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Scene-Motion Thresholds During Head Yaw for Immersive Virtual Environments

Jason Jerald,
Digital ArtForms

Mary Whitton, and
University of North Carolina at Chapel Hill

Frederick P. Brooks Jr.
University of North Carolina at Chapel Hill

Abstract

In order to better understand how scene motion is perceived in immersive virtual environments, we measured scene-motion thresholds under different conditions across three experiments. Thresholds were measured during quasi-sinusoidal head yaw, single left-to-right or right-to-left head yaw, different phases of head yaw, slow to fast head yaw, scene motion relative to head yaw, and two scene illumination levels. We found that across various conditions 1) thresholds are greater when the scene moves with head yaw (corresponding to gain < 1:0) than when the scene moves against head yaw (corresponding to gain > 1:0), and 2) thresholds increase as head motion increases.

Keywords

Experimentation; Human factors; Measurement

Additional Key Words and Phrases

Psychophysics; Scene-motion thresholds; head motion; redirected walking, latency

1. INTRODUCTION

The real world remains stationary as one rotates the head, and one perceives the world to be stationary even when the world's image moves on the retina. The perceptual stability of the

Author's address: jason@dartforms.com

world occurs due to extra-retinal cues that come from the vestibular system, proprioception, our cognitive model of the world, intent, etc. When two or more of these cues conflict, as is often the case for computer-generated worlds, the virtual world may be perceived to be spatially unstable.

A computer-generated *immersive virtual environment* (IVE) provides stimuli to users' senses so that they feel present in a virtual world. *Scene motion* is improper visual motion of the scene, motion that would not occur if the IVE behaved as the real world. We define scene motion to be relative to an earth-stationary environment. 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 latency, or imprecise calibration (e.g., incorrect field of view, incorrect world-to-eye transformations), and

— **intentional scene motion** injected into the system in order to make the virtual world behave differently than the real world (e.g., redirected walking [Razzaque et al. 2001], a technique that rotates the scene around the user so that users can walk in IVEs larger than the tracked lab space).

Whereas error and scene motion in IVEs are well defined mathematically [Adelstein et al. 2005; Holloway 1997], user's perception of unnatural scene motion while the head is moving is not as well understood. Investigators do know that noticeable visual instability can degrade an IVE experience by causing simulator sickness [Draper 1998], reducing task performance [So and Griffin 1995], lowering visual acuity [Allison et al. 2001], and decreasing the sense of presence [Meehan et al. 2003]. However, IVE researchers know less about how much scene motion there must be for head turners to notice.

A perceptual *threshold* is the change in intensity of a stimulus that is required for a subject to detect that change with some specified probability. Measuring and comparing scene-motion thresholds under different conditions while the head is turning provides

— an improved understanding of how we perceive scene motion while the head is moving, —improved design for redirected walking systems [Razzaque et al. 2001].

— a step toward a better understanding of latency perception for head-mounted display (HMD) users, and

We conducted three experiments that investigated scene-motion perception during head yaw. Two have been previously published [Jerald et al. 2008; Jerald et al. 2009] and all are described in the first author's dissertation [Jerald 2009]. The experiments found that across various conditions 1) scene-motion thresholds are greater when the scene moves with head yaw than when the scene moves against head yaw, and 2) scene-motion thresholds increase as head motion increases.

2. BACKGROUND

It is understood that perception of scene-motion is suppressed when a person moves [Wallach 1987; Loose and Probst 2001; Adelstein et al. 2006; Dyde and Harris 2008; Li et al. 2009]. Redirected walking studies have measured scene-motion thresholds during subject movement so that this suppression can be taken advantage of [Engel et al. 2008; Bruder et al. 2009; Steinicke et al. 2010].

For a tracked HMD, the graphics in the HMD must move in the opposite direction of a head turn in order to remain stable in earth-stationary space. We define *gain* to be the negative ratio of image motion in the HMD to head motion in the real world. This work relates specifically to rotational gains (versus translational gains) and our definition is distinct from eye rotation gain. A gain of 0.0 results in the scene turning with the head, the same that would result with no head tracking. A gain of 1.0 results in the scene being stationary in space (assuming the scene is at a distance).

Studies disagree whether scenes appear more stable when the scene moves (relative to the earth) in the same direction as head motion [Wallach and Kravitz 1965; Bruder et al. 2009; Steinicke et al. 2010] or when the scene moves against the direction of head motion [Jaekl et al. 2005; Engel et al. 2008].

Wallach and Kravitz [1965] used a mechano-optical device (the most similar to our system) to measure visual stability of scenes and reported scenes appear most stable when the scene moves slightly with the direction of head turns. They did not report the details on the type of head motion their subjects made.

Steinicke et al. [2010] measured thresholds for scene motion when walking in general using an HMD, without focusing on head rotations. Subjects had to perform a physical body turn which was mapped to a virtual target rotation. They found that subjects judged scenes to be most stable with gain = 0.96. Using similar methods, Bruder et al. [2009] found similar results. Bruder et al. also measured scene-motion thresholds for different amounts of body rotation.

Jaekl et al. [2005] had HMD wearing subjects adjust scene motion until the scene appeared most stable and scenes appeared to be most stable when gain = 1.26.

Engel et al. [2008] manipulated gain while HMD-wearing subjects walked around a block. Subjects were then asked to report whether they turned more or less than 90° in the real world. They found that scenes appeared most stable with a gain slightly greater than 1.0. Subjects also reported rotational gains smaller than 1.0 as being less comfortable.

Given some HMD system latency, the scene first moves with the head before moving back to the correct position. One way users perceive latency in tracked HMD systems is by this resulting scene motion [Adelstein et al. 2003]. Experiments performed at NASA Ames Research Center [Adelstein et al. 2003; Adelstein et al. 2005; Ellis et al. 1999; Mania et al. 2004] measured tracked HMD latency thresholds for quasi-sinusoidal head yaw.

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Adelstein et al. [Adelstein et al. 2005] found tracked HMD latency thresholds to be greater during the reversal of quasi-sinusoidal head yaw, i.e., when head velocity is lowest and head direction changes, than in the center of head yaw, when head velocity peaks. Two factors may explain their results:

— Scene velocity due to latency peaks at the reversal of quasi-sinusoidal head turns (when the head reverses directions) and is near zero at the center of quasi-sinusoidal head turns.

— Scene-motion thresholds may be different for different phases of head turns.

In this work, we study scene-motion thresholds where scene motion is directly controlled as an experimental variable, independent of head motion and latency.

3. OVERVIEW OF EXPERIMENTS

Experiment 1 investigated for which phases of quasi-sinusoidal head yaw scene-motion thresholds were highest. Experiment 2 investigated, for a single head yaw, whether the results from Experiment 1 were repeatable for different phases of head yaw: start, center, and end; and for different scene brightness levels. Experiment 3 investigated whether scene-motion thresholds increased as head-yaw velocity and acceleration increased. The study methods were similar, and common elements are described here.

We defined the scene-motion threshold to be the scene velocity (degrees per second) at which the subject correctly chose the presentation that contained scene motion 75% of the time. Scene velocity was held constant during each trial. A *psychometric function* normally relates detection probabilities to stimulus intensities as is the case for Experiment 1. However, for Experiment 2 and 3, our “psychometric functions” were based on subjects’ subjective ratings of their confidence in their responses instead of detection rates.

Whereas some of our measurements are similar to gain and can be compared to previously reported gains, we do not measure with gain because scene motion was controlled by the experiment, independent of head motion.

For each trial, subjects yawed their heads while a non-moving or moving scene with constant velocity was presented. At the conclusion of each trial, subjects judged scene motion (i.e., did the scene seem to move from an earth-stationary position?) via mouse buttons. No communication between the experimenter and the subject occurred during trials. Each subject experienced hundreds of trials. Subjects were encouraged to take breaks at any time.

Experiment 1 was a mixed design (within and between subjects) where different subjects yawed their heads with different frequencies. Because Experiment 1 found that thresholds varied considerably among subjects, we thereafter used a repeated-measures design (all subjects experienced all conditions).

The specifics of head motions, scene presentation times, scene motions, scene luminances, psychophysics methods, and analysis varied across experiments.

3.1 Materials

We used a minimum virtual environment system—a projector that displayed a simple 2D object. Using such a minimal system enabled us to control variables precisely and minimize confounders. The use of a projector, instead of an HMD, enabled us to emulate a zero-latency HMD system. This is because the visuals located on an earth-stationary display remain stable independently of head motion and latency, unlike the visuals in an HMD. We added different levels of scene-motion (implemented as different levels of scene velocity in earth-stationary screen space) to enable us to measure scene-motion thresholds.

We designed the scene to be a rotated green monochrome square with diagonals and a 20° horizontal span (Figure 1) for the following reasons:

- A 2D scene colocated with the display surface eliminated possible depth issues that could confound results. —To be consistent with another experiment [Jerald and Whitton 2009].
- Prior work has not found differences in scene-motion thresholds across different levels of scene complexity [Ellis et al. 2004; Mania et al. 2004]. Thus, we expect the results to generalize to more complex scenes.

A BARCO CRT projector displayed the scene onto a world-fixed planar surface four meters in front of the seated subject (Figure 1). The CRT projector was chosen for its fast phosphor response and decay. Unlike LCD and DLP projectors, with the CRT there was no ghosting, and no light was projected for black pixels.

A Virtual Research V8 HMD was modified by replacing the display elements with cardboard cutouts so that subjects could see through the casing to the world-fixed display (Figure 2). The cutouts limited the user's field-of-view to 48° by 36°, the same as an unmodified Virtual Research V8 HMD. Head orientation was determined by a 3rdTech HiBall™ 3000 tracking system. The tracking data were used to control auditory cues (See Section 3.2), to check for acceptable head rotations, and to record motion for post analysis (tracking did not affect scene motion). Total weight of the modified HMD and tracker was 0.6 kg.

All object-relative cues were removed by darkening the room and providing a uniform visual field. Only the computer-generated scene was visible so subjects could make only subject-relative judgments. Subjects confirmed they could not see any visual elements other than the computer-generated scene presented by the projector. The scene was presented for some head-yaw phase and blanked otherwise.

A larger scene was shown between trials to provide an earth-stable reference scene. This enabled better judgment and reduced judgment drift between trials. The reference scene was brighter than trial scenes to prevent dark adaptation, as we believed it important that brightness sensitivity be consistent across trials.

Since the number of subjects was small and we could not assume normally distributed samples and homogeneity of variance, we used non-parametric tests throughout. We set $\alpha = 0.05$ for all statistical tests.

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3.2 Head Motion

We focused on head rotation instead of head translation since, for HMDs, visual error due to latency and head rotation is greater than error due to latency and head translation for all but the closest objects [Holloway 1997; Jerald 2009]. We chose to focus on head yaw because yaw reorientation is exploited in redirected walking—the world yaws around the user in order to have the user unknowingly walk in different directions.

For Experiment 1, subjects yawed their heads with quasi-sinusoidal motions. For Experiments 2 and 3, subjects yawed their heads a single time left-to-right or right-to-left for each trial (randomly assigned).

