University of Nevada, Reno

Sensitivity to Visual Gain Modulation in Head-Mounted Displays Depends on Fixation

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Neuroscience

by

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Abstract

A primary cause of simulator sickness in head-mounted displays (HMDs) is conflict between the visual scene displayed to the user and the visual scene expected by the brain when the user's head is in motion. Agreement between visual scene motion and head motion can be quantified based on their ratio which we refer to as visual gain. We suggest that it is useful to measure perceptual sensitivity to visual gain modulation in HMDs (i.e. deviation from gain=1) because conditions that minimize this sensitivity may prove less likely to elicit simulator sickness. In prior research, we measured sensitivity to visual gain modulation during slow, passive, full-body yaw rotations and observed that sensitivity was reduced when subjects fixated a head-fixed target compared with when they fixated a scene-fixed target. In the current study, we investigated whether this pattern of results persists when 1) movements are faster, active head turns, and 2) visual stimuli are presented on an HMD rather than on a monitor. Subjects wore an Oculus Rift CV1 HMD and viewed a 3D scene of white points on a black background. On each trial, subjects moved their head from a central position to face a 15° eccentric target. During the head movement they fixated a point that was either head-fixed or scene-fixed, depending on condition. They then reported if the gain applied to the visual scene motion was too fast or too slow. Gain on subsequent trials was modulated according to a staircase procedure to find the gain change that was just noticeable. Sensitivity to gain modulation during active head movement was reduced during head-fixed fixation, similar to what we observed during passive whole-body rotation. Additionally, conflict detection seems to be significantly improved with higher peak velocity of head rotation. We conclude that fixation of a head-fixed target is an effective way to reduce sensitivity to visual gain modulation in HMDs, and may also be an effective strategy to reduce susceptibility to simulator sickness.

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Sensitivity to Visual Gain Modulation in Head-Mounted Displays Depends on Fixation

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Abstract

A primary cause of simulator sickness in head-mounted displays (HMDs) is conflict between the visual scene displayed to the user and the visual scene expected by the brain when the user's head is in motion. Agreement between visual scene motion and head motion can be quantified based on their ratio which we refer to as visual gain. We suggest that it is useful to measure perceptual sensitivity to visual gain modulation in HMDs (i.e. deviation from gain=1) because conditions that minimize this sensitivity may prove less likely to elicit simulator sickness. In prior research, we measured sensitivity to visual gain modulation during slow, passive, full-body yaw rotations and observed that sensitivity was reduced when subjects fixated a head-fixed target compared with when they fixated a scene-fixed target. In the current study, we investigated whether this pattern of results persists when 1) movements are faster, active head turns, and 2) visual stimuli are presented on an HMD rather than on a monitor. Subjects wore an Oculus Rift CV1 HMD and viewed a 3D scene of white points on a black background. On each trial, subjects moved their head from a central position to face a 15° eccentric target. During the head movement they fixated a point that was either head-fixed or scene-fixed, depending on condition. They then reported if the gain applied to the visual scene motion was too fast or too slow. Gain on subsequent trials was modulated according to a staircase procedure to find the gain change that was just noticeable. Sensitivity to gain modulation during active head movement was reduced during head-fixed fixation, similar to what we observed during passive whole-body rotation. Additionally, conflict detection seems to be significantly improved with higher peak velocity of head rotation. We conclude that fixation of a head-fixed target is an effective way to reduce sensitivity to visual gain modulation in HMDs, and may also be an effective strategy to reduce susceptibility to simulator sickness.

