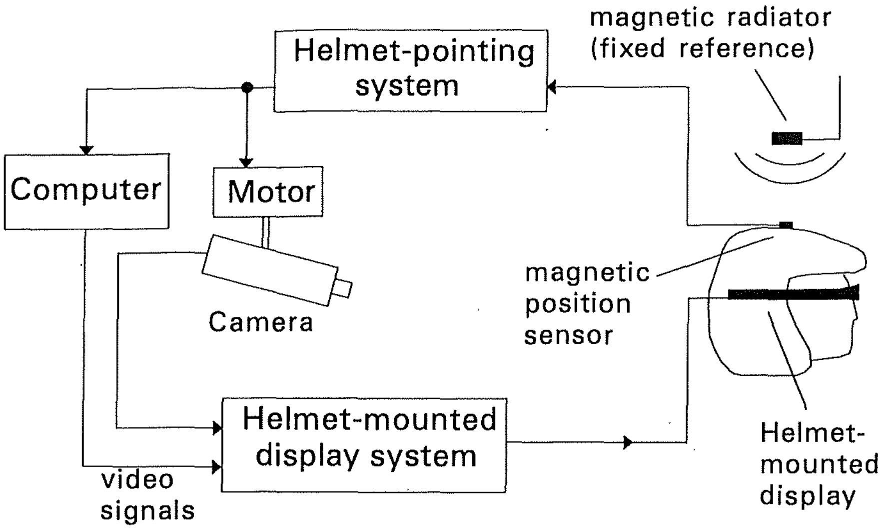

Figure 5.1 *Configuration of a typical head-coupled VR system (adapted from So and Griffin (1992)).*

position on a helmet-mounted display (e.g. on-line instructions), as the head moves, the image on the helmet-mounted display moves with the head. Because human eyes are space-stabilized by the 'vestibulo-ocular reflex' (see section 7.3.4), relative movements between the eyes and the moving image result in the blurring of the image (Figure 5.2). The vestibulo-ocular reflex has been shown to be active for movements from about 2–20 Hz vertically (Wells and Griffin, 1983) and at least 2–10 Hz horizontally (Benson and Barnes, 1978). The extent and causes of this vibration problem have been identified (Furness and Lewis, 1978). A solution has been developed and flight tested in a helicopter (Figure 5.3, Wells and Griffin, 1984, 1987a). The subjects read arrays of numerals presented on a helmet-mounted display during the flights. This space stabilization system utilized accelerometers to measure the movement of the head and electronically deflect the images in the opposite direction. An adaptive system was further developed to suppress the stabilization during voluntary head motions so that the images then followed the head (Lewis, 1984).

5.1.2.2 Lag problems (unwanted image oscillation)

A head-coupled VR system could utilize head position data to space-stabilize images. This, however, is not currently possible because of the lag between the moment at which the head position is sampled and the moment at which the image is displayed. The result is that in a head-coupled virtual environment, a space stationary image appears to 'swim' during the start and finish of a head motion (Allen and Hebb, 1983). This can be very disturbing to an operator and it is not the 'real world' experience (see section 2.2.2.).

Lags affect the dynamic response of the visual field of head-coupled VR systems to head movements. The lag has previously been called 'transmission lag' (Bryson and Fisher, 1990) and 'display lag' (So and Griffin, 1994a). It will hereafter be referred to as 'display lag'. In a computer-generated virtual environment, the display lag is pure and represents the time taken to measure the head orientation and to generate the corresponding graphics. In a virtual environment generated with images captured from a head-slaved camera, the display lag represents the response of the camera position to head movement. This lag is called exponential display lag.