We trained subjects to yaw their heads using both visual (moving crosshairs that followed their head, and vertical lines showing the extent of the desired head yaw) and auditory (metronome beeps, a tone when head yaw exceeded a minimum head-yaw amplitude, and a buzz sound when head yaw exceeded a maximum head-yaw amplitude) cues; the experiment room was otherwise kept dark and quiet. Subjects optionally practiced head turns with all cues before each trial and then pressed a button to start the trial. The visual cues then disappeared, the audio cues continued, and the subjects yawed their heads. If head yaw got out of sync with the metronome, the minimum head yaw was not reached, or the maximum head yaw was exceeded, then the trial was cancelled.

4. EXPERIMENT 1: PHASES OF QUASI-SINUSOIDAL HEAD YAW AND SCENE-MOTION DIRECTION

We wanted to find out if scene-motion thresholds depend on the phase of quasi-sinusoidal head yaw and on scene motion relative to head motion direction. The system presented moving and non-moving scenes for either the central phase of head yaw (with the scene moving in the same direction of head yaw or in the opposite direction of head yaw) or at the extremes when head yaw direction reverses.

4.1 Hypotheses

Working from published results of latency thresholds [Adelstein et al. 2005], our original hypothesis was:

— **Hypothesis 1:** Scene-motion thresholds are greatest during the reversal of quasi-sinusoidal head yaw, when head-yaw direction changes.

During pilot studies, we noticed a trend that for the center-phase of head yaw (when head velocity was near constant), scene-motion thresholds seemed to be greater when the scene moved with the direction of head yaw. Due to this observation, we added the following hypothesis:

— **Hypothesis 2:** Scene-motion thresholds are greater when the scene moves with the direction of head yaw than when the scene moves against the direction of head yaw.

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4.2 Experimental Design

The experiment was a mixed (within-subject and between-subject) adaptive staircase psychophysics design. Table II shows the experiment design.

4.2.1 Independent Variables—Two variables were manipulated: three head frequencies between subjects and three head-phase conditions within subjects. The primary variable of interest was the head-phase condition.

To generalize results across head motion, we measured scene-motion thresholds for three head frequencies: 0.35 Hz, 0.5 Hz, and 0.65 Hz corresponding side-to-side head swings in 1.43 seconds, 1.0 seconds, and 0.77 seconds (with a suggested amplitude of ±11° in all cases). Head frequency was a controlled between-subjects variable, with three subjects per head frequency. The top element of Figure 3 show a specified head yaw of 0.5 Hz and a single subject's actual head yaw over time for several trials.

The head-phase conditions were:

— **With Condition:** The scene moved in the same direction of the head yaw and was presented only during the center phase of quasi-sinusoidal head yaw.

— **Against Condition:** The scene moved against the direction of head yaw and was presented only during the center phase of quasi-sinusoidal head yaw.

— **Reversal Condition:** The scene moved left or right and was presented only during the extremes of quasi-sinusoidal head yaw, during the time that head direction changed, i.e., the scene moved part of the time with the direction of head yaw and part of the time against the direction of head yaw.

4.2.2 Dependent Variable—We extracted 75% scene-motion thresholds from psychometric functions generated by subjects' selections of scene motion for a range of scene velocities.

4.3 Procedure

Trial procedures used a one-up-two-down adaptive staircases algorithm to determine scene-motion thresholds.

Each subject experienced six sessions over one or more days. Each session consisted of three randomly interleaved staircases, with one staircase for each head-phase condition. This interleaving of staircases minimized order effects, and made it difficult for subjects to guess the conditions. Each staircase started with a scene motion of 7.1°/*s* and terminated after eight staircase reversals, resulting in each subject judging a total of 148 to 219 trials for each of the three conditions. The staircase step size started at 3.6°*s* and was halved at every reversal until a minimum step size of 0.22°/*s* was reached.

Each trial consisted of a three-interval two-alternative forced choice (3I-2AFC) identification task. Three presentations were provided with one presentation per head-yaw cycle. The first presentation was a reference scene containing no scene motion so that subjects knew what a stable scene looked like. Some scene motion was randomly assigned to either the second or third presentation. Subjects then selected which of the latter two presentations they believed contained scene motion (i.e., which of the latter two presentations was different from the first presentation?). After each response, the system informed subjects whether they were correct. To encourage good performance, we rewarded subjects $0.05 for every correct response. The bottom of Figure 3 shows head motion and head-yaw phase when the scene is visible for an example trial.

We asked subjects to keep their eyes centered on the middle of the scene so that the scene was seen mostly in the foveal region of the eye. However, the scene appeared randomly within ±3.2°of center so that subjects could not precisely predict where the scene would appear.

4.4 Participants

Nine subjects (7 male and 2 female, age 18–44) participated. The primary author served as one of the subjects; all other subjects were naive to the experimental conditions. Total time per subject, including consent form, instructions, training, experiment sessions, breaks, and debriefing, took three to six hours hours, with an average of approximately five hours.

4.5 Results

For each subject and condition, we computed proportions of correct responses for each scene velocity presented. A cumulative Gaussian psychometric function was fit to these proportions (weighted by the number of samples in each proportion). We required a minimum of two judgments for a scene-motion judgment proportion to contribute to the fit. In addition, we artificially inserted a theoretical proportion of 0.5 for zero scene velocity to help fit the psychometric function (since the two presentation options with zero scene motion would have been identical, subjects would have been just as likely to choose either option). The Gaussian distribution's mean at 75% yields the scene-motion threshold.

Figure 4 shows percentage of correct responses and psychometric functions for all three phase conditions for a single subject at a head frequency of 0.35 Hz. Figure 5 shows scene-motion thresholds for the three phase conditions from all nine subjects. It is visually evident that thresholds are higher for the With Condition.

Friedman analyses of variance (ANOVA) shows that scene-motion thresholds were significantly affected by the phase conditions ($Q_2 = 16.22$; $p < 0.001$). For comparing differences between conditions, we set $\alpha = 0.05 / 3 = 0.017$ (Bonferroni Correction). With Condition thresholds were statistically significantly greater than both the Against Condition thresholds and Reversal Condition thresholds (both Wilcoxon matched-pairs signed-rank tests: $S_9 = 0$; $p_{two-tail} < 0.01$). The Against Condition thresholds were less than the Reversal Condition thresholds. However, this finding was not statistically significant (Wilcoxon matched-pairs signed-rank test: $S_9 = 6$; $p_{two-tail} < 0.055$).

Since there was no statistically significant difference between the Against and Reversal Condition thresholds, we computed the 95% confidence interval of the differences and the corresponding range of statistical equivalence. The 95% confidence interval of the differences (Against Condition thresholds subtracted from Reversal Condition thresholds)

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was (−0.01°/ *s*; 1.05°/*s*). Thus, the differences were statistically equivalent within ±1.05°/*s* ($p < 0.05$). 1.05°/*s* is 39% of the average of all computed thresholds (2.7°/*s*).

In order to summarize across head frequencies, we computed the ratio of scene-motion thresholds to intended peak head-yaw velocities for the Against and With Conditions. Figure 6 shows these ratios. The ratios ranged from 2.2% to 7.7% (median of 5.2%) for the Against Condition and 7.7% to 23.5% (median of 11.2%) for the With Condition. Thus, on average across subjects and trials, subjects did not notice scene motion that was up to 5.2%–11.2% of intended peak head-yaw velocity. Note these percentages are provided only as guidelines since they do not take into account actual peak head-yaw velocity.

The median of the ratios of the With Condition to the Against Condition was 2.2; twice as much motion can occur without users noticing when the scene moves with the direction of head yaw than when the scene moves against the direction of head yaw.

5. EXPERIMENT 2: SINGLE HEAD YAW, LUMINANCE, AND SCENE-MOTION DIRECTION

Experiment 1 found that scene-motion thresholds were greater when the scene moved with the direction of head yaw than when the scene moved against the direction of head yaw. However, this finding was only for very specific conditions—for the center of head yaw (approximately constant head velocity). We did not define start or end head-yaw phase conditions in that experiment because head yaw was quasi-sinusoidal— the “end” of a head yaw was also the “start” of a head yaw; the head did not accelerate from a fully stopped position or decelerate to a fully stopped position. We wanted to provide a stronger case that scene-motion thresholds are greater for “with” conditions than “against” conditions, and that the results were not simply an artifact of the head motions and other specifics of Experiment 1. Therefore, for Experiment 2, we compared thresholds for “with” and “against” conditions during the time that head yaw started and ended.

We also wanted to know if scene luminance and contrast affected the results of Experiment 1. Graham [1965] described experiments that found subjects are more sensitive to motion of brighter stimuli. Although the measurements were taken when the head was held still, we suspected the findings would be similar when the head moves. It is possible that in Experiment 1 the scene luminance and contrast biased scene-motion thresholds to be greater for the With Condition than for the Against Condition. Such a dependence on luminance and contrast is plausible because of previous findings:

— Brightness is a depth cue that can cause brighter objects to appear to be in front of darker objects [Coren et al. 1999]. The pivot hypothesis [Gogel 1990] states that incorrectly perceived distance can cause a stimulus to seem to move as the head moves when it is fact stable on the display surface. If a non-moving bright scene appears to be in front of the display surface, then the scene could be perceived to move with the direction of head turns and the scene would have to move against the direction of head turns to appear stable. In this case, higher scene-motion thresholds would result when the scene moves against the direction of head turns and lower thresholds would result when the scene moves with the direction of head turns (or the opposite result if a darker scene was perceived to be behind the display surface). We wanted to know if a brighter scene could nullify the results found in Experiment 1, i.e., would "with" condition thresholds still be greater than "against" condition thresholds for bright scenes?

— Contrast can affect the direction a scene seems to move. Freeman and Banks [1998] found that low-contrast scenes can reverse the direction of perceived movement in the Aubert-Fleischl illusion (the false impression that objects move slower when they are pursued with the eyes as compared to when the eyes are stationary) and the Filehne illusion (when one tracks a moving object with the eyes, a stable background appears to move against eye motion). For low-contrast scenes, an object can appear to move faster (instead of slower) when pursued with the eyes compared to when the eyes are stable, and a stable background can appear to move with (instead of against) eye motion when a moving object is pursued with the eyes.

— The differences in delay of human visual processing between a light and dark environment can be up to 100 *ms* [Anstis 1986]. In situations that lack real-world cues, delayed perception of dimmer scenes may result in perceived scene motion, similar to that which occurs with a lagging HMD system.

5.1 Hypotheses

We tested the following hypotheses:

— **Hypothesis 1:** Scene-motion thresholds are greater when the scene moves with the direction of head yaw than when the scene moves against the direction of head yaw, regardless of head-yaw phase and regardless of scene luminance.

— **Hypothesis 2:** Scene-motion thresholds are lower for a bright scene than for a dim scene.

5.2 Experimental Design

Experiment 2 was a repeated-measures adaptive-staircase design. Table III shows the experimental design.

Subjects yawed their heads over a period of one second. Visual cues before the trials, and auditory cues before and during the trials suggested subjects yaw their heads by ±15° from straight ahead.

5.2.1 Independent Variables—Three variables were manipulated—three head-yaw phases, two scene-motion directions, and two scene luminances—resulting in 12 conditions.

5.2.1.1 Head-Yaw Phase: The scene was visible during the *Start* of the head yaw, *Center* of the head yaw, or *End* of the head yaw.

5.2.1.2 Scene Direction: The scene moved *With* or *Against* the direction of the head yaw.

5.2.1.3 Scene Luminance: The scene was *Dim* (scene foreground = 10.0 cd/m^2, scene background = 0.067 cd/m^2; contrast = 167) or *Bright* (scene foreground = 0.11 cd/m^2, scene background = 0.003 cd/m^2; contrast = 37). The Bright Condition foreground had two orders of magnitude more light than the Dim Condition foreground. The Bright Condition contrast was 4.5 times the Dim Condition contrast.

