Tolerance of Temporal Delay in Virtual Environments

Robert S. Allison[1], Laurence R. Harris[2], Michael Jenkin[1],
Urszula Jasiobedzka[1], James E. Zacher
Centre for Vision Research and
Departments of Computer Science[1] and Psychology[2],
York University, 4700 Keele Street,
Toronto, Ontario, Canada M3J 1P3

allison@cs.yorku.ca, jenkin@cs.yorku.ca, harris@yorku.ca, zacher@hpl.crestech.ca

Abstract

To enhance presence, facilitate sensory motor performance, and avoid disorientation or nausea, virtual-reality applications require the percept of a stable environment. End-end tracking latency (display lag) degrades this illusion of stability and has been identified as a major fault of existing virtual-environment systems. Oscillopsia refers to the perception that the visual world appears to swim about or oscillate in space and is a manifestation of this loss of perceptual stability of the environment. In this paper, the effects of end-end latency and head velocity on perceptual stability in a virtual environment were investigated psychophysically. Subjects became significantly more likely to report oscillopsia during head movements when end-end latency or head velocity were increased. It is concluded that perceptual instability of the world arises with increased head motion and increased display lag. Oscillopsia is expected to be more apparent in tasks requiring real locomotion or rapid head movement.

1. Introduction

In typical applications most imagery in a virtual environment should appear stable in three-dimensional space. A head-coupled or head-slaved virtual reality system attempts to achieve this goal by tracking the position and orientation of the user's head in space. From these measurements and knowledge of the relative position of the head-fixed tracking device to the eye, the vantage point of the eye (or eyes in a stereo display) can be estimated and the appropriate perspective view generated. Inaccuracies and imprecision in tracked head position and orientation result in errors and imprecision in the estimated vantage points.

In this paper we consider the consequences of these errors on the perceptual stability of the visual world. The term oscillopsia was originally used to describe a symptom reported by a variety of neurological patients [1]. *Oscillopsia* is the apparent movement of the entire visual world relative to an assumed inertio-gravitational frame of reference. It has been reported with drug toxicity, brain injury and damage to the vestibular system (the motion sensors located in the inner ear). When the vestibular system has been compromised by disease, oscillopsia can result from the mismatch between visually and vestibularly sensed head motion [2]. In a head-slaved virtual-reality display, errors in head tracking also lead to mismatches between the head motion and the visual display. In this paper, we consider the conditions under which this mismatch results in oscillopsia. Oscillopsia can be generalised to describe the apparent movement of the virtual world with respect to the real world in augmented-reality applications. Similar ideas could also be conceived for the illusory motion of auditory or tactile worlds.

2. Head tracking errors

Errors in head tracking can be classified as static or dynamic [3]. Static errors result from inaccuracy, distortion or imprecision in the measurement which results in measured head position differing from ideal, even when the head is still (typically they will also cause errors during head motion). Static errors can also result from miscalibration of the instrument or of the relative position of the eye to the head-fixed tracking device. Dynamic tracking errors result from temporal mismatch between the movements of the head and the resulting motion of the scene in the display. The most common dynamic tracking error results from end-end latency (also known as display lag) between head motion and the resulting update of the display. This delay results from transduction delay, time to transmit the transduced signal, time to calculate the viewpoint and generate the imagery and latency until the double-buffered display is updated (see [4] for examples of typical delays at each stage).

2.1. Static Errors

Human beings can make judgements of the position and orientation of objects using egocentric or exocentric co-ordinate systems [5]. Egocentric judgements are judgements of the distance and direction of objects relative to one's self. They are made with respect to either the eye, head or body – referred to as oculocentric, head-centric or body-centric frames of reference respectively. Static head tracking errors in a head-slaved visual display can cause errors in tasks that rely on egocentric judgements by causing absolute errors or by introducing discord between vision and other senses.