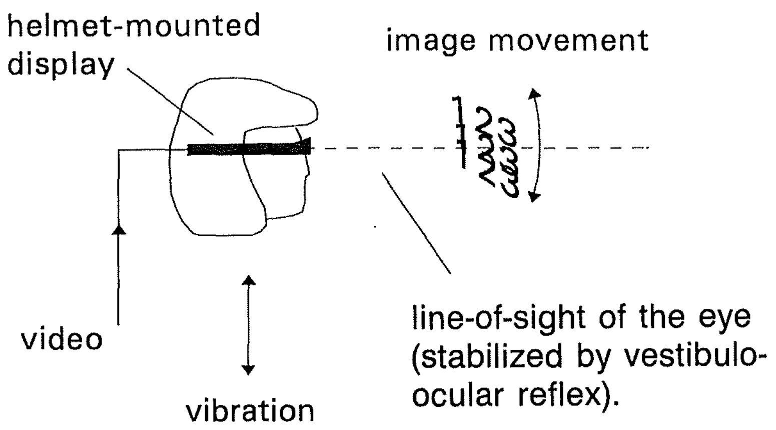

Figure 5.2 Vibration-induced image movements, on a helmet-mounted display, relative to the operator line-of-sight.

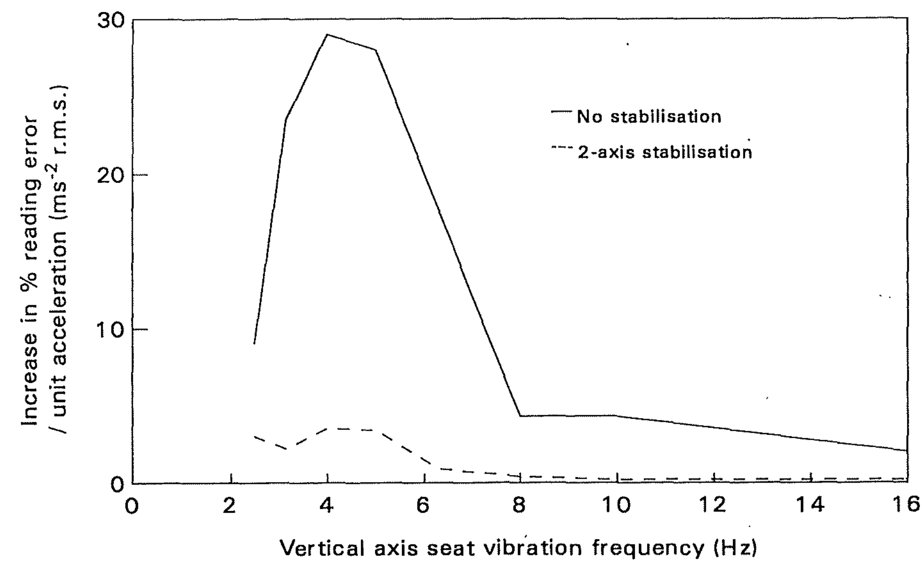

Figure 5.3 Reading performance with a helmet-mounted display during exposure to whole-body vertical vibration (with and without space stabilization, adapted from Wells and Griffin (1984)).

5.2 *Effects of lags on head-coupled virtual environments*

5.2.1 Overview

As discussed above, images in a head-coupled virtual environment are positioned incorrectly because of display lag. Such position error can be disturbing to an operator (Allen and Hebb, 1983). The error increases linearly with head movement velocity (Bryson and Fisher, 1990) and with display lag duration (So and Griffin, 1992). The discrepancies between head motion and the delayed response of the head-coupled VR system may cause motion sickness (Friedmann *et al.*, 1992; Oman, 1990). Regan and Price (1993a, 1993b) reported that with a 20-minute immersion in a head-coupled virtual environment and a 10-minute post-immersion period, 61% of the subjects reported symptoms of malaise. The symptoms ranged from headaches and eyestrain to severe nausea. A total of 150 subjects were used and 5% of the subjects had to withdraw from the experiment owing to severe dizziness. The system had a display lag in the order of 300 ms.

With teleoperation applications involving head-slaved cameras, the dynamic responses of the cameras will introduce exponential display lags. The time taken to search and recognize a symbol in a head-coupled virtual environment was found to increase with increasing exponential lag (Lewis, 1987). Grunwald *et al.* (1991) reported that exponential display lags constrained an operator from making fast head movements in a head-coupled virtual environment.