5.2.2 Dependent Variable

5.2.2.1 Scene-motion thresholds: We extracted 75% scene-motion thresholds from psychometric functions that were generated by subjects' confidence of the presence or absence of scene-motion.

5.3 Procedure

Each condition consisted of two adaptive staircases, one staircase starting with zero scene motion and one staircase starting with a scene motion of 10°/*s*, with the staircase terminated on the eighth reversal. The staircase step size started at 5°/*s* and was halved at every reversal until a minimum step size of 0.625°/*s* was reached. Staircases were randomly interleaved in order to minimize bias.

Judgments consisted of a yes/no rating task (Did the scene seem to move?) with three levels of confidence resulting in six possible judgments per trial (corresponding to 0%, 20%, 40%, 60%, 80%, and 100% confidence). We required these additional confidence ratings due to the large amount of data required for analysis. The wording of the judgement question is shown in Figure 7 (left). After pushing the left or right mouse button, subjects rated their confidence as shown in Figure 7 (right). A similar confidence question was asked if subjects selected the "scene seemed to not move".

5.4 Participants

Nine subjects (7 male and 2 female, age 18—34) participated. The primary author served as one of the subjects; all other subjects were naive to the experimental conditions.

5.5 Results

For each of the 9 subjects and 12 conditions, we fit a cumulative Gaussian psychometric function to the data, derived from yes/no judgments with confidence ratings, and then extracted 75% thresholds. We then computed differences of conditions within subjects and compared these differences across subjects.

The average false alarm rate (the average confidence rating that there was scene motion when there was no scene motion) was 24.8%. The largest false alarm rate (one subject) was 56.4%. These high false alarm rates suggest the subjects were largely guessing when there was no scene motion.

Figure 8 shows data collected from a single subject for the Center-Dim-Against Condition. Individual trial ratings are shown (some Xs represent multiple ratings) along with the mean rating per scene-motion level, a psychometric function fit to the data, and the 75% scene-motion threshold.

Figure 9 shows box plots for all subjects' thresholds for each condition.

We conducted Wilcoxon matched-pairs signed-rank tests comparing the With Condition thresholds to the Against Condition thresholds for each of the six tested Conditions (3 head-yaw phases 3 × 2 scene luminances). We used one-tailed tests since we expected scene-motion thresholds to be greater for the With Condition than the Against Condition. The With Condition thresholds were found to be statistically significantly greater (each $S_9 \leq 7$, each $p_{one-tail} < 0.05$) than the Against Condition thresholds. No correction was required for α = 0.05 since the largest p-value was less than 0.05 [Hochberg 1988].

The median ratio of With Condition thresholds to Against Condition thresholds was 1.89 and the mean ratio was 1.98 with a standard deviation of 0.93. These average ratios agree with the results of Experiment 1 that scene-motion thresholds when the scene moves with the direction of head yaw are approximately twice as large as when the scene moves against the direction of head yaw.

We also conducted Wilcoxon matched-pairs signed-rank tests comparing the Dim Condition thresholds to the Bright Condition thresholds for each of the six tested Conditions (3 head-yaw phases × 2 scene-motion directions). None of the differences were statistically significant with Bonferroni Correction (α = 0.05/6 = 0.008) although there was a trend ($p_{two-tail} < 0.039$) for the Dim Condition thresholds to be greater than the Bright Condition thresholds for the Start-Against Condition.

We also compared thresholds across head-phase conditions. We conducted Wilcoxon matched-pairs signed-rank tests comparing the Head-Phase Conditions. Because no differences were found between the two scene-luminance conditions, we collapsed the Dim and Bright Conditions. Thus, there were 6 comparisons total (3 head-yaw phases × 2 scene-motion directions). We set α = 0.05/6 = 0.008 due to Bonferroni Correction. For the With Condition, the End Condition thresholds were less than both the Center Condition thresholds ($S_{18} = 15$; $p_{two-tail} < 0.002$) and the Start Condition thresholds ($S_{18} = 8$; $p_{two-tail} < 0.001$). We do not claim this generalizes across general head yaw since some subjects stopped yawing earlier than we intended and the scene kept moving, which could have caused the End Condition to result in lower thresholds.

6. EXPERIMENT 3: INCREASING HEAD MOTION

The goal of Experiment 3 was to determine whether scene-motion thresholds increase as head motion increases. We asked subjects to yaw their heads over a period of one second with different suggested head-yaw amplitudes and to start and end at stopped positions. We measured scene-motion thresholds for different phases and measures of head motion. Head motion was both an independent variable (the suggested head motion) and a dependent variable (the actual measured head motion). Because Experiments 1 and 2 found scene-motion thresholds are lower when the scene moves against the direction of head yaw, we only measured scene-motion thresholds for such "against" motion since we were interested in measuring the more conservative thresholds.

6.1 Hypotheses

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

— **Hypothesis 1:** Scene-motion thresholds increase as head yaw range, given constant time, (i.e., average head-yaw velocity) increases.

— **Hypothesis 2:** Scene-motion thresholds increase as peak head-yaw velocity increases.

— **Hypothesis 3:** Scene-motion thresholds increase as peak head-yaw acceleration increases.

6.2 Experimental Design

The experiment was a repeated measures constant-stimuli design. Table IV shows the experimental de-sign.

6.2.1 Independent Variables—Two variables were manipulated: head-yaw phase and intended head-yaw motion.

6.2.1.1 Head-Yaw Phase: For each trial, the system presented a scene for a single head-yaw phase from a start position to a stop position. The scene moved with a random but constant velocity, or did not move at all.

We trained subjects to start yawing their heads 2.0 seconds after an initial audio beep and to stop yawing their heads 3.0 seconds after the same audio beep. The head-yaw phase conditions were:

— **Start Condition:** The scene was presented just before the intended start of the head yaw (1.9 s) to half of the intended head yaw (2.5 s), during the time when head acceleration typically peaks.

— **Center Condition:** The scene was presented during the central phase of the head yaw (2.2 to 2.8 s), during the time when head velocity typically peaks.

— **End Condition:** The scene was presented from half of the intended head yaw (2.5 s) to just after the end of the intended head yaw (3.1 s), during the time when head deceleration typically peaks.

— **All Condition:** The scene was presented for the entire duration of the intended head yaw (1.9 to 3.1 s).

Unlike in Experiment 2, the system blanked the scene when head-yaw velocity fell below a threshold value, so that subjects would not judge motion when their heads were not moving.

6.2.1.2 Intended Head-Yaw Amplitude: Visual cues before the trials, and auditory cues before and during the trials suggested subjects, over a period of one second, yaw their heads by ±5°, ±10°, ±15°, or ±20° from straight ahead. Actual head motions varied substantially; the suggested head motions were provided to ensure a wide range of head motions.

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6.2.2 Dependent Variables

6.2.2.1 Head-Motion Measures: We analyzed three measures of head motion—*Yaw Range*, *Peak Yaw Velocity*, and *Peak Yaw Acceleration*. By acceleration, we mean absolute acceleration (deceleration or acceleration). For each head yaw (i.e., for each trial), the three measures of head motion were calculated over the period of time the scene was visible for that condition.

6.2.2.2 Scene-Motion Threshold: We measured 75% scene-motion thresholds for the four head-yaw phases and three head-motion measures. For each one of these head-yaw phases and measures, six levels of head motion (slow to fast) were measured for a total of 72 thresholds per subject.

6.3 Procedure

We used the method of constant stimuli because both scene motion and head motion varied between trials and head motion could not be precisely controlled (which is required for staircase methods). As in Experiment 2, judgments consisted of a yes/no rating task with three levels of confidence resulting in six possible responses per trial.

6.4 Participants

Eight subjects (5 male and 3 female, age 18—27) participated. 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. Seven subjects each judged 576 trials—144 judgments for each phase condition. One subject judged only 535 trials due to time constraints.

6.5 Results

False alarm rates (the average confidence rating that there was scene motion when there was no scene motion) were 12.9% or less for each of the eight subjects. The mean of all ratios of scene-motion thresholds (in degrees per second) to the corresponding Peak Head-Yaw Velocity Measure was 14.7% (median = 11.5%), with a standard deviation of 11.2%.

Since head motion could not be precisely controlled, we divided head motions for each of the three head-motion measures and for each of the four head-yaw phase conditions into sextiles (i.e., six bins of head motion from slow to fast with each bin having an equal number of samples per bin). We fit a cumulative Gaussian function to the data for each sextile. 75% scene-motion thresholds were then extracted for each sextile and plotted against the sextile's head-motion mean. This resulted in 72 scenemotion thresholds per subject. Figure 10 shows a psychometric function and 75% scene-motion threshold for a single range of peak head-yaw acceleration for a single subject. Figure 11 shows one subject's 75% threshold values versus Peak Head Yaw Acceleration for all four phase conditions.

For each of the 8 subjects, we computed Pearson correlations of scene-motion thresholds to head-motion measures for each of the 12 conditions/measures (4 head-yaw phases × 3 head motion measures). Figure 12 shows box plots of the distribution of those correlations. Sign tests across all 8 subjects yielded statistically significant correlations greater than zero for each of the 12 conditions/measures (each $p_{one-tail} < 0.035$). We used a one-tailed test since we expected positive correlations. No correction was required for $\alpha = 0.05$ since the largest p-value was less than 0.05 [Hochberg 1988].

The results show that scene-motion thresholds increase as head motion increases, independently of the head-motion measure used and the phase of the head yaw for which the scene was presented.

7. DISCUSSION

7.1 Results

7.1.1 Scene Motion Direction—Experiments 1 and 2 found that for a variety of conditions, scene-motion thresholds are two times greater when scenes move with head yaw (corresponding to gain < 1.0) than when scenes move against head yaw (corresponding to gain > 1.0).

These with/against differences suggest a perceptual illusion—when no object-relative cues are visible, scenes appear to be most stable when the entire scene moves slightly in the same direction as head turns and scenes appear to move slightly against the direction of head turns when in fact the scene is not moving. Jerald and Steinicke [2009] and Jerald [2009] performed a pilot study that found a trend ($p_{two-tail} < 0.058$) that is consistent with this illusion.

We believe the following may have contributed to these results:

—*Head-relative judgments.* Subjects may have partially judged scene motion relative to their heads instead of entirely relative to an earth-stabilized reference, even though we instructed them to judge scene motion relative to the real world and not their head.

— *Edge of HMD.* The edge of the simulated HMD, which may have blocked out part of the scene for large head turns, might have caused subjects to partially judge scene motion relative to the head due to the edge of the HMD serving as an object-relative cue.

— *Magnitude of head-relative visual motion.* The difference between head motion and scene motion increases as gain increases. Observers might be biased towards smaller differences.

— *Magnitude of head-relative eye motion.* If the eyes follow the scene, the difference between head motion and eye motion increases as gain increases. If the eyes remain stabilized, the difference between head motion and retinal slip also increases as gain increases. Observers might be biased towards smaller differences.

— *Incorrect depth perception.* If subjects perceived the scene to be behind the display surface, then the scene may have appeared most stable when in fact it was moving in the direction of head turns

[Gogel 1990], resulting in greater thresholds for the With Condition.