Exocentric judgements refer to judgements of the spatial relationship between objects in an external (for example an object-centred or earth-fixed) frame of reference. Static tracking errors can cause errors in exocentric as well as in egocentric judgements. An extreme example occurs in augmented-reality displays where the head-slaved virtual display is superimposed upon an image of the real world. The virtual and real worlds should appear fixed and stable with respect to each other and the earth. Static tracking errors result in a variable misregistration of the synthetic and real-world images when the head takes up different positions since the real and measured vantage points differ. The human visual system is keenly sensitive to relative spatial differences compared to absolute spatial differences and hence this misregistration is quite apparent unless tracking errors are very small.

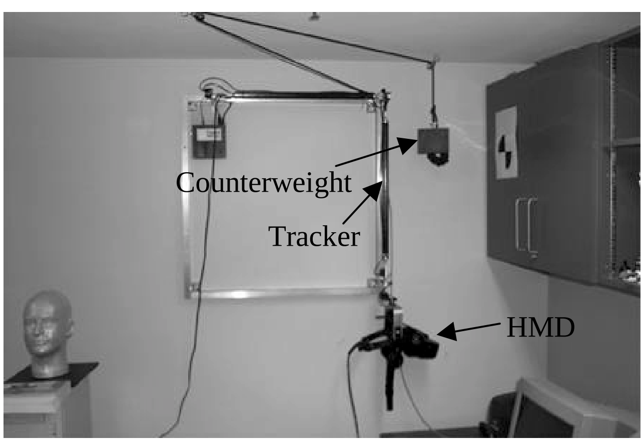

Figure 1. Mechanical head tracker in its calibration jig. The tracker has four joints linked by rigid links and is anchored to the frame on the wall. Each joint has two independent rotational degrees of freedom. The weight of the tracker is counter-balanced by a weight and pulley system.

In previous work [6], we considered the impact of static gain errors on perceptual stability. The implications and various techniques to deal with static tracking errors have been discussed in the literature - for review see [7]. In this paper we concentrate on dynamic rather than static errors.

2.2. Dynamic Errors

In terms of dynamic tracking errors, end-end tracking latency in head-slaved displays has been identified as one of the most important problems in helmet-mounted virtual-reality, augmented-reality and simulator applications [8-10]. Holloway [11] has argued that end-end latency is the largest source of objectively measured misregistration for typical augmented-reality applications. Considerable effort has been expended in the flight-simulation industry and in the virtual-environment research community to minimise and compensate for tracking latency. Solutions include short-latency tracking systems, low-latency image generators [12,13] and predictive head tracking [7,9,10,14-16]. These steps can minimise the effects of end-end tracking latency but dynamic errors will always exist [7].

Given that dynamic errors and display lag are unavoidable what are the consequences for perception and performance? Consequences include degraded vision, reduced performance on visual and visuo-motor tasks, simulator sickness and oscillopsia. Display lag can cause intersensory discord and errors in tasks relying on both egocentric and exocentric judgements. An example of display lag affecting an egocentric judgement based task would be errors in tracking and following a target [14,17]. An example of an exocentric effect would be the illusory motion of the virtual or real world in space[18]. This apparent movement of environmentally stable features is known as oscillopsia and is our focus here.

2.3. Oscillopsia

For descriptive purposes, but without loss of generality, let us assume a long tracking delay such that when the head moves rapidly to a new posture the display does not get updated until the movement is complete. In this situation, the head changes position in space but features in the display stay fixed to the head rather than fixed in space during the head motion.

When the head moves the motion is detected by the vestibular system in the inner ears to give a perception of head motion. From these vestibular signals the brain also generates compensatory eye movements to keep gaze stable in space and hence the image of the world stable on the retina. The visual system normally assumes that world is stable. If everything moves (relative to the head) in a rich visual scene then the brain assumes that the visual motion results from self motion. Movement of the world over the retina (or more precisely over the optic array if the eye is mobile in the head) is known as optic flow. The percept of self motion generated by optic flow is known as vection.

Normally, the percepts of self motion from vection and the vestibular sense are concordant. If the display stays head-fixed during the head movement due to tracking delay, then vection signals that the head is not moving while the vestibular system signals that the head is moving. If this discord is too strong then subjective equivalence of the visual and vestibular percepts is destroyed and the visual world appears to move.