5.2.2 Specific results

5.2.2.1 Head motion stimuli

In a head-coupled virtual environment, the characteristics of head motion depend on the tasks. Examples of such tasks include visual search, target acquisition, tracking and aiming (see also section 2.2.3.). To study the effect of lag in a head-coupled virtual environment, a representative task is needed to stimulate head motion in a controlled manner. Two-axis continuous tracking tasks have been used for two reasons: (i) most head control tasks involve some tracking activity; (ii) the use of a continuous tracking task enables frequency domain analyses to be conducted.

5.2.2.2 Duration of lag

Head tracking error appears to be increased with pure display lags greater than, or equal to, 40 ms. The lags were imposed on a 40 ms system lag. Examples of head tracking error measurements are shown in Figure 5.4. As the lag increased, the error increased.

The effect of lags on head tracking responses has been modelled as the sum of two components: (i) an input-correlated response, and (ii) the remnant. The former represents the linear tracking response of the operator to the target and is expressed as the head tracking transfer function. The latter represents the nonlinear response of the operator. To determine how much of an operator tracking response was correlated with an input, a squared coherency function was measured between the two signals (Bendat and Piersol, 1986). Examples of such squared coherency functions are reproduced in Figure 5.5: as the lag increased, the squared coherency functions between the target motion and the head motion decreased. This is undesirable and a lag compensation technique is required.

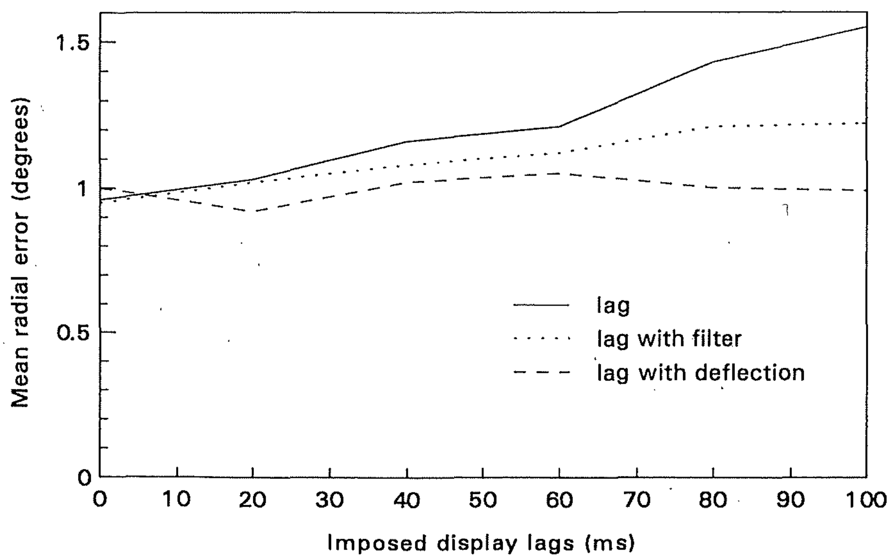

Figure 5.4 Mean radial tracking error with different display lags and three lag compensation conditions: no compensation, compensation with phase lead filter (48 ms lead) and compensation with image deflection (medians of six subjects, adapted from So and Griffin (1994b)).

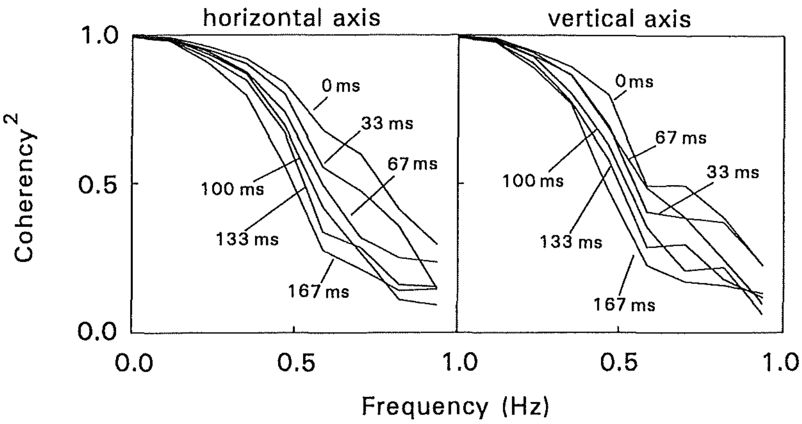

Figure 5.5 Squared coherency functions between the target motions and the head motions during head tracking tasks with display lags (medians of six subjects).