7.1.2 Scene Luminance—We were surprised we did not find differences between the two luminance conditions in Experiment 2 considering the luminances differed by two orders of magnitude. We suspect there would be differences with greater differences in luminance/contrast and/or more statistical power. However, the lack of statistically significant differences implies luminance/contrast plays less of a role than the direction a scene is moving relative to head motion direction.

7.1.3 Increasing Head Motion—Experiment 3 found that scene-motion thresholds increase as head motion increases, independent of the head-motion measure and the phase of the head yaw for which stimuli are presented.

7.2 Comparison to Previous Work

7.2.1 Scene Motion Direction—Wallach, in his review of his own work [Wallach 1987], reported that scene-motion thresholds were the same whether the scene moved with or against the direction of head turns. However, in his original work [Wallach and Kravitz 1965], subjects judged scenes to be the most stable when scene moved slightly with head turns. Wallach and Kravitz stated this result to be negligible, even though the result was statistically different from no scene motion. He argued this was due to the object being at a finite distance and that this would be further investigated. We could find no report further investigating this finding. Bruder et al. [2009] and Steinicke et al. [2010] report findings similar to Wallach and Kravitz. Our findings from Experiments 1 and 2 are consistent with these results.

Jaekl et al. [2005] had subjects adjust scene motion until scenes appeared the most stable for quasi-sinusoidal head turns. Scenes with a gain greater than 1.0 appeared to be the most stable. Engel et al. [2008] found similar results when subjects physically walked and turned. Our findings from Experiment 1 and 2 conflict with these results.

We believe the following may have contributed to the different results:

— *Latency and imperfect calibration.* Scene motion due to latency and miscalibration is impossible to avoid in an HMD system (the reason why we chose to use a simulated HMD by projector in our experiments). Wallach and Kravitz used a mechano-optical system that presumeably had little or no latency. Jaekl et al., Engel et al., Bruder et al., and Steinicke et al. all used HMDs. The specifics of the HMD implementation may have contributed to the different results. For example, the HMD system of Jaekl et al. did not take into account the offset of the eyes from the center of head rotation. HMD system latency, given some head motion, results in more error than all other factors combined [Holloway 1997]. Peak scene velocity for the ±11.25/degree head motion amplitude and 122 *ms* of latency reported by Jaekl et al. is 14°/*s* for a perfectly smooth sinusoidal head motion. Real head motions are not perfectly sinusoidal and result in more scene motion. The peak accelerations of 235° / *s* reported by

Jaekl et al. results in peak scene velocity of 28°/*s*—an order of magnitude more than the average thresholds measured in Experiment 1. Because HMD system latency causes scene motion that is out of phase with head motion and Experiments 1 and 2 found the phase of head motion affects thresholds, latency may bias scene-motion thresholds. Studies measuring latency thresholds for HMDs found subjects' thresholds to be as low as 3.2 *ms* [Jerald and Whitton 2009; Jerald 2009].

— *Depth.* For HMD systems, the rendered point of view is offset from the center of head rotation. As a result, gain must be greater than 1.0 for close objects to be geometrically stable in space. Because the scenes of Wallach and ours were truly stable in space independent of head motion, this does not explain these results but could explain the results of others. Even when geometrically correct, when objects appear to be closer to users than they should, as is the case for HMDs [Loomis and Knapp 2003], the scene appears to move with the head [Gogel 1990]. In this case, the scene would have to move against the direction of head motion to appear stable in space. This is consistent with the findings of Jaekl/Engel but in the opposite direction of Steinicke/Bruder and our measurements.

— *Head direction reversal.* Our results that correspond to gain don't apply during head direction reversal. The gains reported by others may have been affected by judging scene motion during head direction reversal.

— *Earth-stable reference scenes.* Jaekl, Engel, Steinicke, and Bruder judged scene motion in an HMD such that they did not have an earth-stable reference (assuming the real world beyond the edges of the HMD could not be seen). Our subjects saw a genuinely earth-stable scene before and after seeing the test scene.

7.2.2 Increasing Head Motion—Unlike the results of Loose and Probst [2001], Experiment 3 found that scene-motion thresholds increased as head acceleration increased. This may be due to:

— Our subjects' head velocities varied as head acceleration varied, whereas Loose and Probst carefully controlled head velocity to be approximately constant for different amounts of head acceleration.

— Our subjects judged scene motion relative to the real world, whereas where as Loose and Probst's subjects judged scene motion relative to the head.

— Our subjects experienced only subject-relative cues, whereas Loose and Probst's subjects experienced both subject-relative cues and a stable object-relative cue.

— Our subjects actively rotated their own heads, whereas Loose and Probst's subjects were passively rotated via a rotary chair.

Bruder et al. [2009] reported that the ability to detect scene motion decreases when turning the body, which at first seems to contradict the results of Experiment 3. However, their thresholds were reported in relative terms (the ratio of scene motion to body motion) and our

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thresholds were reported in absolute terms (scene velocity). Their results would be consistent with our results if the same threshold measures were used. For example, they found thresholds were up to 101% greater than body turns when the body turned by 10° and up to 31% greater than body turns when the body turned by 180°. This corresponds to a threshold of 10.1° when the body turned 10° and 55.8° when the body turned 180°.

7.3 Application of Results

7.3.1 Redirected Walking—Ideally, scene motion should be below the thresholds of the most sensitive subjects. Our lower thresholds were in the 1° /*s* range. Assuming a moderate 3 mph walking speed and 1° /*s* maximum scene motion, a space 460 feet across would be needed to walk an entire circle—not realistically feasible nor useful. Conservative upper bounds for the amount of scene motion that can be inserted imperceptibly, as measured in this work or others work, may be too low to be useful in practice, but the results can be useful for determining how thresholds differ under different conditions. Moving the scene when users are least likely to notice is clearly preferred.

Redirected walking systems typically limit the maximum scene-velocity θ'_{max} to be a proportion of the current angular head velocity φ':

$$\theta'_{max}=m_{vel}\phi' \quad (1)$$

where m_{vel} is a unitless number.

Experiment 3 suggests a better function of maximum scene-velocity θ'_{max} to be a function of the form

$$\theta'_{max}=b_{vel}+m_{vel}\phi' \quad (2)$$

where b_{vel} is in units of degrees per second.

Experiments 3 suggest developers could also limit maximum scene-velocity θ'_{max} to be a function of the current angular head acceleration φ'' with the form

$$\theta'_{max}=b_{acc}+m_{acc}\phi'' \quad (3)$$

where b_{acc} is in units of degrees per second and m_{acc} is in units of seconds. A later case study of the primary author [Jerald 2009], with 3556 trials that took nearly 20 hours, found scene-motion thresholds to be highly correlated (r = 0.90) with peak head-yaw acceleration. This suggests equation 3 may be a better model.

The results of Experiments 1 and 2 suggest different parameters should be used in the equations above, depending if the scene moves with the direction of head turns or against the direction of head turns. Approximately twice as much scene motion can occur imperceptibly if the scene moves with the direction of head yaw than against the direction of head yaw.

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Distractors, as first implemented by Miller [2002] and later investigated by Peck et al. [2008], can be used for redirected walking by occasioning the user to turn his viewpoint so that the scene can be rotated without the user noticing. Our results suggest these distractors could be used most effectively by having a distractor trigger a head turn in the same direction that the system rotates the world.

The primary task of our subjects was to look for scene motion. Such is not the case in most virtual reality applications. Our experience is that when users are engaged in a task or are not actively looking for scene motion, it is possible to insert significantly higher levels of scene motion without users noticing.

Even by taking advantage of these concepts, greater scene motions for useful redirected walking may result in users still noticing some scene motion. However, by moving the scene when users are less sensitive to scene motion, the perception of stable scenes can be drastically improved.

7.3.2 HMD Latency Perception—The scene in a lagging HMD system moves with the head until shortly after head acceleration goes to zero or the head starts to decelerate [Adelstein et al. 2005; Jerald 2009]. With constant head velocity, the scene is stable in space (i.e., no scene-motion) with a constant offset from where it would correctly appear with no head motion or no latency. As the head decelerates, the scene starts to move back to where it should be in space, moving against the head turn. Maximum latency-induced scene velocity occurs near the reversal or start/stop of head turns, when head acceleration/deceleration peaks. These facts combined with the results of Experiments 1 and 2 suggest users are less likely to notice latency in an HMD system when starting a head turn (when the scene moves with the head turn) than when ending a head turn (when the scene moves against the head turn).

Experiment 1 also showed scene-motion thresholds of scenes moving against head yaw to be ”close” (or, as the trend suggests, lower) to scene-motion thresholds during head-yaw reversals. This suggests that the reason subjects have the lowest latency thresholds at the reversal of head yaw [Adelstein et al. 2005] is because latency-induced scene velocity is maximized at the reversal of head yaw, not because scene-motion thresholds are lowest during head-yaw reversals.

Jerald [2009] further explores the relationship between scene-motion thresholds and latency thresholds.

7.4 How Subjects Made Their Judgments

We expected subjects to judge scene motion directly from visual sensation of the stimuli. However, several subjects reported making judgments about the smaller motions based on a vection-like sensation (i.e., self motion). Some subjects commented on this orally and some reported it in written form on the exit questionnaire. Two subjects from Experiment 1 wrote in response to “Explain in your own words how you went about making the scene-motion judgments”:

> "Most of the times I detected the scene with motion by noticing a slight dizziness sensation. On the very slight motion scenes there was an eerie dwell or 'suspension' of the scene; it would be still but had a oating quality. " (Subject ID103)

> "At the beginning of each trial [sic:session—when scene velocities were greatest], I used visual judgments of motion; further along [later in sessions] I relied on the feeling of motion in the pit of my stomach when it became difficult to discern the motion visually. " (Subject ID109)

7.5 Limitations

7.5.1 Absolute Versus Relative Thresholds—We believe the specific threshold values found in these experiments are not the most significant result of this research (because individual subjects and the methods used can result in different thresholds); rather, it is the relative difference of thresholds across conditions that is important. Different conditions such as training effects, type of head turns, learning and fatigue effects, scene size, field of view, etc. likely result in different thresholds. Experiments 1 and 2 found scene-motion thresholds for the scene moving with head yaw to be greater than thresholds for the scene moving against head yaw for a multitude of conditions, so we suspect this to remain consistent across conditions.

7.5.2 Yes/No Rating Tasks—For Experiments 2 and 3, we chose to use a yes/no rating task instead of an unbiased alternative-forced choice task as used in Experiment 1. This may have biased thresholds, although we suspect the same bias would be consistent across conditions.

7.5.3 Average Thresholds—The thresholds reported are average responses over many trials; users might occasionally notice lower scene-motions than the threshold values reported.

7.6 Future Work

7.6.1 Other Conditions—The contradicting results with other researchers [Jaekl et al. 2005; Engel et al. 2008] warrants further investigation. Further experimentation could test the explanations described in Sections 7.1.1 and 7.2.1. Other conditions to test could include attention, adaptation, training, etc.

7.6.2 Redirected walking—The mathematical models in Section 7.3.1 are theoretical and have not been tested with users of redirected walking systems. We also suspect scene-motion thresholds to be higher with distractors [Peck et al. 2008] or some distracting task, similar to change blindness [Goldstein 2007]. Further experimentation would be required to confirm if and how distractors affect scene-motion thresholds.