Oscillopsia due to display lag has been anecdotally reported in the literature (e.g. [18]) but has not been studied psychophysically. The objective of this study is to determine the temporal stimulus conditions under which oscillopsia becomes apparent. We make several predictions that we will test experimentally. In the case of tracker delay, the amount of sensory discord for a given delay should be strongly dependent on the velocity of the head movement. Thus it is readily apparent that oscillopsia should be more pronounced for rapid head movements. Oscillopsia should also be more apparent as amount of delay increases. Vection is driven by motion of the entire visual field not by object motion. We predict that display lag will produce more apparent motion of objects in the display when only discrete objects are visible rather than an entire virtual environment. As a result we use a visual stimulus that surrounds the observer.

Figure 2. Photograph of a subject wearing the system. Stops for the desired head positions are made from wood covered with foam and are under the black cloth in this picture.

3. Method and Apparatus

We performed psychophysical experiments studying the effect of time delay on oscillopsia. The experiments used a mechanically head-slaved helmet-mounted display to present a virtual environment to the user.

3.1. Virtual Environment

The immersive visual display was a Virtual Research V8 stereoscopic head-mounted display used in monoscopic mode. The displays, one for each eye, presented full-colour, 640 by 480 pixel images at 60 Hz. The displays subtended a diagonal field of view of 60 degrees. Stereo headphones presented stereophonic sound to the subject.

The motion of the head was sensed by an eight degree of freedom mechanical head tracker (Puppetworks, Toronto, Canada, see Figures 1 and 2). One end of the tracker was earth-fixed by a rigid mount to a calibration/storage jig. The opposite end was fixed rigidly to a custom mount on the helmet. The head tracker sensed the orientations of two axes at each of four joints joined by rigid limbs. The transduced position of each joint was transmitted to the host computer via a serial link. From these measures, head position was calculated in real time and used to drive the simulation. Standard kinematics were used to calculate the six degrees of freedom corresponding to the orientation and position of the head and, by a final transformation, of the eye.

A Silicon Graphics O2 (SGI, Mountainview, CA) was used to generate the virtual environment. The virtual environment was created using custom code and Open-GL graphics. The modelled virtual world (Figure 3) was deliberately kept simple for both computational and scientific reasons. A simple environment allowed an update rate of 30 Hz. The world used was a sphere similar to that used earlier in vection research [19]. The sphere was 2 meters in diameter and the subject's head was initially placed in the centre for each trial. One advantage of the use of a sphere is that all imagery is equidistant and complications of parallax are minimised.

The sphere was patterned with a grid lattice similar to lines of latitude and longitude (and hence the lines of longitude converged to a point above and below the subject). Over the sphere, 7 lines of latitude and 12 lines of longitude were drawn. Alternate squares were coloured red or white to form the pattern. The sphere was illuminated by a single light source located at its centre.

3.2. Tracker Lag

The mechanical head tracker has minimal inherent lag. However the signal must be transmitted to the host computer, processed to generate an updated viewpoint, the updated image must be generated and the display updated. Thus even in the absence of experimentally added lag some baseline tracking lag existed. We estimated this lag theoretically and compared it with measured lag.

Baseline lag was measured as follows. The joint of the tracker transducing yaw movement was oscillated back and forth. A minimal latency, analogue, instantaneous position signal was generated by a potentiometer on the axis of rotation. As the end of the head tracker moved in yaw, the head-slaved image on the monitor moved in the opposite direction in synch with the tracker motion but delayed by the end-end tracker latency. The green video signal was processed to determine when the video signal was updated to reflect the head motion. The sampling was performed at a pixel located on the vertical boundary between a red and white square when the head tracker was in the zero position (so that the time delay between the two signals could be easily registered). However, the image was a raster image so proper synchronisation of sampling was required to demodulate the video signal and recover the luminance at the desired pixel. Sampling was done at the time of the pixel excitation by a custom circuit triggered to the horizontal and vertical synchronisation signals which sampled the appropriate pixel and held the sampled value until the display was refreshed.

