Perception of Image Motion During Head Movement

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Abstract

Previous studies have shown that self-motion has an inhibiting effect on concurrent 3D motion perception. To investigate whether self-motion similarly impairs concurrent image motion perception, we examined human perception of head-referenced horizontal image motion during head movement. The displayed stimulus was composed of a checkerboard image in a head mounted display oscillating from side to side at four frequencies (0.25, 0.5, 1 and 2 Hz) with half peak-to-peak amplitudes ranging from 0° to 5.64. Eight observers rated the magnitude of the checkerboard motion while either rotating their head about a vertical axis (yaw), about a horizontal axis (pitch), or holding it still. For all image oscillation frequencies, perceptual sensitivity to image motion amplitude was reduced during both horizontal and vertical head movements (mean reduction: 0.44 and 0.17, respectively). In contrast, perceptual bias was affected only at 2 Hz (mean shift: –9.9% and –12.2% of the full image motion amplitude for horizontal and vertical head movements, respectively). The results indicate that head movement causes gain reductions in motion magnitude estimation at image oscillation frequencies ≤1 Hz. At an oscillation frequency of 2 Hz, head movement produces both a gain reduction and a bias shift. Virtual environment developers could take advantage of such effects by relaxing requirements for image stability as well as motion fidelity during head movement.

Keywords

Head movement, head oscillation, image motion, motion perception, VE latency.

CCS

Categories and subject descriptors: J.4 [Computer Applications]: Social and Behavioral Sciences --- Psychology

General Terms: Human Factors, Design, Measurement, Performance

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1 Introduction

Studies of locomotion in both the real world and virtual environments (VEs) have reported that self-motion impairs concurrent visual perception of 3D motion. To illustrate, in the case of real-world driving, Probst, Krafczyk, Brandt, and Wist [1984] found that the time for detecting an approaching or receding car was increased by a factor of 2 to 4 in a moving vehicle compared to stationary conditions. For locomotion studies in a VE, Banton, Stefanucci, Durgin, Fass, and Proffitt [2005] asked observers to match the speed of an expanding flow pattern in a head-mounted display (HMD) to their walking speed on a treadmill and found that observers often perceived their visually specified speed to be slower than their actual walking speed. Asking observers to estimate the speed of an expanding flow pattern in an HMD, Durgin, Gigone, and Scott [2005] found that subjective magnitude estimation of speed from visual flow could be reduced both by active self-motion (regular and treadmill walking) and by passive self-motion (e.g., being pushed forward or backward on a chair). They attributed this self-motion induced reduction in perceived speed to a "subtractive" operation (i.e., a bias shift in response), rather than a "divisive" operation (i.e., a gain reduction), consistent with Barlow's [1990] inhibition theory. According to Barlow, highly correlated events such as walking and an expanding flow pattern mutually specify each other. Consequently, the perceptual system uses this redundancy to modify its sensory coding. Neurophysiologically, these coding shifts are produced by strengthening the inhibitory connections between simultaneously active neural units.

During self-motion, one often has to control both one's physical translation and head motion while simultaneously registering the motion of objects in the world in order to avoid obstacles. If physical translation inhibits 3D self-motion perception, can head motion similarly affect 1D or 2D object motion perception? To answer this question, Wallach, Stanton, and Becker [1974] first studied how head turning influenced perception of related environmental motion. They found that during head turning, observers perceived the environment as stationary if the added environmental motion was less than 3% of head motion regardless of whether the environmental motion was in the same or opposite direction of head motion. Wallach et al. termed the 3% value the immobility range and attributed this range to a compensatory mechanism seeking to stabilize the world during head motion. Later, Probst, Brandt, and Degner [1986] reported increased manual reaction times for detecting 1D object motion in a variety of settings when the head was rotating with respect to the body. In fact, Probst and Wist [1982] also observed the increased reaction time when object motion was head-referenced as presented in an HMD, effectively suppressing the vestibulo-ocular reflex (VOR) that maintains eye fixation on an object as the head turns.