7.6.3 Relating Scene-Motion Thresholds to IVE Dynamic Error—Scene motion occurs in a miscalibrated HMD (e.g., incorrect field of view) as users move their heads, similar to the way latency causes scene-motion in an HMD. Scene-motion thresholds could be used to determine user tolerance of miscalibrations (similar to the way Jerald and Whitton [2009] and Jerald [2009] relate scene-motion thresholds to latency thresholds).

7.6.4 Eye Motion—The vestibular-ocular reex (VOR) rotates the eyes against head turns to keep the eyes looking straight ahead in the world—even in the dark with no visual stimuli. The optokinetic reex (OKR) stabilizes images on the retina by rotating the eye as a function of visual input from the entire retina. In the real world, the VOR and OKR normally work in concert to achieve the goal of minimal retinal image motion. Since we did not measure eye motion, we do not know if subjects' eyes remained stationary in space (because of the VOR) resulting in retinal image slip when the scene moved, or if the eyes followed the scene (because of OKR) resulting in minimal retinal slip. Eye tracking would enable an investigator to study how scene motion affects image motion on the retina and how such image motion may affect scene-motion thresholds.

7.6.5 Other Effects of Scene Motion—Scene motion below an individual's perceptual threshold may still affect performance and/or cause simulator sickness. Testing for such effects would require a very different experiment design than what we used here.

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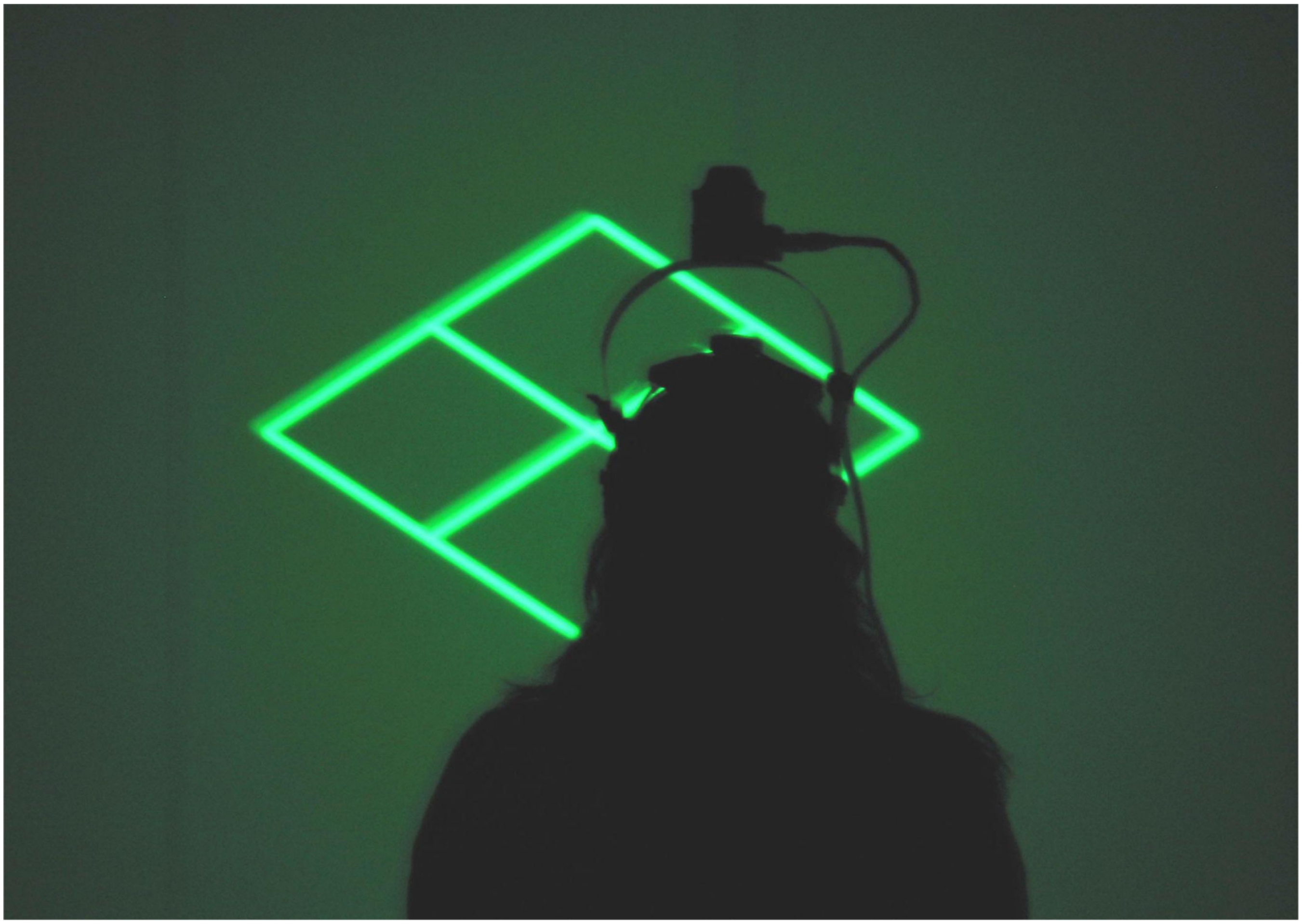

Fig. 1.
A subject and scene as the subject yaws her head. The motion blur is due to the exposure time of the camera and the image has been brightened substantially.

Fig. 2.

The modified V8 HMD, with display elements removed so that subjects could see through the casing to the world-fixed display. The Hiball tracker not shown in this picture was mounted on the top loop during use.

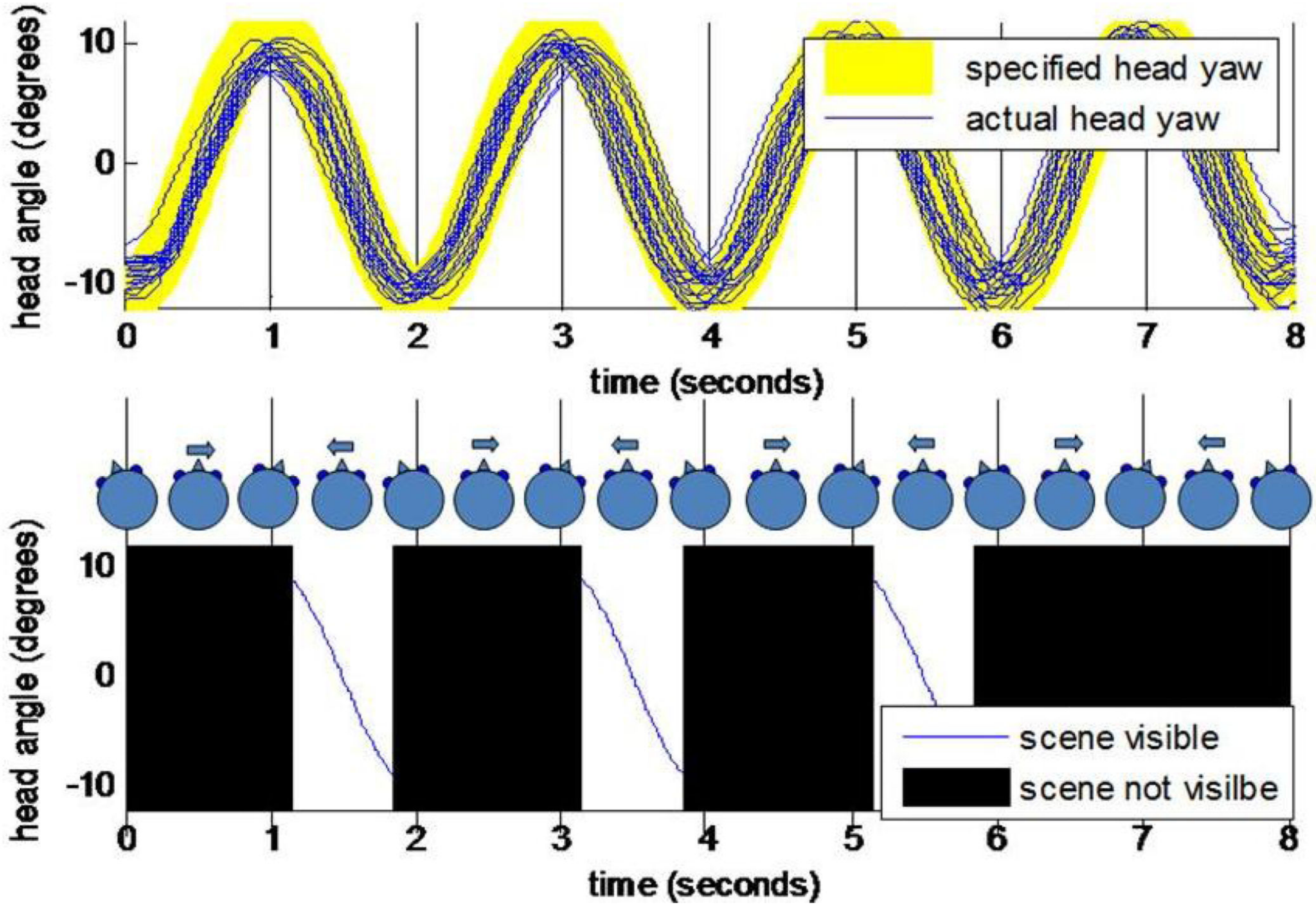

Fig. 3.

Experiment 1 head yaw and scene visibility (head-yaw phase) for a single subject. The top part of the diagram shows specified and actual head yaw with a head frequency of 0.5 Hz and a head-yaw amplitude of ±11° from straight ahead. The head icons represent head orientation and head yaw direction. The bottom of the figure shows that the scene is visible during the center-phase of head yaw. The scene is presented three times for 0.5 seconds each as the head yaws right to left. The scene is not visible for the black area of the diagram.

