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Scene-Motion Thresholds Correlate with Angular Head Motions for Immersive Virtual Environments

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Abstract

To better understand motion perception in immersive virtual environments, we conducted a user study to quantify perception of scene motion as subjects yawed their heads. We measured psychometric functions of scene-velocity thresholds for different head motions and then extracted 75% thresholds, creating scene-velocity thresholds as functions of three measures of head motion: 1) Angular Range, 2) Peak Angular Velocity, 3) and Peak Angular Acceleration. We also measured scene-velocity thresholds for four phases of head motion: 1) the Start of the head turn, 2) the Center of the head turn, 3) the End of the head turn, 4) and All of the head turn. Scene-velocity thresholds increased as head motion increased for all tested conditions.

1. Introduction

The real world remains stationary as we rotate our heads and we perceive the world to be stable even when the world's image moves on the retina. A computer-generated *immersive virtual environment* (IVE) provides stimuli to a user's senses so that she feels present in a virtual world. In contrast to the real world, an IVE may not be stationary, as the real world is, due to

- **unintentional motion** caused by shortcomings of technology, such as system delay, or imprecise calibration (incorrect field of view, incorrect world-to-eye transformations, etc.), and
- **intentional motion** injected into the system in order to have the virtual motion behave differently than the real world (e.g., redirected walking [14], a technique that allows users to walk in IVEs larger than the tracked lab space).

Whereas error and motion in IVEs are well defined mathematically [1, 6], our perception of error and motion when the head is moving is not well understood. We do know that noticeable visual instability can degrade an IVE experience by causing simulator sickness [4], reducing task performance [16], lowering visual acuity [3], and decreasing the sense of presence [12]. However, IVE researchers know little about when users who are turning their heads start to notice scene motion.

We are conducting a series of experiments that investigates scene-motion perception during head turns. Our goal is to improve the usability of IVEs and determine design requirements for future systems. In this paper, we describe an experiment that expands upon an earlier experiment that investigated whether sensitivity to scene motion depends upon the phase of head motion [8]. The primary differences in this experiment are that different hypotheses are tested, a different experimental design is used, different psychophysical procedures are used, head motions consist of single turns (left to right or right to left) instead of quasi-sinusoidal turns, and actual head motions are used for analysis instead of intended head motions. Specifically, we investigate if scene-motion thresholds increase as head motion increases.

2. Background

Probst et al. [13] found time to detect a moving light spot increased as head motion increased. Loose and Probst [10] found increasing angular velocity of the head decreases sensitivity to visual stimuli moving relative to the head. They used random-dot kinematograms where visual-motion thresholds were measured in percentage of coherently moving pixels. Loose and Probst presented the moving visual stimuli in head coordinates (stimuli moving relative to the head), and stimuli were judged object-relative to a head-stabilized target. Their conditions were different from those of an IVE, where visual stimuli are judged to be moving in world coordinates and judgments are subject-relative (no visual cues other than the virtual scene are present). They found no significant effect of angular acceleration of the head on sensitivity to moving visual stimuli. However, they varied head acceleration while keeping head velocity constant and greater than zero. Head acceleration may be an important factor when head velocity is near zero.

Adelstein et al. [2] and Li Li et al. [9] also showed head motion suppresses perception of visual motion. They used a head-mounted display (HMD) without head tracking which results in the image moving relative to head-centric coordinates.

Wallach [18] concluded that healthy subjects report visual scenes appear unstable when the scenes move at a rate more than 2–3% of head motion. He did not report the types of head motion his subjects performed in either his summary or in earlier work [19].

2.1. Experimental Design Decisions

In a previous study, we found subjects to be twice as sensitive to scenes moving against the direction of head yaws than for scenes moving in the same direction as head yaws [8]. Steinicke et al. [17] proposed thresholds for human's sensitivity to scene velocity when walking in general. Their subjects did not notice up to 68% compression of head rotation, where the scene rotated with head rotation. When the scene rotated against their head rotation, participants were more sensitive, and head rotations could be scaled by only 10% without subjects noticing. Based on these results, this study measures thresholds for the more sensitive condition of the scene moving against head rotation.