In the current study, we used a magnitude estimation task similar to Durgin et al. [2005] to systematically assess the effect of head motion on perceived image motion amplitude. Specifically, we had observers wear an HMD that showed a checkerboard image moving from side to side. The observers were asked to rate the amplitude of the checkerboard movement while they either rotated their head horizontally from sided-to-side (yaw movement), vertically up and down (pitch movement), or held it stationary. We tested seven sinusoidal image motion amplitudes and four image lateral oscillation frequencies to examine whether the effect of head movement on perceived 1D motion amplitude varied with image displacement amplitude and frequency. We also investigated what happens when the image motion differs in direction from the observers' own head movement. Given that the side-to-side image motion is more similar to the relative motion caused by horizontal head movement than to that caused by vertical head movement, both the inhibition theory [Barlow 1990] and an accurate compensation process leading to perceived environmental stability [Wallach 1987] predict that horizontal head movement would have a larger suppression effect on image motion perception than would vertical head movement. Such suppression effects could be beneficial and result in less salient dynamic artifacts in VE systems, such as spatial instability and head tracking overshoot, during head movement,

2 Methods

2.1 Participants

Eight observers (six naïve as to the specific goals of the study, plus two co-authors) aged between 19 and 58 years participated in the experiment. All observers had normal or corrected-to-normal vision.

2.2 Stimulus generation and control

The stimulus image, a red checkerboard pattern on a black background (Figure 1), was presented binocularly to participants via a Kaiser ProView 50ST HMD (Figure 2), which provides VGA resolution (640 x 480 pixels) across a 50° H x 40° V field of view. The bright red squares were set to 8-bit RGB triples of (100, 0, 0); the dark red squares were (50, 0, 0). The center of the checkerboard pattern had a cross composed of four dark red squares. Each square subtended a visual angle of 6.8° on a side. The Michelson luminance contrast between the two square colors was 58%, defined as

$$(L_{max} - L_{min})/(L_{max} + L_{min}),$$

where L_{max} and L_{min} respectively are the luminance of the bright and dark squares. A Gaussian mask (σ = 12°) was used to obscure sharp edges of the checkerboard toward the boundaries of the image element in the HMD, which otherwise could have provided differential motion cues.

During a trial, the checkerboard pattern was oscillated sinusoidally from side to side at one of four frequencies (0.25, 0.5, 1, and 2 Hz) with one of seven amplitudes of 0°, 0.94°, 1.88°, 2.82°, 3.76°, 4.70°, and 5.64° (one-half of peak-to-peak). The image motion amplitudes were selected to be nominally equivalent to the image slip expected for VE latencies from 0 to 120 ms for head motion of the magnitude in the present and in our prior studies [Adelstein et al. 2003; Adelstein et al. 2005]. Participants were instructed to fixate the center cross in the checkerboard image and, depending on the experiment block, either to keep their head stationary, yaw their head from side to side, or pitch up and down while making subjective magnitude estimates of the amplitude of the checkerboard motion. During the yaw and pitch movements, a computer-generated metronome (2 beeps/cycle) paced the subjects in a 0.5 Hz repetitive pattern lasting three full cycles. Head movements began either from the left (horizontal) or at the bottom (vertical). An audible alarm based on Polhemus FasTrak readings of head rotation reminded participants to limit yaw to approximately ±15° about the straight-ahead direction, and pitch to 10° deg above and 20° below the horizontal. As in Probst and Wist [1982], the image was stabilized with respect to the HMD, not the external world, thus requiring participants to voluntarily suppress the VOR during head movement. The HMD was covered with an opaque hood and the laboratory room was darkened to remove uncontrolled and unwanted external visual stimuli.

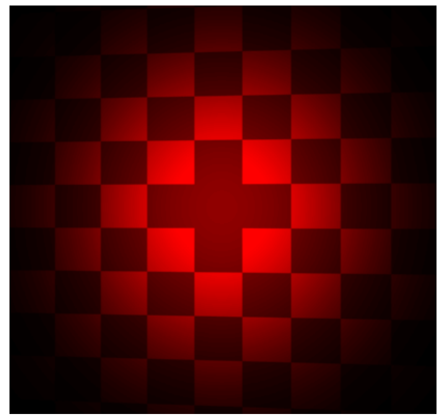


Figure 1. The checkerboard pattern with a cross in the center.