Keywords: Motion sickness, vection, simulator sickness, visual-vestibular, conflict detection, passive vs. active, head rotation, gender difference, optic flow

1. Introduction

Head-mounted displays work by presenting a rendered view of a virtual environment that is updated based on the users head movement. Consequently, when the user turns the head, optic flow is presented on the HMD that is consistent with the users head movement. Disagreement between the head movement and the visual motion that is rendered is the most widely accepted explanation for the initiation of simulator sickness symptoms [1, 2, 3, 4, 5, 6, 7, 8]. However, user tolerance for this disagreement has not been extensively studied [9, 10]

In prior work, we evaluated this tolerance by introducing conflicts between the physical head motion and the visual scene motion and measuring participants' ability to detect these conflicts[Anon]. We found that sensitivity to conflict

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depended on how participants moved their eyes, with the best sensitivity observed when participants moved their eyes to track scene-fixed targets. Head motion in these experiments was generated through passive full-body rotation with participants seated on a moving platform and with visual stimuli presented on a display mounted to the platform. Here we examine whether our previous findings generalize to the most common VR use-case, that is active turning of the head relative to the body with visual stimuli presented on a HMD.

By employing active head movements we encourage more natural neural evocation. However, increasing realism comes at a cost. In this study we sacrifice some experimental control due to self-generation of head rotations by the user. Additional non-visual sensory cues, (or information flows), are evoked in several forms including proprioception and efference-copy. Self-generated head rotations also lack the absolute consistency of velocity and duration afforded by the motion platform.

Variations of this type naturally restrict certain direct comparisons with previous findings while still increasing overall comprehension in the domain. Prior work utilized both conflict detection (visual-vestibular) and single cue (visual only, vestibular only) tasks. Variability estimates for single cues, combined with those from crossmodal conflict detection, enabled for the development of more robust models to explain the findings. In this study we included a single cue, visual speed-discrimination task, which suffered none of the variations described. With zero self-motion the task closely resembled the corresponding experimental condition previously observed. By only varying the medium of display (HMD vs. 3D monitor) we looked to both, (i) validate the usefulness of an HMD as a tool in psychophysical experimentation, and (ii) confirm the robustness of the previous work. Unfortunately, we were not able to include an equivalent single cue vestibular condition. We are yet to develop a solution in which the vestibular signal may be isolated in an active movement.

Much remains unknown regarding the underlying mechanisms mediating simulator sickness. This includes a lack of conclusive evidence for an effect of gender. While some studies claim a females are three times more susceptible [11, 9, 12], many others fail to replicate this finding [13, 14]. In this study participant numbers were balanced accordingly. In this way we attempt to offer additional insight on this ever more pressing issue which threatens to limit accessibility.

Building directly upon previous work while altering experimental conditions, both by choice and necessity, allowed us to examine several hypotheses concurrently. We may categorize as *replication* of previous work using an HMD, differences resulting from *self-motion*, and differences in *simulator sickness* across groups/conditions.

Replication	*Self-Motion*	*Simulator Sickness*
H_1 : No significant effect of fixation in visual speed-discrimination task. H_2 : Significant effect of fixation in conflict detection task.	H_3 : Significant improvement in discrimination sensitivity due to additional sensory cues.	H_4 : Significant effect of gender on VR sickness ratings. H_5 : VR sickness ratings and conflict sensitivity shall be highly correlated.

2. Methods

2.1. Participants

Nineteen healthy participants (nine F, ten M), ranging in age from 20 to 41 (mean age = 26.5 years) completed the study. All possessed normal, or corrected-to-normal vision, unrestricted head/neck movement, and had no history of visual, or vestibular sensory disorders. All but two were naive to the hypothesis being tested. Three further participants began the study. Two were excluded due to an inability to consistently execute the trials, one dropped out due to time demands. All procedures were approved by the Institutional Review Board of the University of Nevada, Reno and all participants provided informed consent.