Motion perception is different for active head motions (controlled by the subject) than for passive head motions (controlled by an external force) [7]. Since IVE users control their own head motion, we chose active head motions at the cost of us having less control of head motion. We constrained head motion by canceling trials where subjects' head motions did not match intended head motions within some tolerance.

Most researchers agree that scene velocity is more important for motion perception than is scene acceleration [15]. Therefore, in this study, we set scene velocity to be constant within each trial.

3. Experiment

Our goal was to find whether scene-motion thresholds increase as as head motion increases. We used psychophysics methodologies to measure scene-velocity thresholds for different phases, amounts, and measures of head motion. We defined the *scene-velocity threshold* to be the scene velocity (degrees/second) at which a subject is able to detect the presence of scene motion 75% of the time.

Three measures of head motion were tested *Angular Range*, *Peak Angular Velocity*, and *Peak Angular Acceleration*. Note by acceleration we mean absolute acceleration (deceleration or acceleration). We measured thresholds for four phases of a single head turn —the *Start* of the head turn, the *Center* of the head turn, the *End* of the head turn, and *All* of the head turn. Table 1 shows the conditions for which thresholds were measured. For each one of these conditions, six levels of head motion (slow to fast) were measured.

3.1. Hypotheses

We tested the following hypotheses for the four phases of head turns:

- **Hypothesis 1:** Scene-velocity thresholds increase as head angle range, given constant time, increases.
- **Hypothesis 2:** Scene-velocity thresholds increase as peak angular head velocity increases.
- **Hypothesis 3:** Scene-velocity thresholds increase as peak angular head acceleration increases.

3.2. Materials

We designed the experiment to emulate a zero-latency HMD. A BARCO CRT projector displayed images of approximately one lux onto a world-fixed planar surface four meters in front of the seated subject (see Figure 1). The CRT projector was chosen for its fast phosphor response and decay times. With the CRT, there was no ghosting and no light was projected for black pixels, which is not the case for LCD and DLP projectors. A Virtual Research V8 HMD was modified by removing the display elements so that subjects could see through the casing to the world-fixed display. This limited the field of view to 48° by 36°.

All object-relative cues were removed by darkening the room and providing a uniform visual field. Since only the computer-generated scene was visible, subjects could make only subject-relative judgments. Material identical to the display surface was curved around the subject in a quasi-cylindrical shape. The floor was similarily covered, so that the subject saw a uniform visual field. Subjects confirmed they could not see any visual elements other than the computer-generated scene presented by the projector.

A ten-lux green screen was shown between trials to prevent dark adaptation, so that brightness sensitivity would be consistent across trials.

A simple 2D visual scene (a rotated green monochrome square with diagonals and a 20 horizontal span as shown in Figure 1) was chosen for the following reasons:

- Prior work has not been able to find significant differences in scene-motion thresholds across scene complexities [5, 11].
- We wished to minimize depth issues (stereo cues, motion parallax, incorrect head tracking, etc.) that could confound the results.

The horizontal starting position of the stimulus for each presentation was randomly set within 1.8° of the screen center. Scene motion was a constant velocity within each trial and was independent of head movement; head position/orientation did not affect the position or motion of the visual scene. Likewise, latency did not cause additional scene motion as it does for HMD systems. Head orientation was determined by a 3rdTech HiBall 3000 tracking system. The tracking data were used to check for acceptable head rotations and to record motion for post analysis. Total weight of the modified HMD and tracker was 0.6 kg.