Figure 2. Experimental set-up.

2.3 Procedure

The checkerboard image was visible for 5 s of the 6 s comprising each trial's head motion interval. The HMD was otherwise "black," i.e., at its minimum luminance. The image motion start was randomized with respect to the head motion cycle for each trial in which the head moved. Participants were instructed to rate the magnitude of the checkerboard movement on a continuous scale by verbally announcing their evaluation as a percentage relative to a 100% of a scale on which they were trained. The experiment monitor who was generally blind to the specific experimental condition then recorded their response and advanced to the next trial.

Each observer participated in four experimental sessions over at least two days, with each session corresponding to one of the four image oscillation frequencies. Image oscillation frequencies were presented in a counterbalanced order. Each session consisted of four head movement condition blocks (initial head still, horizontal, vertical head movement, and final head still), with 35 trials in each block (five repetitions of the seven image motion amplitudes). Image motion amplitude was randomized, with the same sequence followed for each block. In order to train and anchor their individual responses at the start of each condition, participants were shown 0°, 2.82°, and 5.64° image motion amplitudes while their head was still. They were instructed to observe these motions and use them as references for 0, 50, and 100% of maximum motion amplitude. They could view these anchor stimuli as many times as they wished prior to starting a block. Participants were also told that the image motion to be presented during testing could exceed 100%, so that responses greater than 100 were acceptable. Note that Durgin et al. [2005] provided their observers with only one reference stimulus, termed "100," for comparison, while we provided multiple anchor points for our estimation scale in an effort to linearize their response. Given that the image motion was relative to the HMD, we expected that participants would make their judgments with respect to the moving head (HMD) reference frame. The 0° image motion, i.e., the stationary condition, repeatedly inserted throughout each condition, permitted us to verify that participants maintained this reference frame.

During each session, the no-movement condition was tested first to get a baseline judgment scale. Participants then completed the horizontal and vertical head movement blocks in a counterbalanced order. A final, fourth no-movement condition was run to determine whether there had been any shift in participants' judgment criteria. Each head movement block typically lasted 8 min, with the experimental session completed in less than 40 min.

2.4 Data analysis

To investigate the impact of head motion on the subjective judgment of head-referenced image motion, we conducted a linear regression analysis of judged image motion (Ψ_a) against actual image motion (Ψ_b) specified as follows:

$$\Psi_a = A + K\Psi_b \qquad (1)$$

The slope K represents the proportional increase of perceived amplitude of motion for a given input stimulus, and the intercept A represents the estimation bias. A decrease in K indicates a reduction in sensitivity, or gain, to physical changes in motion amplitude. A decrease in A represents a downward shift of response bias, which can be expressed as a percentage of maximum image motion amplitude and converted to its equivalent in degrees, is independent of the gain change in K.

Before the regression analyses, we first converted input image motion amplitudes to percentages with 5.64° image motion corresponding to 100%. We then computed the median from the five responses provided by each participant at each of the image motion amplitudes for use in the regression analyses. Zero image motion amplitude was analyzed separately. Finally, we performed linear regressions of judgment percentage, described by Equation 1, as a function of the six non-zero image motion amplitudes for each participant for each head movement condition at each image oscillation frequency. With the rescaling of input motion to percentages, a regression with unity slope and zero intercept would correspond to perfect estimation.

126 out of 128 regressions (4 image oscillation frequencies x 4 head movement conditions x 8 participants) were statistically significant ($p < 0.05$); the other two were not ($p = 0.15$ and $p = 0.19$). Figure 3 shows a regression line for one head motion condition from one participant. Subsequent analyses and discussion focus on the slopes and intercepts computed from the regressions.