The demodulated video signal (i.e. pixel luminance) from this circuit and the potentiometer sensing the motion of the head-tracker were displayed on an oscilloscope for measurement and also digitised and recorded onto digital tape (16 bit at 5 KHz). Data for a number of oscillations were used to estimate mean end-end latency between tracker input and image response and the variability of this latency. The results indicated a mean latency of 122 ms with a standard deviation of 14 ms, which was close to but somewhat larger than theoretical predictions.

Controlled amounts of additional lag were required for the experiments. This lag was introduced by buffering the incoming tracker estimates in a FIFO queue in order to delay them. At each graphics update the delayed position of the head tracker was obtained from taking estimates from the queue until they matched the time delay required. Linear interpolation of the position estimates between the closest available estimates was used to improve the performance of the estimation.

3.3. Procedure

On each trial, the subject was required to move their head from a central posture to the right in a single, smooth movement. During the motion, the subject was instructed to attend to the stability of the world. The subject was required to report on whether the visual world appeared stable and fixed to the ground or whether it appeared to swim or oscillate *during* the head motion.

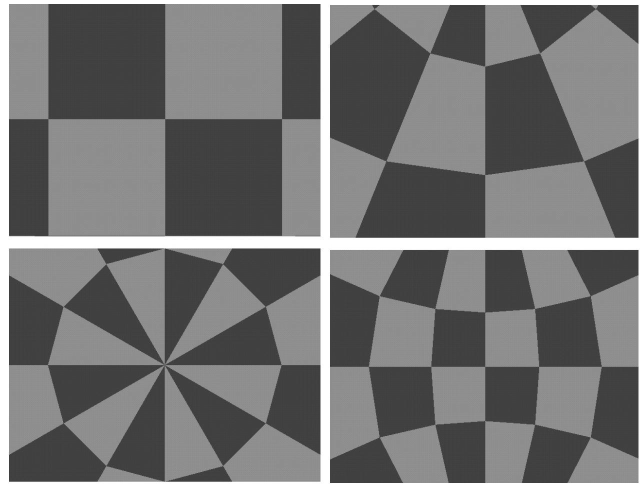

Figure 3. Selected views of the sphere virtual environment. Clockwise from bottom right: view up, ahead, 45° up, and an exaggerated perspective view from the back of the sphere.

The subject was required to move their head 45 degrees in yaw at an experimentally controlled rate. To help guide the magnitude of the movement, physical stops were placed beside the subject’s cheeks to provide feedback and prevent movements larger than desired. To control the speed a computer-generated metronome signal was played through the headphones. The subject was instructed to adjust to the rhythm and when prepared execute the 45 degree movement smoothly in a single count of the metronome. The metronome signal was either 0.5, 1.0 or 2.0 Hz giving average head velocities of 22.5, 45 or 90 degrees per second, respectively.

For each head velocity the head motion signal was delayed 0, 50, 100 and 200 ms. This resulted in 3 velocities x 4 delays for 12 conditions, each of which was repeated 10 times for each session for each subject. The order of the trials for each session was randomised.

4. Results

When increased end-end latency was introduced subjects became less likely to report that the virtual world appeared stable (Figure 4). When a large delay was present this effect was quite apparent and striking. When the head moved the world seemed to turn with the head initially. As the head slowed and stopped the visual world appeared to swim back into its proper position in space. It was as if the visual world was a ‘high-viscosity’ version of the real world [13]. The amount of latency tolerated was strongly dependent on the speed of the head motion as predicted. This is reflected in a narrowing of the range of delays that resulted in a stable visual environment as the speed of the head motion was increased (Figure 4). The figure shows the results for three typical subjects and the mean response for the 8 subjects. An additional ninth subject was tested but did not report the world as stable under any condition and gave inconsistent results between the two sessions. This subject's data was excluded from the analysis.

For each head velocity, we estimated the delay at which the subjects would report that the world appeared stable on 50 percent of the trials. This point can be considered an oscillopsia threshold. The 50 percent criterion is a reasonable but arbitrary choice. The estimated oscillopsia threshold, averaged across the subjects, increased from about 60 ms to nearly 200 ms when average head velocity was decreased from 90 to 22.5 degrees per second (500 to 2000 ms head movement duration). It is interesting to note that, on average, the product of head velocity and oscillopsia threshold remained approximately constant for all conditions.