3.3. Methods

We asked subjects to yaw their heads starting and ending at stopped positions, with different angular head amplitudes over a period of one second. Before each trial, subjects optionally practiced head turns, as prompted by visual and auditory cues, and then pressed a button to start the trial. The visual cues then disappeared, and subjects rotated their heads in time to auditory cues. If head motion got out of sync with the auditory cues by more than 0.25 seconds, the trial was cancelled and a new trial chosen. The aim was for each head turn to last one second from start to end.

We trained subjects to start turning their heads at two seconds and stop moving their heads at three seconds. Note angular velocity peaks during the center of head turns and angular acceleration peaks during the start and end of head turns. We wished to analyze scene-motion thresholds during these three phases of head turns. Thus, for each trial the system presented a scene for a single phase of the head turn. The scene appeared at some point during the head turn and moved to the left or to the right (against the direction of the head turn) with constant velocity or did not move at all.

The phase conditions were:

- **Visible at the *Start* of the head turn**, where the scene was presented just before the intended start of the head turn (1.9 seconds) to half of the intended head turn (2.5 seconds).
- **Visible at the *Center* of the head turn**, where the scene was presented during the central part of the head turn (2.2 to 2.8 seconds).

- **Visible at the *End* of the head turn**, where the scene was presented from half of the intended head turn (2.5 seconds) to just after the end of the intended head turn (3.1 seconds).
- **Visible for *All* of the head turn**, where the scene was presented for the entire duration of the intended head turn (1.9 to 3.1 seconds).

For each head turn (i.e., for each trial), the three measures of head motion (Angular Range, Peak Angular Velocity, and Peak Angular Acceleration) were calculated for the time of the phase condition.

We turned off the scene when head velocity fell below a threshold value, even when the scene would otherwise be apparent, so that subjects would not judge motion when their heads were not moving.

A method of constant stimuli (stimulus levels are randomly assigned independent of previous judgments) determined random ordering of trials. Judgments consisted of a yes/no task (Did the scene seem to move?) along with a confidence rating (1 to 3). This resulted in six possible judgment levels per trial. Such a design contains bias, but we attempted to keep bias as constant as possible for individuals across trials by randomly interleaving trials across all conditions. Thresholds may vary substantially between subjects, so we chose a repeated measures design (all subjects experienced all conditions).

The wording of the judgement question was:

- Did the scene seem to move or did it seem not to move?
  - The scene seemed to not move
    - ♦ Left button
  - The scene seemed to move
    - ♦ Right button

After pushing the left or right mouse button, subjects rated their confidence in that judgment:

- How confident are you that the scene seemed to move on a scale of 1 to 3?
  1. I guessed that the scene seemed to move
     - Left Button
  2. The scene seemed to move, but I could be wrong
     - Middle Button
  3. The scene certainly seemed to move
     - Right Button

A similar question was asked if subjects selected the “scene seemed to not move” with the word “not” inserted into the rating options.

3.4. Participants

Eight subjects (5 male and 3 female, age 18–27) participated (a minimum of five subjects is required to achieve statistical signficance using the sign test employed in this study). We informed subjects that the scene motion, if any, would occur only in the opposite direction of their head turn—scene motion would never occur in the same direction as their head turn. Otherwise, all subjects were naive to the experimental conditions. We encouraged subjects to take breaks at will. Total time per subject, including consent form, instructions, training, experiment sessions, breaks, and debriefing, took four hours or less. Seven subjects judged 576 trials—144 judgments for each phase condition. One subject judged only 535 trials due to time limitations.

4. Results

Head motions for each of the four phase conditions were divided into six bins with an equal number of samples per bin. We computed psychometric functions, using a probit regression model, for each bin. 75% thresholds were then extracted for each bin and then plotted against the bin’s head-motion mean. Figure 2 shows one subject’s 75% threshold values versus Peak Angular Acceleration for all four phase conditions.