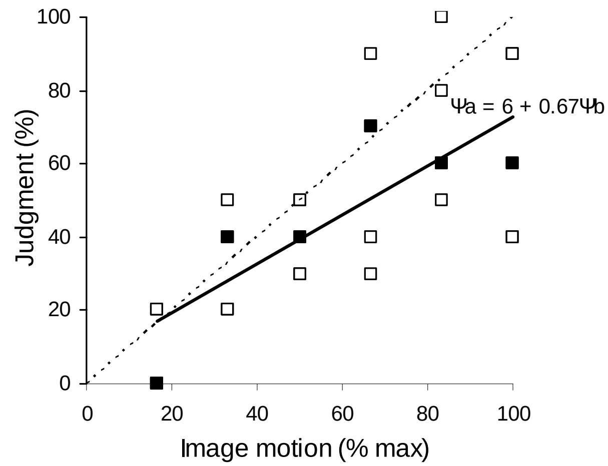


Figure 3. Summary regression line for a sample horizontal head movement condition for an observer. White squares represent all 30 image motion judgments to the six non-zero image motion amplitude levels at the oscillation frequency of 1 Hz. Black squares indicate median of the five judgments at each stimulus level. The dashed line indicates perfect judgment.

3 Results

Of the 128 medians (4 image oscillation frequencies x 4 head movement conditions x 8 participants) at zero image motion amplitude, all but one were reported as 0% amplitude. The remaining one median was 5%. These observations for the zero image motion amplitude indicate that participants were maintaining an HMD (i.e., head) reference frame when making all their judgments. Had they adopted a world reference frame, they would have reported considerable motion.

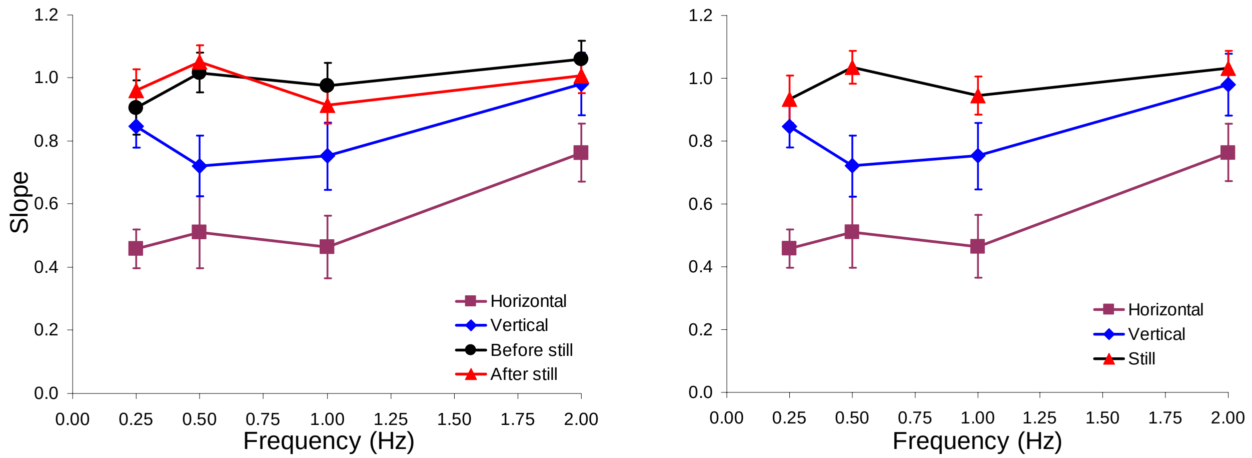
3.1 Slope (*K*)

The mean slope averaged across eight participants is plotted against image oscillation frequency for the four head movement conditions in Figure 4a. A planned paired *t*-test did not find the average slope for the "before" no head movement condition (0.99 ± 0.04, mean ± SE across participants) significantly different from that for the "after" condition (0.98 ± 0.03), with $t_{31} = 2.04$, $p_{2\text{-}tail} = 0.79$. Hence, we averaged the "before" and "after" slopes for each participant, yielding a single, combined "no head motion" value. The overall mean across participants of the combined no head motion slopes (0.99 ± 0.03) was not significantly different from the ideal unity slope response to which participants were trained ($t_{31} = -0.44$, $p_{2\text{-}tail} = 0.66$), indicating that participants' average magnitude estimations of image motion were essentially veridical when the head was stationary.