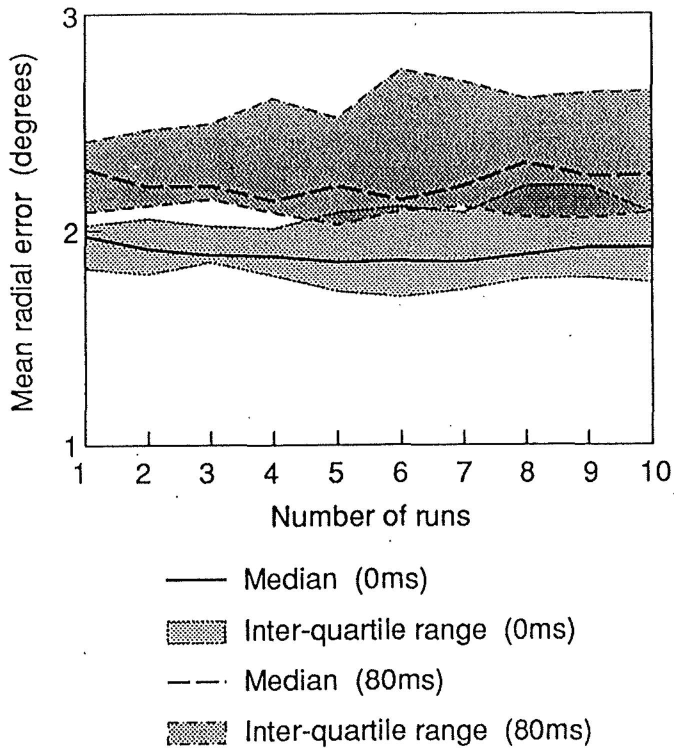

Figure 5.6 Radial tracking error for 10 learning runs with 0 ms and 80 ms display lag imposed on a system display lag of 40 ms (medians of eight subjects, adapted from So and Griffin (1994a)).

5.2.2.3 Effects of practice

Mean radial head tracking error was measured for ten consecutive runs with 0 ms and then with 80 ms pure display lag. With the 80 ms lag, no significant change in tracking performance with practice was found (Figure 5.6). This suggests that the problem with lags cannot be overcome with practice.

5.3 Lag compensation

5.3.1 Overview

The most natural solution to the lag problem will be to reduce the lags at source. But lags are inevitable in applications involving radio linkage, such as 'teleoperation', or with mechanical moving parts, such as head-slaved cameras. One possible solution to the display lag problem is to predict the future head position with a signal processing algorithm. For random movements of the head, prediction is, by definition, impossible. Fortunately, lags in the human operator restrict useful tracking to frequencies below about 1 Hz and prediction of head position becomes possible (Wells and Griffin, 1987b). List (1983) reported a simulation study with a simple nonlinear prediction algorithm. The objective was to compensate for lags during high-velocity step movements of the head. The algorithm used acceleration data and was implemented in a fibre-optic helmet-mounted display. Smith (1984) also conducted simulations to compensate for lags during step movements of the head. Although no human performance data were presented, it was reported that the predictor introduced jumps in the visual field which might be disturbing to an operator. An adaptive least-mean-square predictor was used to predict pilot head pointing direction (Albrecht, 1989). Simulation results showed that the predictor could predict input signals that change their characteristics linearly with time (e.g. a swept sine with decreasing amplitude). Improvement was necessary, however, to predict head movements whose characteristics change randomly with time. These studies investigated the nature of the predictors but human responses to the predictors in the presence of lags were not studied.