96 Pearson correlations were computed for the 12 conditions (3 head motion measures × 4 phases of head turns) for each of the 8 subjects. Figure 3 shows box plots of the 8 subjects for all 12 conditions. Although all Pearson correlations were not statistically greater than zero, sign tests across all 8 subjects yielded correlations greater than zero for all 12 conditions. 8 of 8 subjects had positive correlations for 10 of the 12 conditions ($p = 0.004$ one-tail). 7 of 8 subjects had positive correlations for 2 of the 12 conditions ($p = 0.035$ one-tail): Peak Angular Velocity for the Start condition and Peak Angular Acceleration for the Center condition.

5. Discussion

5.1. Conclusions

We found scene-velocity thresholds to correlate with all three measures of head motion for all four phases of head yaws. These results suggest sensitivity to scene motion decreases as head motion increases independent of the head-motion measure used or for what phase of the head turn stimuli are presented.

In contrast to Loose and Probst [10], we found thresholds to increase as head acceleration increases. These differences may be due to experiment differences:

- our subject’s head velocities varied as head acceleration varied, whereas they kept head velocity constant as head acceleration varied,
- our stimuli moved in world coordinates, whereas their stimuli movemed in head coordinates, and
- our subjects experienced only subject-relative cues, whereas their subjects experienced both subject-relative cues and a stable object-relative cue.

The only trend evident in the data was lower thresholds for the All-phase condition for some of the subjects. This is expected, since subjects saw the scene twice as long as in other conditions. We did not find trends for any other phases of head turns. This may be due to the diversity of head motions between subjects—although we attempted to have users make similar head turns, we had to reduce synchronization tolerances so that all subjects could get through the trials within a reasonable amount of time. Also, the Start and End phases may have had shorter presentation periods than the Center phase due to the scene being turned off when head velocity was below a threshold value.

Two subjects spontaneously reported they thought scene motion was easier to detect with faster head motion contrary to their collected data. This is a good example of the advantage of psychophysics over intuitive speculation.

5.2. Limitations

We do not expect scene-velocity thresholds to hold across other conditions (type of head turns, contrast, scene size, field of view, training effects, etc). We do suspect that the increase in scene-velocity thresholds as head motion increases to hold across different conditions. However, further study would be required to verify this expectation.

Due to the large number of trials per subject, a yes/no judgment task was chosen to reduce subject time. Such a task comes at a cost of a larger amount of subject bias than the alternative-forced choice task used in our previous experiment [8]. Signal detection theory could also be used to better determine absolute thresholds.

5.3. Future Work

Although linear relationships were not reported due to the small sample sizes, regressions could be computed with more data to determine scene-velocity thresholds as a function of the different head-motion measures.

Our results suggest more imperceptible scene motion can occur in IVEs for larger head motions. Our thresholds provide guidelines on how much scene motion can be intentionally injected into IVEs for reorientation purposes (e.g., redirected walking [14]). Scene motion should not be limited by a constant maximum value, but should be limited by the current amount of head motion. We plan to further measure scene-velocity thresholds and use the results for redirecting walking purposes.

Scene motion due to latency and incorrect geometric field-of-view increases as head motion increases. We are currently conducting experiments to study the relationship between scene-motion thresholds and latency thresholds. Latency requirements might be able to be determined indirectly from scene-motion thresholds.