To determine the effects of head movement and image oscillation frequency, we conducted a 3 x 4 repeated-measure ANOVA on slopes. Both the main effects of head movement and image oscillation frequency were significant, with $F_{(2,14)} = 19.09$, $p < 0.001$ and $F_{(3,21)} = 3.26$, $p < 0.05$, respectively. No significant interaction was observed between the two factors. For the main effect of head movement, post hoc Newman-Keuls tests of slopes for the three head movement conditions plotted in Figure 4b showed that the average slope for the no head motion condition (0.99) was significantly larger than that for the vertical (0.82) and horizontal (0.55) head movement conditions ($p < 0.05$ and $p < 0.001$, respectively), and that the slope for the vertical head movement condition was significantly larger than that for the horizontal condition ($p < 0.01$). This indicates that suppression effect of head movement on image motion perception was larger for horizontal head movement (0.44 gain reduction) than for vertical head movement (0.17 gain reduction). For the main effect of image oscillation frequency, post hoc Newman-Keuls tests revealed that the slopes at 0.25, 0.5, and 1 Hz (0.75, 0.76, and 0.72) were not significantly different from each other, but the slope at 2 Hz (0.93) was significantly larger than that for the other three frequencies ($p < 0.05$), indicating greater perceptual sensitivity (i.e. less suppression) at higher frequency image motion.

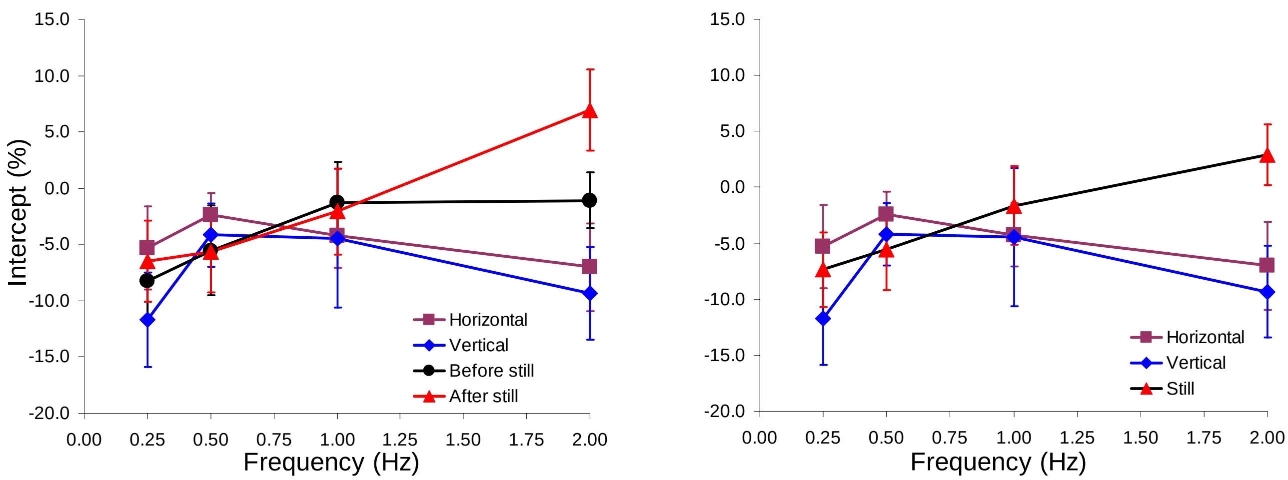
3.2 Intercept (*A*)

The mean intercept averaged across eight participants is plotted against image oscillation frequency for the four head movement conditions in Figure 5a. Again, a planned paired *t*-test did not find the average intercept (mean ± SE across participants) for the "before" no head movement condition (–4.03% ± 1.53%) significantly different from that for the "after" condition (–1.80% ± 1.88%), with $t_{31} = 2.04$, $p_{2\text{-}tail} = 0.10$. Hence, we also averaged the "before" and "after" intercepts for each participant, yielding a single, combined "no head motion" value (Figure 5b). The overall mean across participants of the combined no head motion intercepts (–2.92% ± 1.73%) was not significantly different from the ideal zero intercept (i.e., bias free) response to which participants were trained ($t_{31} = -1.68$, $p_{2\text{-}tail} = 0.10$).