Another possible solution to the lag problem employs image deflection. With image deflection, an image in a head-coupled virtual environment with lags can be deflected to the correct angular position with respect to the Earth. Image deflection was originally developed to stabilize images projected on helmet-mounted displays exposed to vibration (see section 5.1.2.1). Applied to computer-generated images, the computational lag is measured and translated into horizontal and vertical position offsets. These offsets are then used to deflect the video image on the helmet-mounted display (So and Griffin, 1992). Image deflection can also be applied to images captured from a head-slaved camera. Allen and Hebb (1983) used a similar technique to restore the correct positions of images in a head-coupled virtual environment. No human experimentation was reported, however, and a helmet-mounted display was not used. The head-coupled virtual environment was projected on a dome-shaped screen with a head-slaved projector.

5.3.2 Specific results

5.3.2.1 Image deflection

As explained above, two-axis continuous tasks were used to control the head motion in a virtual environment. Image deflection was found to eliminate totally the degradation in head tracking performance with pure display lags up to 100 ms (Figure 5.4) and 380 ms (So and Griffin, 1992). Loss of field-of-view occurs with image deflection: as the display lag increases, the loss of field-of-view increases (Figure 5.7). With a 380 ms pure display lag, a loss of field-of-view of about 3·5 degrees r.m.s. was encountered. The required image deflection is proportional to both the lag and the head velocity. If these are large, the target may need to be deflected beyond the field-of-view; performance would then deteriorate rapidly. Also, deflection of graphics in three-dimensional perspective will generate parallax distortion. The effect of the loss of field-of-view was not apparent in the reported data (Figure 5.4). The study used a small circular target which, once captured within sight, was kept around the centre part of the total field-of-view. Any reduction of the field-of-view was not noticeable unless the target reached the edge of the displayed visual field. In addition, no parallax error was produced as the target was presented in two-dimensional graphics.

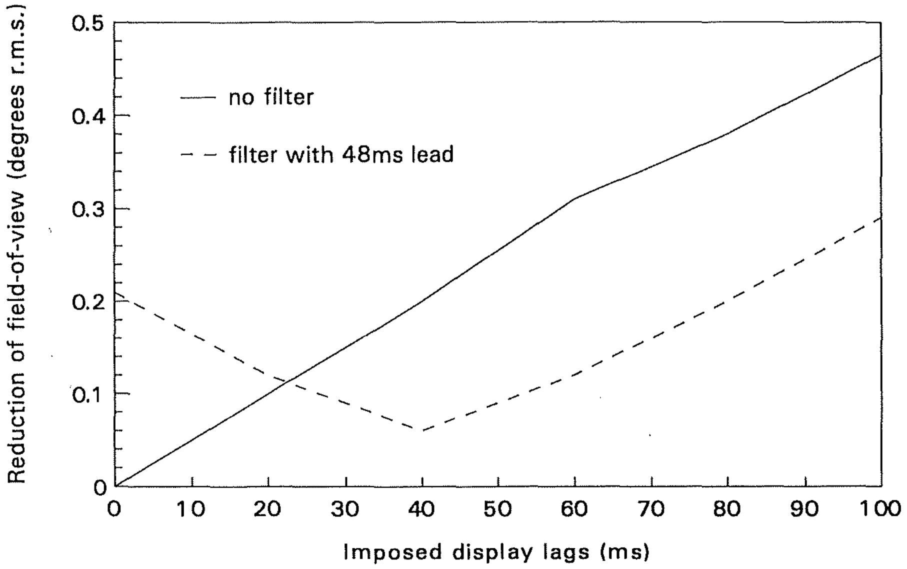

Figure 5.7 Reduction of field-of-view by image deflection with different display lags (with and without head position prediction, medians of six subjects).