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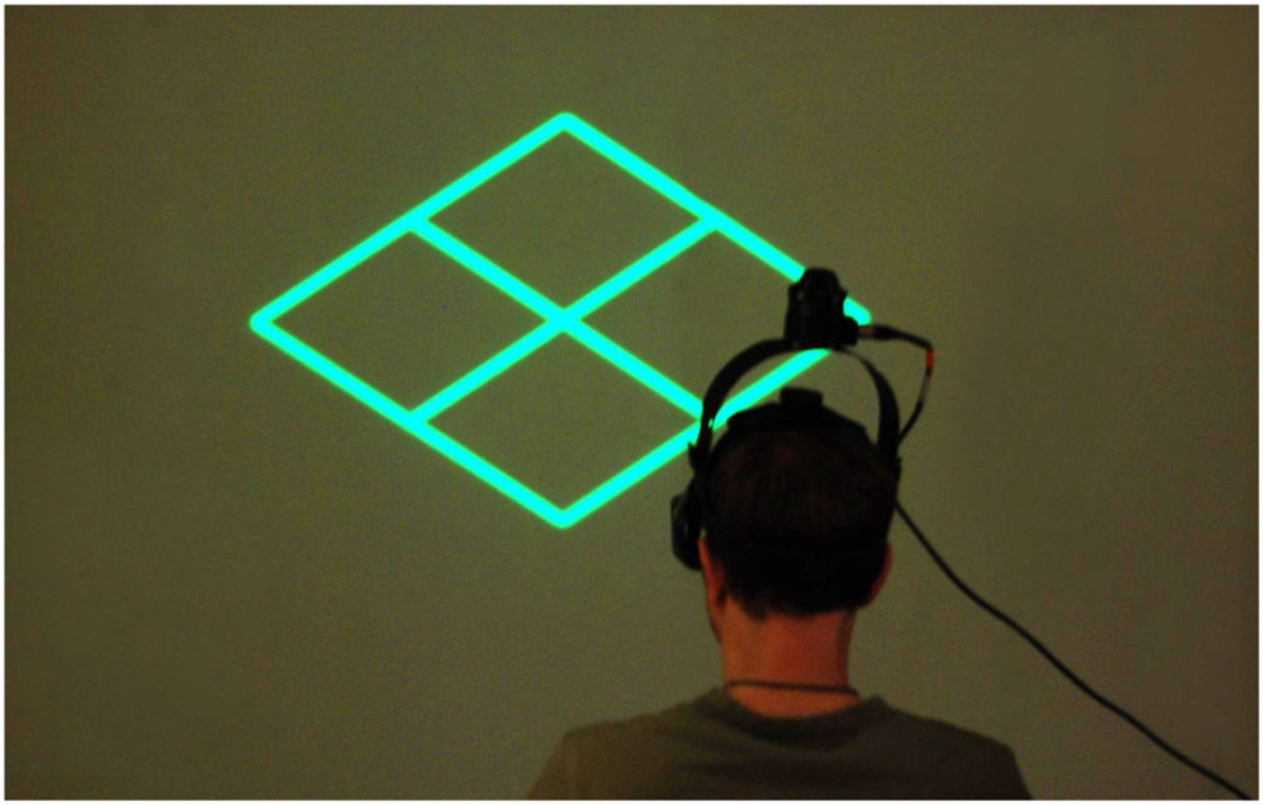

Figure 1.
A subject and scene as the subject yaws his head.