Logistic regression was used to analyse the effects of head movement duration and tracking delay on the perception of environment stability. The subject's responses were treated as a dichotomous variable that indicated whether the subject experienced a stable environment for a given trial or not. The analysis of deviance of the logistic regression model showed that the effects of head movement duration and tracking delay were significant ($p < 0.01$). The analysis resulted in a model of independence of the two independent variables with their interaction term being non-significant. Increasing head movement duration increases the chances of experiencing stability and increasing tracking delay decreases the chances of experiencing stability in the model, as expected from the figures.

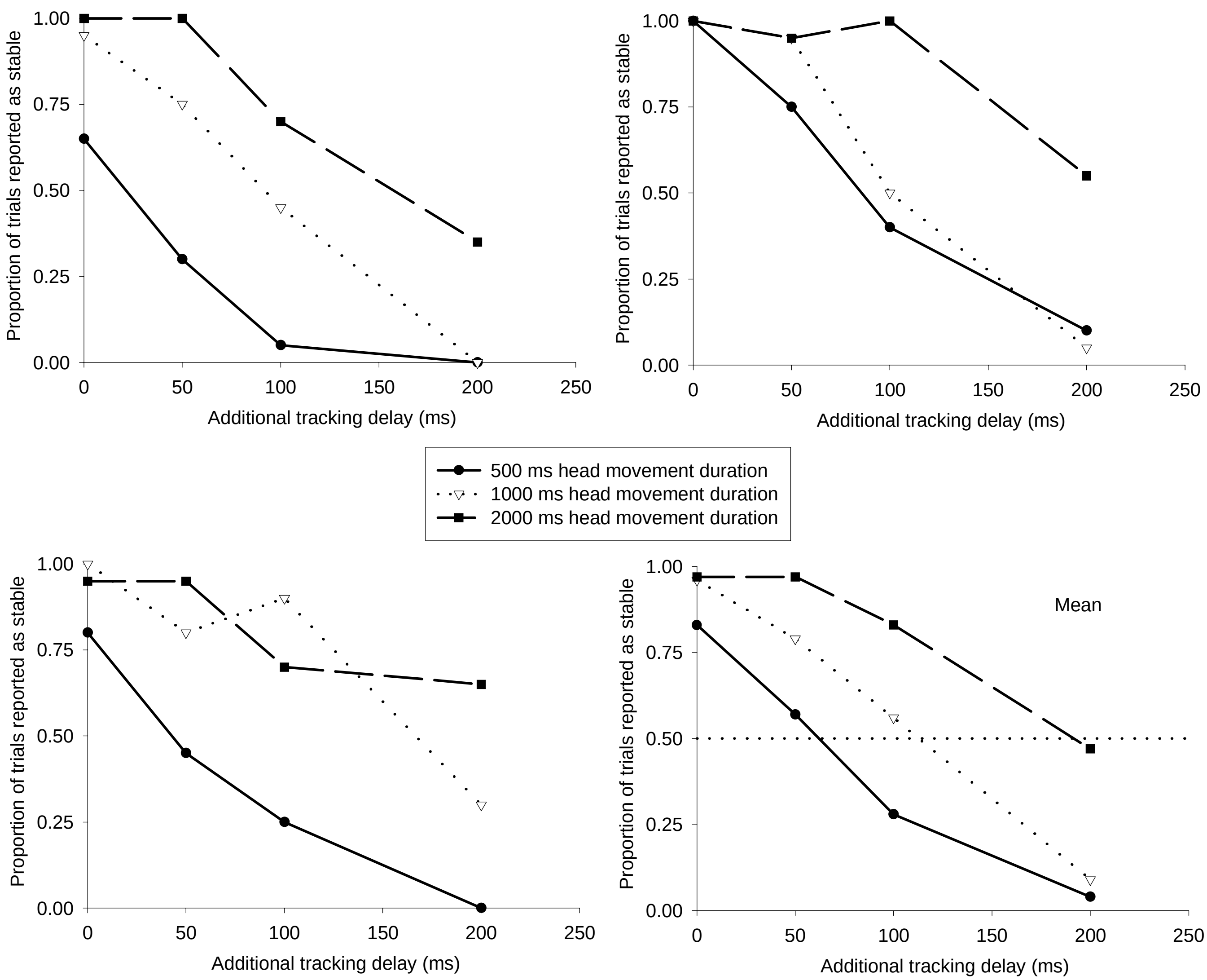

Figure 4. Effect of temporal delay on perceptual stability in three typical observers and the mean response. In the plot of the mean data, the intersection of the curves with the reference line at 0.5 provides an indication of relative oscillopsia threshold for the different head velocities.