(a) (b)

Figure 4. (a) Mean slopes for before and after no head movement, horizontal and vertical head movement conditions against image oscillation frequencies; (b) Mean slopes for averaged before and after no head movement, horizontal and vertical head movement conditions against image oscillation frequencies. Error bars are SEs across all eight participants.



(a) (b)

Figure 5. (a) Mean intercepts for before and after no head movement, horizontal and vertical head movement conditions against image oscillation frequencies; (b) Mean intercepts for averaged before and after no head movement, horizontal and vertical head movement conditions against image oscillation frequencies. Error bars are SEs across all eight participants.

A 3 (head motion) x 4 (image oscillation frequency) repeated-measure ANOVA on the intercepts revealed that only the interaction was significant, with $F_{(6,42)} = 2.91$, $p < 0.05$. Post doc Newman-Keuls tests showed that for the image oscillation frequency at 2 Hz, the intercept for the no head movement condition (2.92% or 0.16° image motion amplitude) was significantly higher than those for the horizontal (–7.02% or –0.40°) and vertical (–9.33% or –0.53°) head movement conditions ($p < 0.05$ and $p < 0.01$, respectively). The horizontal and vertical conditions were not significantly different from each other. This indicates that the participants' image motion estimation intercept was influenced only by the 2 Hz head movement. At 2 Hz, their response bias averaged 9.9% (0.56°) and 12.2% (0.69°) lower during separate horizontal and vertical head movement than during no head motion.

4 Discussion

Our regression analyses quantitatively show the direct effects of head movement on perceived amplitude of horizontal image motion. For 30° peak-to-peak head oscillation at 0.5 Hz with corresponding relative environmental slewing velocities up to 70.8°/s, horizontal and vertical head movements respectively reduce perceptual sensitivity to image motion displacement amplitude by about 0.4 and 0.2 from the veridical levels reported when the head was still. At the highest image oscillation frequency studied, i.e., 2 Hz, the response bias in participants' motion magnitude estimation was shifted downward by approximately 10% of the maximum image displacement, equivalent to ~0.6°. Our findings reinforce the observation that head movement has an inhibitory effect on motion perception.

4.1 Gain vs. bias change in inhibitory processes

Wallach [1987] proposed that the inhibitory effect of self-motion on concurrent visual perception of motion reflects a compensation process that stabilizes the world during motor activities. For instance, head movements produce viewer-relative motions similar to those produced when the world is moving, but nonetheless we normally perceive the world as being stationary during head motion. The activation of this compensation process during head movements may be partially attributed to VOR-triggered compensatory eye movements. Indeed, it has recently been reported that perceived motion smear was significantly less during VOR-compensated movements than during fixation, particularly for target durations of 100 ms or longer [Bedell and Patel 2005]. However, in Probst and Wist's [1982] and in our current study, the image motion was head-referenced with the VOR suppressed by eye fixation. Thus, on the assumption that the eyes are relatively fixed in the head reference frame, the retinal image motion should be determined largely by the image motion in the HMD. Furthermore, in the present study, there was no fixed phase relationship between head movement and image motion. The suppression of image motion perception during head movement still observed in both these studies therefore supports the idea of a direct sensory inhibitory process based on inner ear (e.g. otoliths) signals or proprioceptive systems rather than a purely mechanical stabilizing process using the VOR (e.g., [Berthoz 1981]).

As a mechanism to implement Wallach's compensation process for self-motion, Barlow [1990] proposed the inhibition theory of sensory correlation. According to this theory, highly correlated events mutually specify one another and consequently produce inhibitory interactions between their respective sensory coding. The perceived reduction of image motion amplitude during head movement in this account "serves the functions of de-emphasizing predictable events in favor of detecting deviations from the norm" [Durgin et al. 2005]. The findings from our current study support this theory in general by showing that horizontal head movement, which is more highly correlated with the side-to-side image motion, produces a larger reduction in perceptual sensitivity to image motion than vertical head movement. We propose that the partial suppression of image motion during the vertical head movement, on the other hand, reflects the lack of specificity of the compensation mechanism for self-motion.