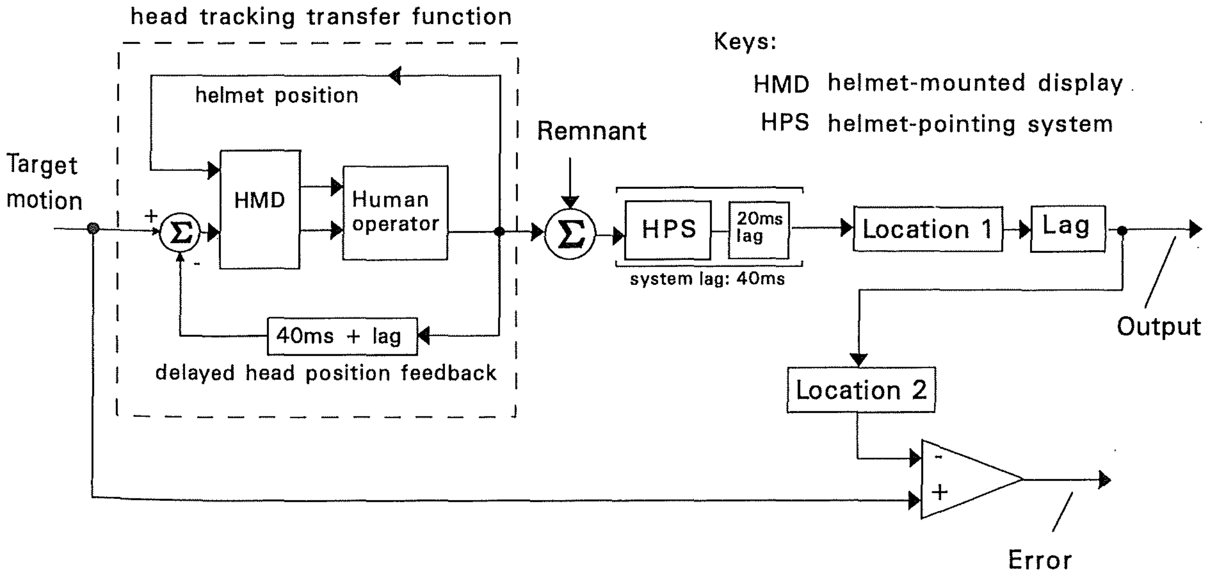

Figure 5.8 Model of a head tracking system illustrating the possible locations of head position predictors (adapted from So and Griffin (1994b)).

5.3.2.2 *Head position prediction*

The appropriate location to insert a head position predictor in a head-coupled VR system has been addressed. A quasi-linear model of a head tracking system is shown in Figure 5.8 and a predictor was placed at Location 1.

A simple predictor based on a first-order Taylor series expansion was shown to be unacceptably noisy. But its combined use with image deflection was beneficial (see section 5.3.2.3). Further studies with phase lead filters showed that when performing head tracking tasks, human operators compensated for any non-unity gains introduced by the predictors. The gain compensation was associated with additional lags in the tracking responses which, in turn, increased the tracking errors. It was concluded that an ideal predictor should have unity gain with phase lead within its operational frequency range. For head position prediction, this frequency range will be about 0–1 Hz (Wells and Griffin, 1987b). A phase lead filter with 48-ms lead, optimized to predict head position, reduced tracking error with pure display lags of 80 ms or more (Figure 5.4).

It is concluded that head position prediction can reduce tracking error with lags. Owing to the inability of a filter to predict the random part of the measured head movement, errors will always remain.

5.3.2.3 Combined image deflection and head position prediction

Studies with combined image deflection and head position prediction have shown that the two techniques complement each other and enhance the overall lag compensation capability. This technique utilizes head position prediction, to reduce large position errors due to the lag, and image deflection to remove remaining errors. The use of a phase lead filter has been shown to reduce the loss of field-of-view introduced by image deflection (Figure 5.7).

5.4 Summary

Lags are inevitable within head-coupled virtual reality systems, especially with head-slaved cameras. This impairs the ability to present space stationary images in a head-coupled virtual environment. The lags affect the realism of the simulations and discourage operators from making fast head movements. Human performance with visual search tasks is also degraded. Immersion in a head-coupled virtual environment with a large display lag may cause motion sickness.

With two-axis continuous head tracking tasks, display lags affect the tracking gain and phase responses and, therefore, performance measures such as mean radial tracking error and time-on-target.

Combined head position prediction and image deflection techniques have been shown to significantly improve tracking performance with lags.

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