5. Discussion

In earlier experiments we studied the effects of static gain errors on perceptual stability of the visual world [6]. In the present experiments we have extended this work to consider the effects of display lag on perceptual stability in a virtual environment. In a virtual environment with display lag, the head motion signal from the visual system lags the head motion signal from the vestibular system and other cues. If the discrepancy is not too severe then the vestibular signal and visual signal can be reconciled and the visual and vestibular worlds appear fused and stable. If the discrepancy becomes too large this illusion breaks down and the visual world appears to move and swim about.

5.1. Implications for specific application domains

As the head moves faster the relative slip velocity between the image motion and the head motion increases. Thus, the effects of display lag become more important with rapid head motions. Also, vection would contribute weakly with rapid head movement and would not be expected to compensate for oscillopsia. In agreement, we found that oscillopsia became more common with increased head velocity for a given lag. Tasks that are usually performed with a stable head should be less prone to oscillopsia due to display lag. For example, tasks that require precise motor action such as microsurgery, are usually performed with the head held as stable as possible. In contrast, tasks that are typically performed with rapid head motions may be more adversely affected by display lag. For example, fighter pilots typically make rapid head movements during simulated combat. During locomotion, especially jogging or running, the predominant frequencies of head motion extend to frequencies beyond 10 Hz [20,21]. We would expect that modest display lag would cause oscillopsia during simulated fighter aircraft combat or during rapid locomotion.

In contrast to virtual environments, display lag in augmented realities or tele-operation applications is more troublesome. In optical augmented-reality systems based upon see-through displays, the real world is viewed directly without delay while virtual imagery is delayed by the end-end latency. Thus, tracker lag causes dynamic tracking error that results in the virtual imagery swimming with respect to the image of the real world. Typically the real world would provide a stronger frame of reference [22] and would appear stable while the virtual imagery would oscillate. Human beings are much more sensitive to relative than absolute motion and thus this form of oscillopsia should be apparent with end-end tracker latency that would not cause instability in an isolated virtual environment. This lack of dynamic registration has been reported as a particularly bothersome artefact in augmented-reality systems [18]. In video-based augmented-reality displays, the video imagery can be delayed in an attempt to compensate for the end-end latency in the synthetic imagery. Such systems are analogous to the VR case with respect to end-end latency induced oscillopsia. In teleoperation applications, oscillopsia results in a mismatch between the perceived world and the physical, inertially stable world in which the operator must act.

5.2. Related perceptual effects

Beyond oscillopsia there are a range of other perceptual effects of display lag. These include degraded vision, compromised visuo-motor performance and motion sickness. A comprehensive understanding of the effects of display lag in virtual environments will require careful psychometric study. We are undertaking a research program to study these issues and the current work is a small but significant step towards this goal.

When the head moves the motion is sensed by the vestibular system in the inner ear and compensatory eye movements occur to keep gaze stable in space (this is known as the vestibulo-ocular reflex or VOR). This keeps the retinal image stable and protects visual acuity. Retinal image motion of more than 2-3 degrees per second results in blurring of the retinal image and degraded acuity [23,24]. People with loss of vestibular function do not generate these compensatory movements. Many report that they cannot recognise familiar faces or read signs with any vibration of the head [25]. With head-slaved displays a similar but less severe problem occurs. When a user views a head-fixed display, vibration or movement of the head results in a VOR eye movement to compensate. Normally this is compensatory but in this case, since the display is head-fixed, the VOR causes motion of the image on the retina. This resulted in decreased ability to read information displayed in a head-fixed HMD during high performance flight or imposed oscillations [26], which presumably reflected decreased visual acuity. Moseley et al [27] have shown that this performance decrement is more pronounced with random rather than predictable vibrations.