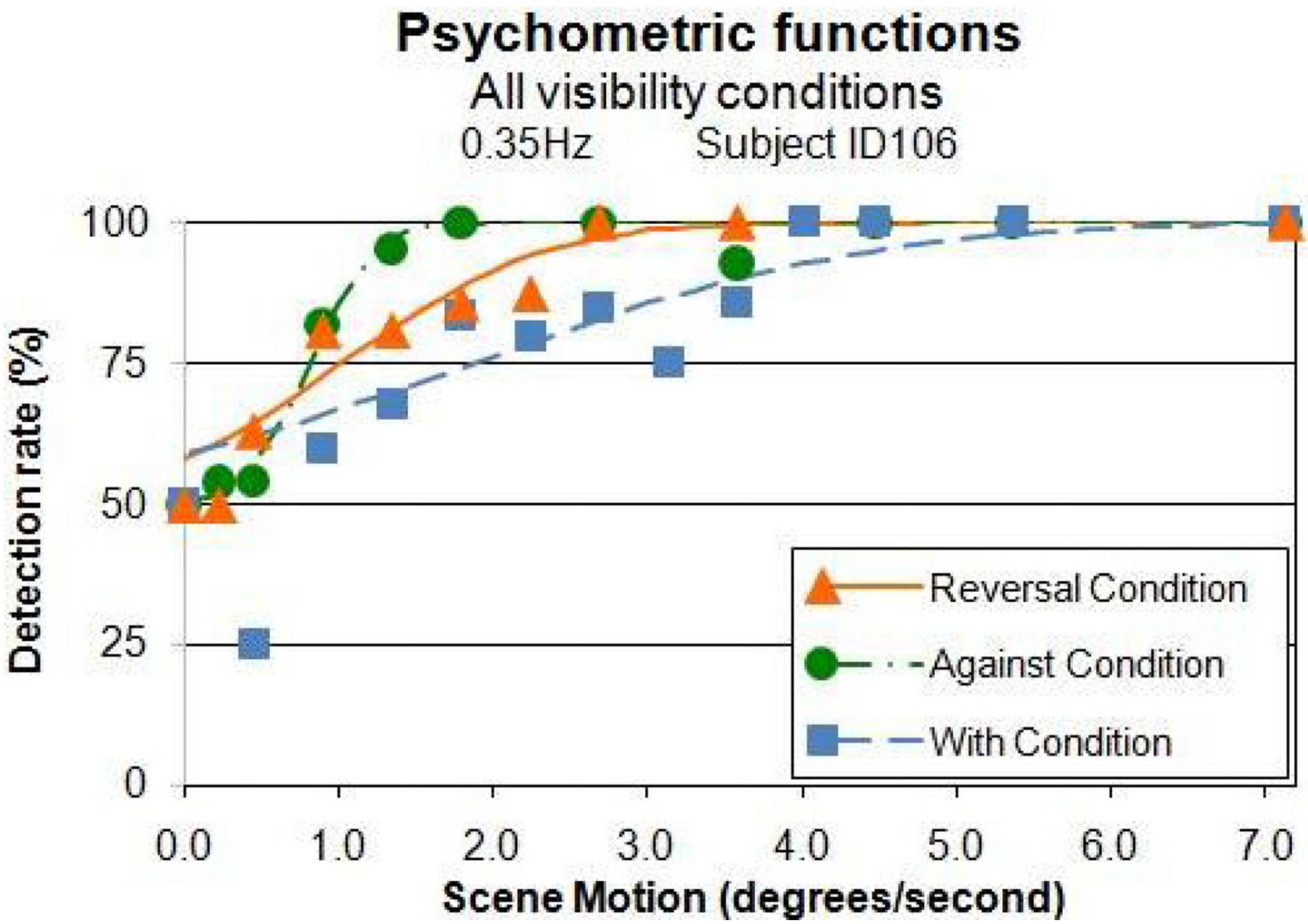

Fig. 4.
Experiment 1 psychometric functions for all phase conditions for a single subject.

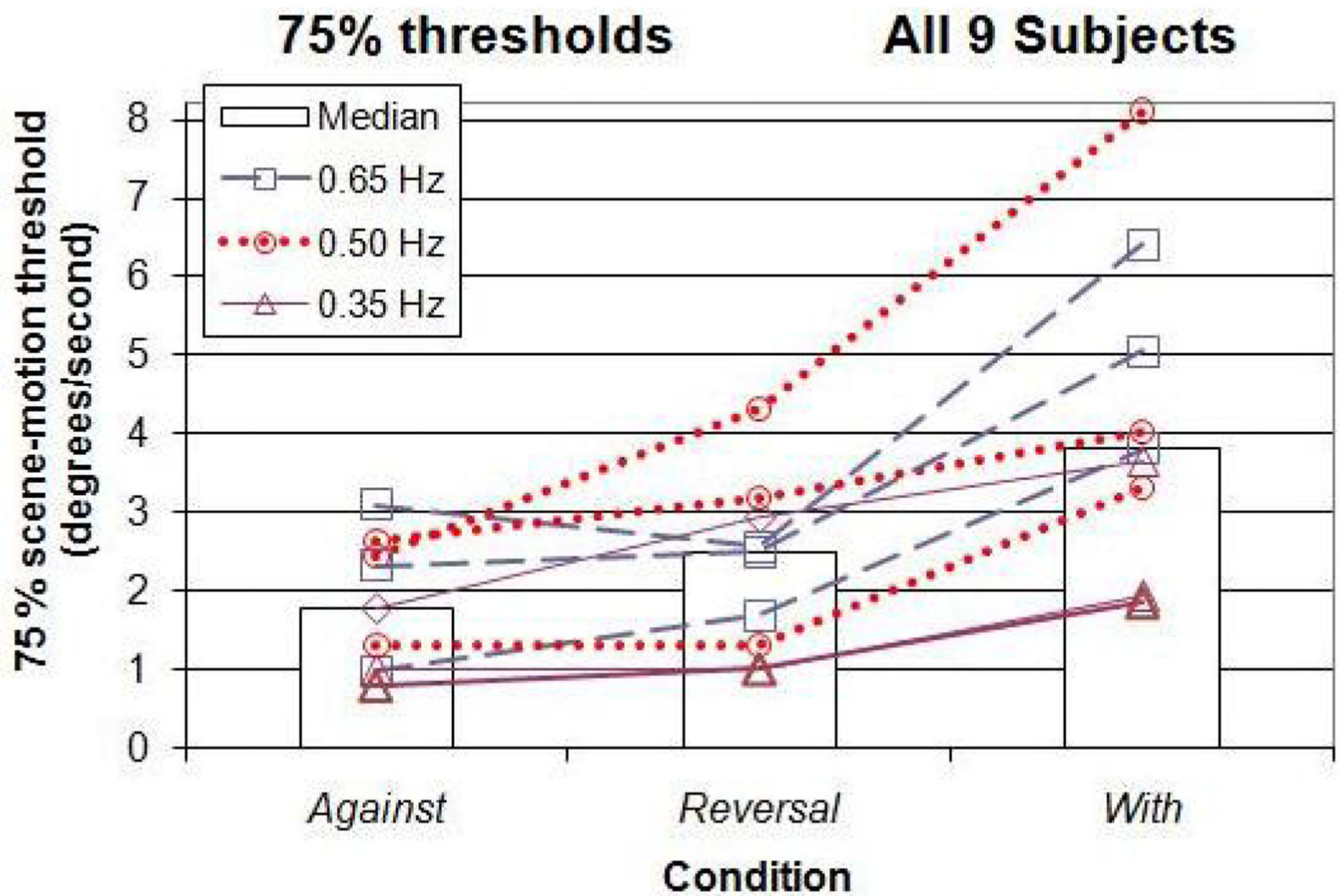

Fig. 5.

Experiment 1 scene-motion thresholds for all nine subjects for the three head-phase conditions. Bars indicate medians for each condition.

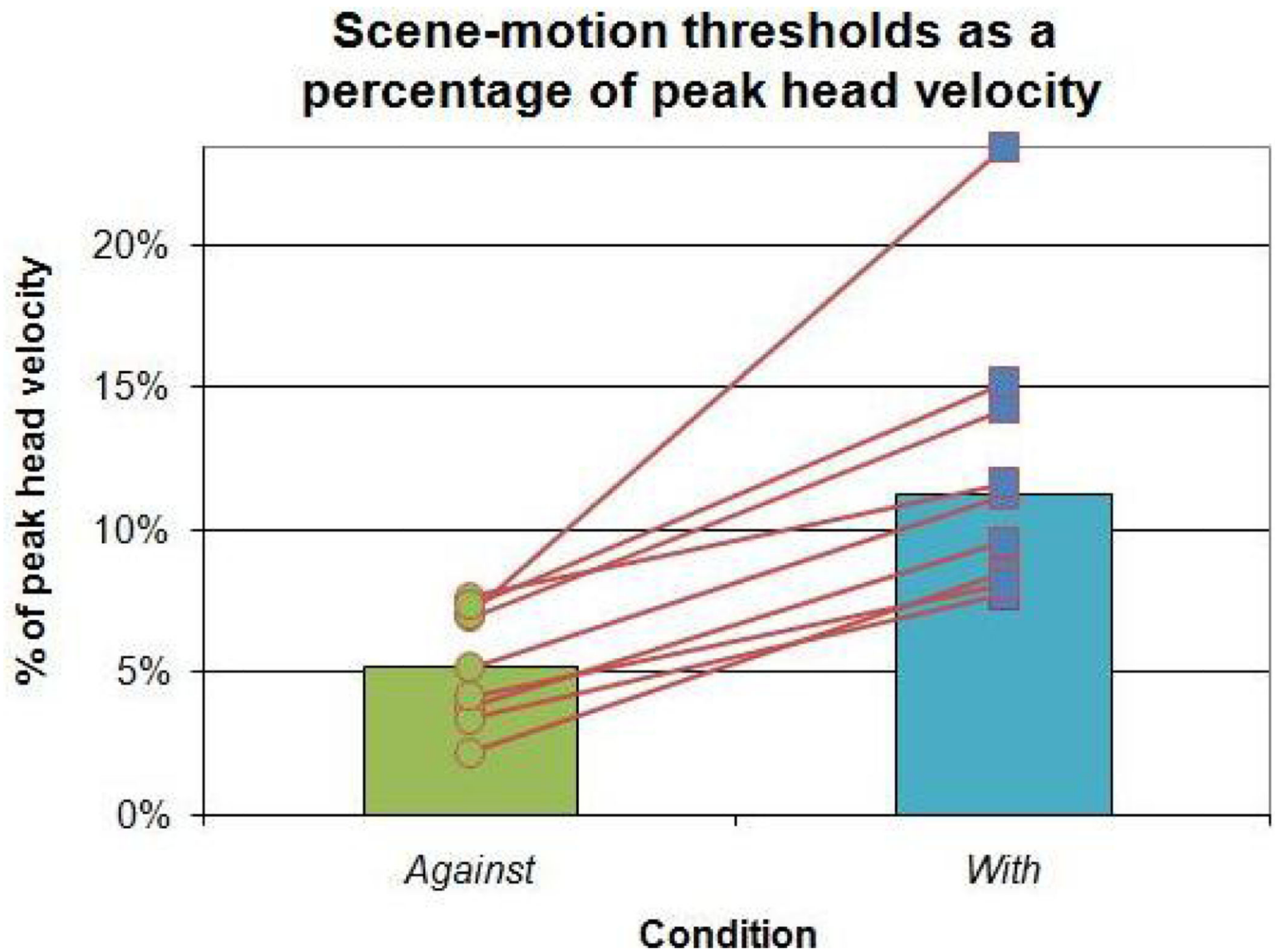

Fig. 6.
Experiment 1 ratios of scene-motion thresholds to intended peak head velocities.

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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)	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)

Fig. 7.
Experiment 2 and 3 Questions.