Barlow [1990] is unclear about whether the inhibitory process involves a bias shift in response or a gain (i.e., sensitivity) change exemplified for instance by the inhibitory gain adjustment in contrast gain control (e.g., [Heeger 1992]). Durgins et al. [2005] found that the inhibitory effect of concurrent self-motion on perceived amplitude of 3D motion could be modeled by a "subtractive" (i.e., a bias shift) operation. However, in our present study, we found that for slower image oscillation frequencies ≤1 Hz, suppression of image motion sensitivity with head motion indicates a gain reduction. For the 2 Hz image oscillation, head movements appear to produce both a downward response bias shift and a gain reduction. Aside from experimental task and stimuli, the difference in our interpretation of the suppression mechanism may stem from the subjective magnitude estimation and data analysis procedures employed. Durgin et al. [2005] provided their participants with only one reference stimulus, termed "100," for comparison, while we anchored three points (0, 50, and 100%) of our estimation scale in an effort to linearize participants' responses. Additionally, Durgin et al.'s logarithmic transformation of data makes it impossible to interpret simultaneous gain and bias effects as one otherwise would from concurrent changes in slope and intercept of linear regressions of untransformed data.

Given that we kept the seven image motion amplitudes constant while varying the image oscillation frequencies, higher image oscillation frequencies correspond to faster peak image motion velocities. Thus, the findings from our study suggest that at high relative motion velocities, both gain and bias can change and that, therefore, the motion suppression effect might be larger than at low velocities when only gain is reduced. Indeed, Probst et al. [1986] found that when head yaw frequency (amplitude ±20º) was increased from 1 to 2 Hz to increase the relative motion between the head and the visual stimulus, the reaction time for detecting a horizontally moving target was also increased by about twice. Our subsequent studies will measure head movements and examine how different head oscillation frequencies directly affect perceived image-motion amplitude.

4.2 Motion suppression effect and VE latency

VE system latency is the time delay between a user's input movement and the system's rendering of the response to this movement. Latencies induce dynamic errors in image position that cause virtual objects to "slip" from their expected real-world stable locations (Adelstein et al. 2003; Azuma and Bishop 1994). If sufficiently large, such "image slip" will hamper perception and performance. In prior studies, Adelstein et al. [2003, 2005] found that observers make use of the motion associated with image slip to discriminate the presence of latency. Additionally, latency compensation schemes, such as prediction (e.g., [Azuma and Bishop 1994]), are themselves imperfect, potentially introducing image motion errors that may have perceptual consequences approaching those of the original latency [Jung et al. 2001]. While the dynamic characteristics of errors introduced by VE latency and predictive compensation are easily described analytically, such imperfections remain a significant challenge in the implementation of successful VE systems [Brooks 1999].

The suppression of head-referenced image motion perception during head movement demonstrated by our present study is potentially advantageous in diminishing observer sensitivity to image slip errors caused by VE latencies as well as imperfect latency correction techniques. When the head is moving, perception of image motion errors is suppressed regardless of whether head motion is in the same or different direction of the image motion. Thus, VE designers might incorporate knowledge of this diminished sensitivity to image motion errors into countermeasures to help mitigate the disturbing effects of VE latency.

5 Conclusion

This study provides a quantitative description and analysis of the effects of head movement on an image motion magnitude estimation task. We conclude that 1) image motion perception is suppressed during both highly related and unrelated head movement, showing approximately a gain reduction of 0.4 and 0.2, respectively; and 2) at an image oscillation frequency of 2 Hz, head movement also causes approximately a 10% downward shift in response bias corresponding to 0.6° in motion magnitude estimation. The data reported here and in our recent parametric study of the effects of head motion on image motion perception [Adelstein et al. 2006], provides an estimate of the influence of head movement on perceived image motion amplitude. VE developers could take advantage of this quantitative information in the design of countermeasures that would more effectively mitigate user perception of erroneous image motion caused by VE latencies.

6 Acknowledgments

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