When an image of the world moves across the retina it signals head motion and generates compensatory eye movements through the optokinetic reflex (OKR). In a head-slaved display with display lag these movements tend to cancel the retinal image motion induced by the discrepancy between the VOR and the image motion. The VOR is the dominant reflex at high frequencies and the OKR dominates at low frequencies and modest velocities of head motion [28]. Thus, it would be expected that the effects of display lag on visual acuity would be more pronounced at high frequencies and velocities of head motion. This effect is in addition to the previously mentioned fact that retinal slip velocity is larger with faster head motions for a given display lag, which would also be expected to give a larger degradation of acuity for rapid head motions. The effects on visual acuity may become more important as visual displays used in virtual environments improve and hopefully one day approach the acuity limits of human vision.

End-end tracking latency has impact on visually guided motor action for at least two reasons. The first is the reduced visual acuity mentioned above. The second is errors in egocentric localisation of objects that are the targets of visual guided actions. Display lag can also lead to instability in tracking and other manual control tasks that require visual feedback. Errors in tracking and following a target with the head have been shown to increase with display lags of greater than 40 ms [14,17]. Operational flying errors have also been reported for flight simulator delays of between 80 and 240 ms (for a survey see [29]) and increase in workload and fatigue were postulated for even shorter delays. Display lag in hand tracking applications has been shown to result in reduced reaching speed [30]. Subjects can reportedly discriminate increases or decreases in end-end hand-tracking latency as small as 33 ms during manipulation of virtual objects [31].

Head tracker induced display lag can also cause a form of motion sickness called simulator sickness (however Draper [32] has argued that display lag may be less provocative than other forms of visual-vestibular discord such as errors in virtual-image scaling). Some of our subjects reported some discomfort in our experiments. A popular theory of motion sickness proposes that it is due to sensory conflict between visually and vestibularly sensed motion [33]. One possible cause of such a discord is poisoning and thus a default defence mechanism is nausea and vomiting. Prolonged exposure to inter-sensory discord in a virtual environment can lead to simulator sickness. In motion sickness the user is not always aware of the conflict. The effect is largely subconscious and may or may not be correlated with the occurrence of overt oscillopsia.

6. Summary and future work

End-end tracking latency results in the visual display lagging head motion. This has a number of perceptual consequence such as oscillopsia, motion sickness, degraded vision and reduced performance. Oscillopsia generated by display lag has been anecdotally reported previously. In the present experiments we have shown that oscillopsia is likely with increased end-end tracking latency and rapid head movements. Display lag is likely to have more pronounced effects in teleoperation and augmented-reality applications where a gravitationally stable frame of reference exists. In virtual-environment applications display lag will be bothersome where rapid head movements are common.

In general, it may be necessary to consider the effects of the signal processing involved in a head-coupled display using more realistic models than simple constant time delay. For example, predictive head tracking with Kalman filtering has been used to minimise the effects of lag. However, predictive filtering becomes less reliable as the prediction interval increases and thus low inherent latency is still required to minimise oscillopsia and registration errors [34]. Predictive filtering introduces complex changes in the image motion and the dynamics of remaining the image slip are strongly dependent on the predictor [34]. Since the occurrence of oscillopsia is also strongly dependent on the dynamics of the signal it may be fruitful to evaluate compensation schemes in terms of the ability to combat oscillopsia. It would also be interesting to compare effects of display lead and display lag on perceptual stability.

Compensatory VOR and OKR eye movements and the perception of motion during head movements depend on whether the head motion was generated actively or passively [35-37]. In the virtual-environment literature most effort has been concentrated on active head movements. As virtual environments improve and more realistic locomotion becomes possible, passive head movements (i.e. vibration resulting from heel strike) may become common. It would be interesting to study the differences between active and passive head motion in the generation of oscillopsia.

Finally, display lag introduces a variety of symptoms. From an operational standpoint it would be interesting to see how the thresholds for various adverse effects compare and correlate.

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