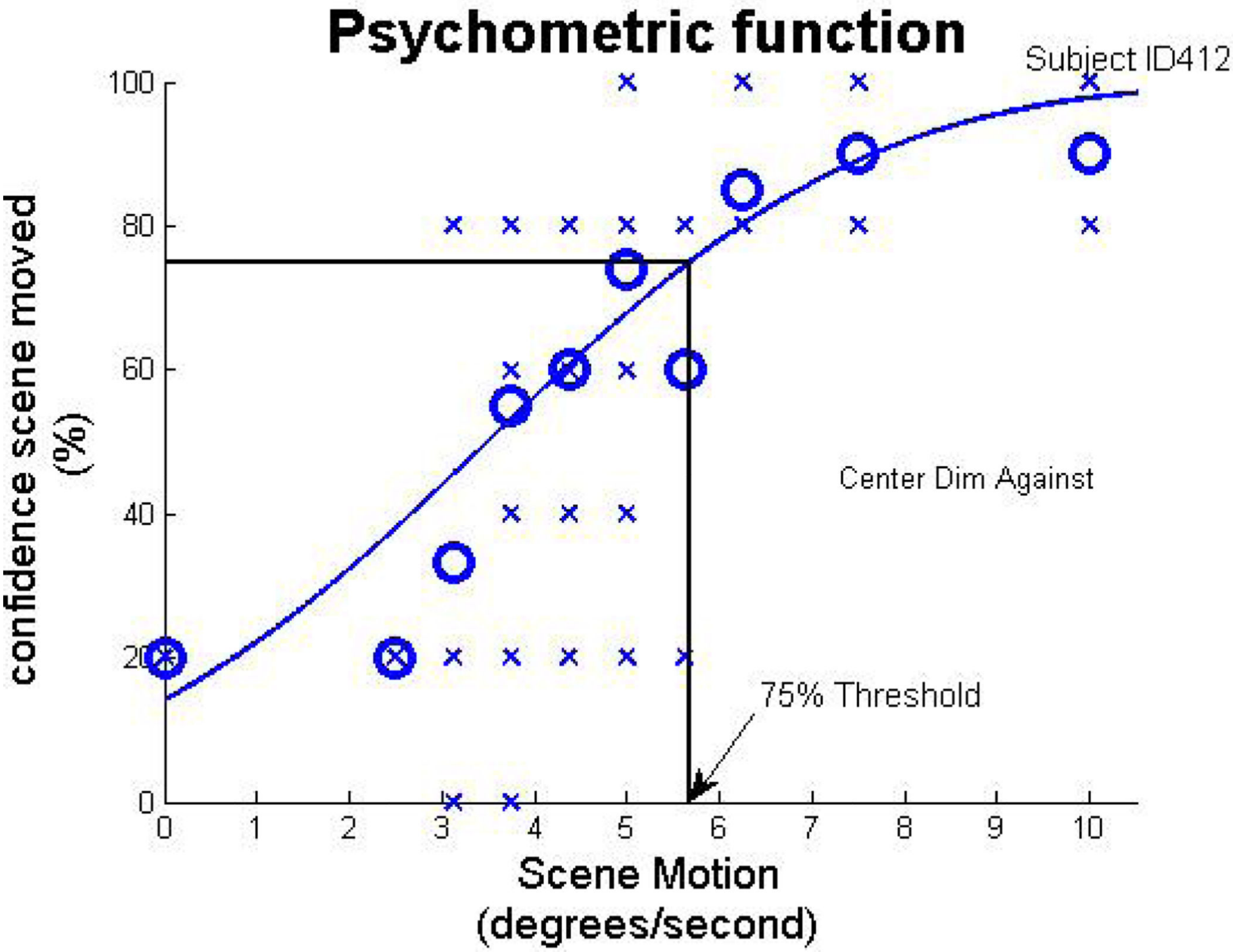

Fig. 8.
Experiment 2 confidence ratings and the resulting psychometric function and scene-motion threshold for a single subject for the Center-Dim-Against Condition. The small Xs represent ratings for one or more trials (some Xs represent multiple ratings), the Os represent the mean rating for that scene-motion level, and the curve is the psychometric function (a cumulative Gaussian function fit to the data). For this condition, the subject rated the scene to move with 75% confidence when the scene moved at 5.7° /*s*.

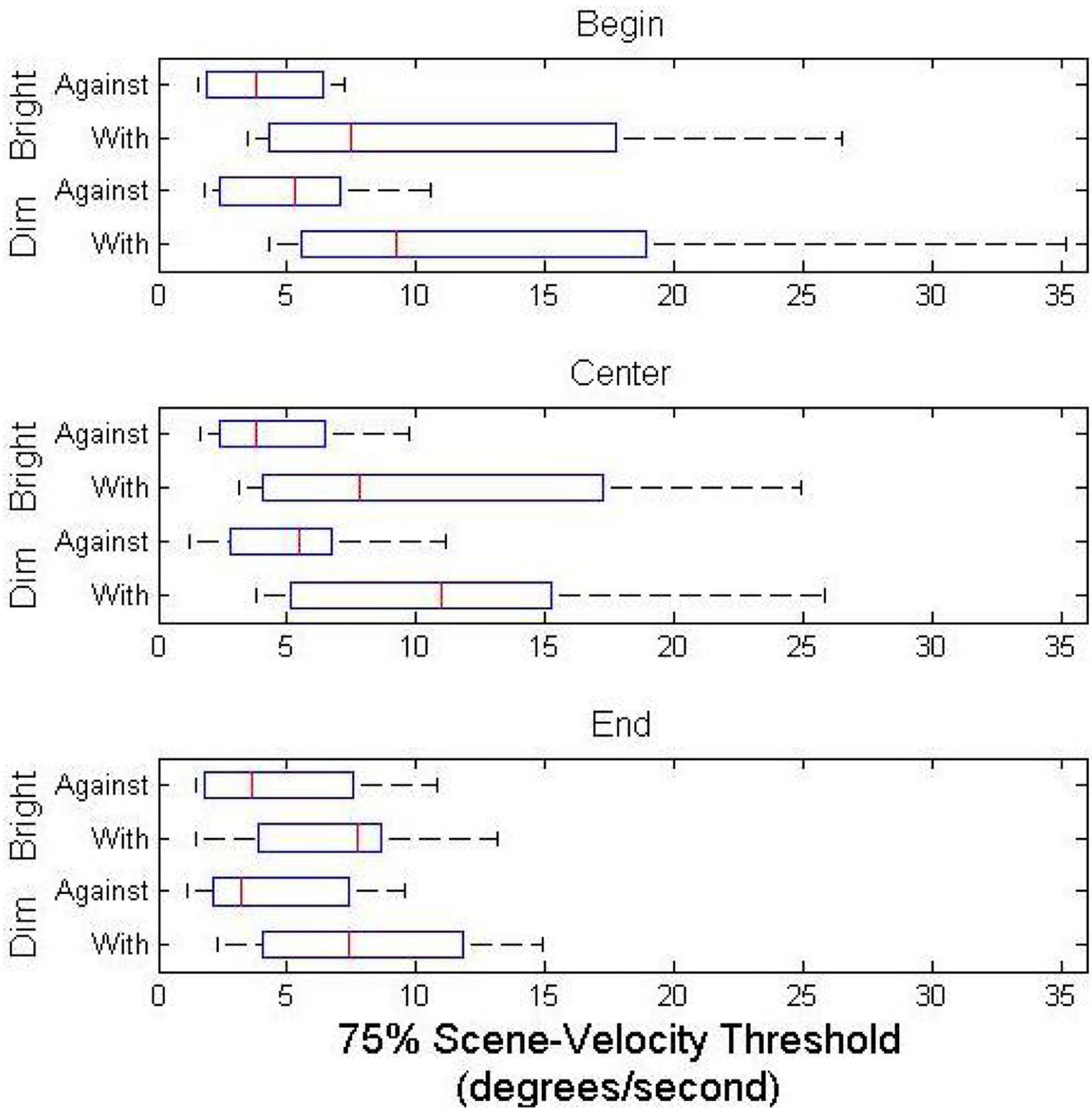

Fig. 9.

Experiment 2 box plots of all scene-motion thresholds. With Condition thresholds were statistically significantly greater than Against Condition thresholds for each of the three head-yaw phases for each of the two scene-luminance conditions. No statistically significant differences were found between the two scene-luminance conditions.

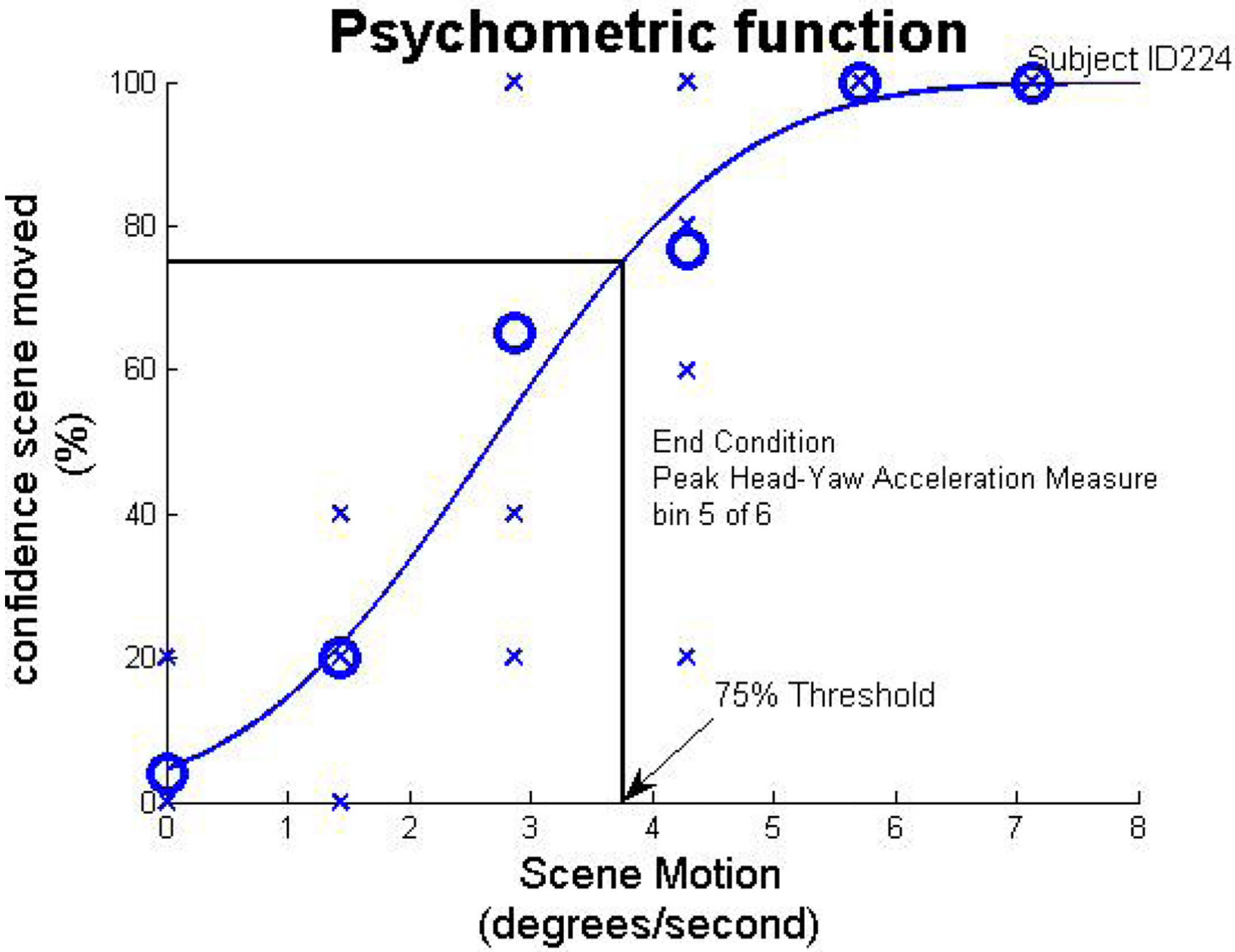

Fig. 10.

Experiment 3 confidence ratings from a single subject for the End Condition and sextile five of the Peak Head-Yaw Acceleration Measure. The small Xs represent ratings for one or more trials (some Xs represent multiple ratings), the large Os are the mean rating for that scene-motion level, and the curve is the psychometric function. For this sextile, the subject rated the scene to move with 75% confidence when the scene moved at 3.8°/*s*.