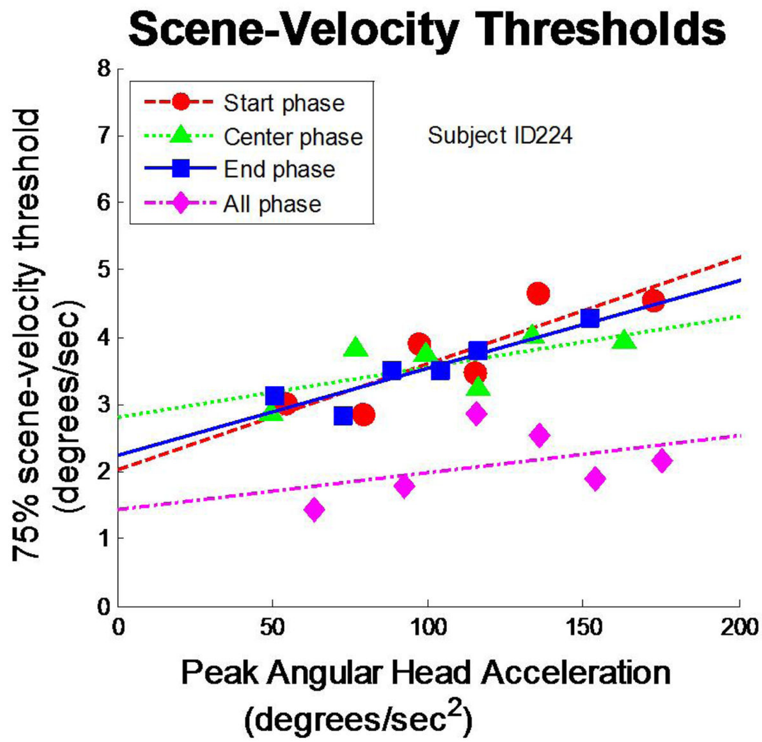

Figure 2.

Thresholds for a single subject where head motion is defined by Peak Angular Acceleration. Note the lower thresholds for the All-phase condition and the similarities of the other conditions—such trends were not consistent for all subjects.

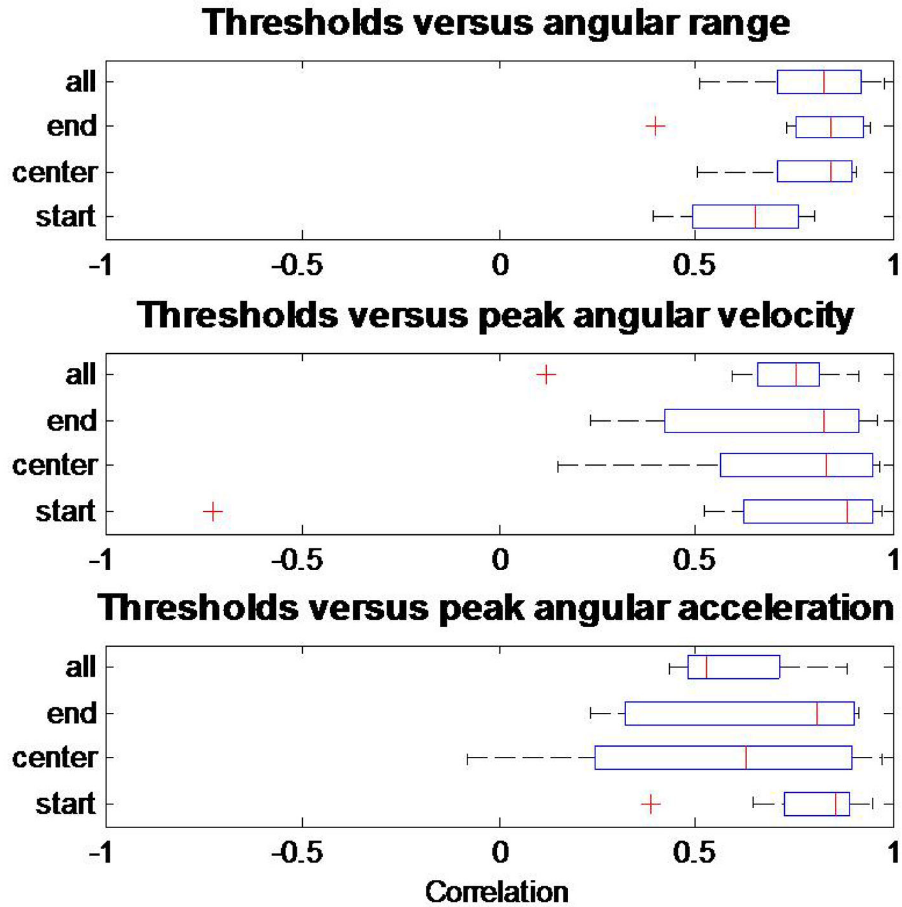

Figure 3.

Box plots of Pearson Correlations for the eight subjects.

Table 1

Experiment conditions.

		Head Phase			
		Start	Center	End	All
Measure	Angular Range				
	Peak Angular Velocity				
	Peak Angular Acceleration				