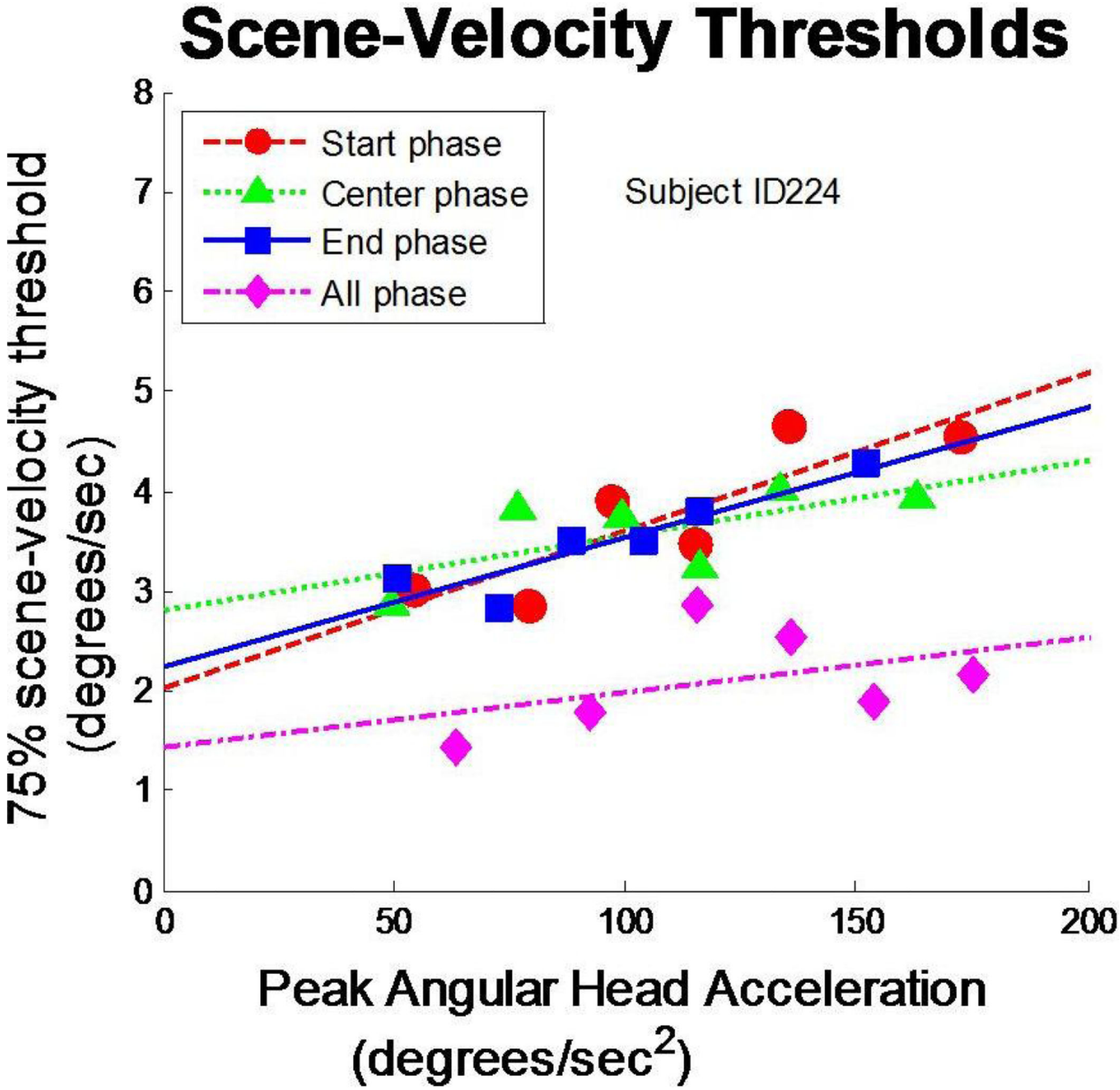

Fig. 11.

Experiment 3 scene-motion thresholds for a single subject for all four head-yaw phase conditions where head motion is defined by the Peak Head-Yaw Acceleration Measure. Note the lower thresholds for the All Condition and the similarities of the other conditions—such trends were not consistent for all subjects.

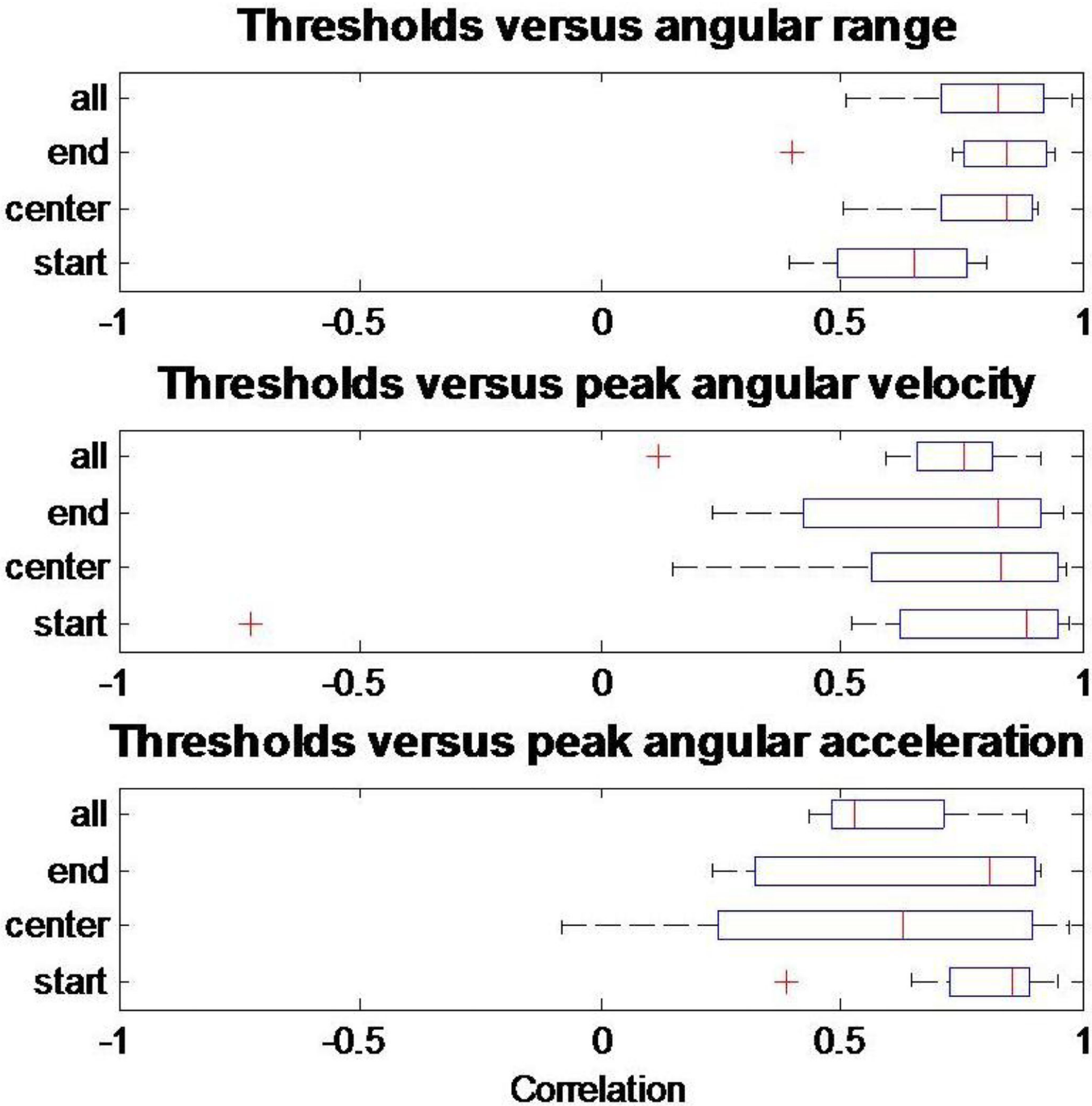

Fig. 12.

Experiment 3 box plots of Pearson Correlations for the eight subjects.

Table I

Factors and findings for the three experiments.

			Experiment		
			1. Quasi-sinusoidal Head Yaw and Scene-Motion Direction	**2. singal Head Yaw, Luminance, and Scene-Motion Direction**	**3. increasing Head Motion**
Factors		**# of subjects**	9	9	8
	Head Motion	**head turn type**	Quasi-sinusoidal	Single	Single
		head-yaw freq	0.35 Hz, 0.5 Hz, 0.65 Hz	0.5 Hz	0.5 Hz
		head-yaw range	±11°	±15°	±5°, ±10° ±15° ±20°
		head-motion measure	Theoretical peak velocity(deg/s)		Range(deg/s), peak velocity(deg/s), peak Acceleration (deg/s2)
	Visibility	**head-yaw phase(time visible)**	center (0.5 s), Reversal (0.5 s)	center (0.6 s), Start(0.6 s), End (0.6 s)	center (0.6 s), Start(0.6 s), End (0.6 s), All(1.2 s)
	Direction	**Scene-motion direction**	With Against	With Against	Against
	Brightness	**contrast**		Bright: 167, Dim 37	
	Methods	**stimulus selection**	Adaptive staircase	Adaptive staircase	Method of constant stimuli
		Judgment Task	31-2AFC	Yes/no with confidence ratings	Yes/no with confidence ratings
Findings	**Hypotheses**	**Hypothesis 1**	Scene-motion thresholds are greatest for the Reversal Condition	Scene-motion thresholds are greater for the with Condition than the Against Condition for each visibility and for each brightness.	Scene-motion thresholds increase as head-yaw range, given constant time, (i.e., average head-yaw velocity) increase.
		Hypothesis 2	Scene-motion thresholds are greater for the with Condition than the Against Condition	Scene-motion thresholds for the Bright Condition are lower than those for the Dim Condition for each head phase & direction.	Scene-motion thresholds increase as peak head-yaw velocity increase.
		Hypothesis 3			Scene-motion thresholds increase as peak head acceleration increase.
		Results	Hypothesis 2 accepted	Hypothesis 1 accepted	Hypothesis 1, 2, and 3 accepted

Table II

Experiment 1 conditions.

		Head Phase		
		Against	**With**	**Reversal**
Head Frequency	0.35 Hz	subjects 1–3	subjects 1–3	subjects 1–3
	0.50 Hz	subjects 4–6	subjects 4–6	subjects 4–6
	0.65 Hz	subjects 7–9	subjects 7–9	subjects 7–9

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Table III

Experiment 2 conditions.

	Scene Direction	Head-Yaw Phase		
		Start	**Center**	**End**
Dim	With	all 9 subjects	all 9 subjects	all 9 subjects
	Against	all 9 subjects	all 9 subjects	all 9 subjects
Bright	With	all 9 subjects	all 9 subjects	all 9 subjects
	Against	all 9 subjects	all 9 subjects	all 9 subjects

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Table IV

Experiment 3 conditions.

	Head Phase			
	Start	**Center**	**End**	**All**
Yaw Range	all 8 subjects	all 8 subjects	all 8 subjects	all 8 subjects
Peak Yaw Velocity	all 8 subjects	all 8 subjects	all 8 subjects	all 8 subjects
Peak Yaw Acceleration	all 8 subjects	all 8 subjects	all 8 subjects	all 8 subjects