2.2. Equipment

The experiment was conducted using an Oculus Rift head mounted display (HMD) and Oculus-ready Alienware PC with NVIDIA GeForce GTX 1060 video card. Participants were seated in a fixed, high-backed chair, to ensure head rotations originated from the neck while avoiding postural rotation. Participant responses were input using a standard keyboard. Textured Velcro tape was attached to the response keys to allow them to be identified haptically. All conditions were conducted in a quiet darkened room. Headphones in the HMD enabled delivery of auditory beeps, tones and instructions that helped orient the subjects in the experiment. The virtual environment was programmed using C# within the Unity programming environment. Visual stimuli were rendered with a refresh rate of 90 Hz. Participants altered the HMD's interaxial distance (distance between the centers of the HMD's lenses) to account for individual differences in interpupillary distance.

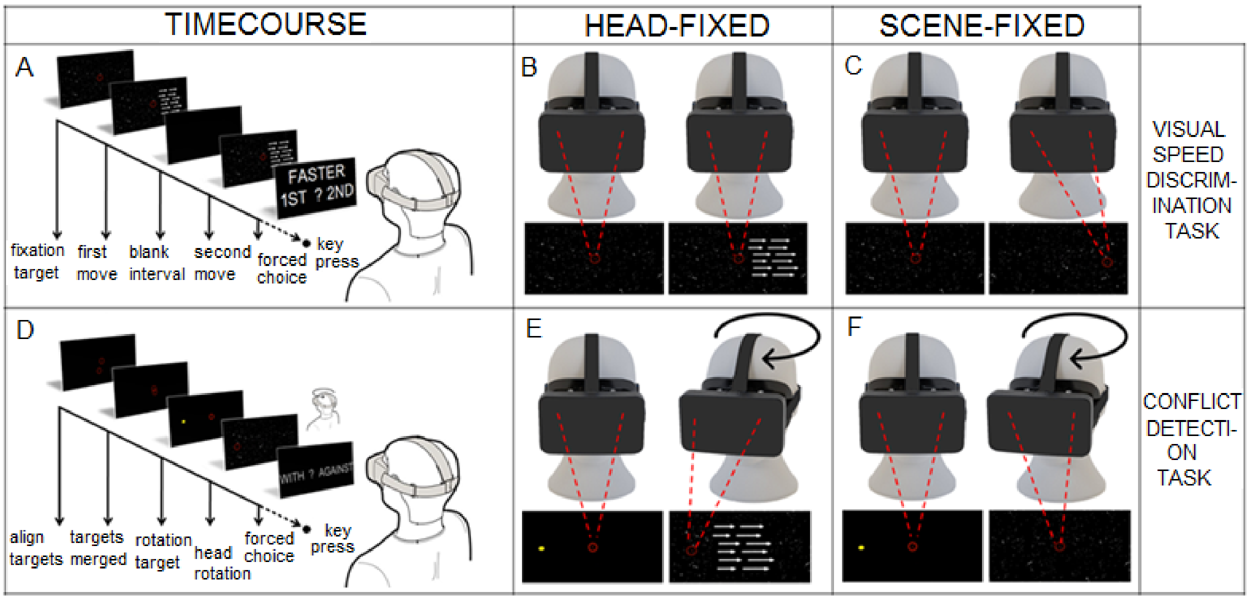

Figure 1. Experimental set up: Tasks focused on either visual speed discrimination (A,B,C) or conflict detection (D,E,F). A illustrates the timecourse for the visual speed discrimination task. Participants focused on a red fixation target in the center of the scene. Participants judged which of two yaw rotations, (separated by 0.5s of empty black scene), of the background scene was faster (2AFC). B and C highlight the different conditions for this task. In B participants eyes were fixed in their head while the visual stimulus moved across the retina. In C, the fixation target moved with the scene movement and thus by focusing on the target the image was stable on the retina. D illustrates the timecourse for the conflict detection task. To ensure a consistent starting point participants evoked each trial by aligning a red fixation target fixed in the scene with one attached to their virtual head. On doing so a yellow rotation target flashed (0.1s) to guide the participant's head rotation. The visual gain was modulated to create conflict between the physical motion and visual scene displayed. At the culmination of the rotation participants answered whether the visual scene had moved with, or against, their rotation. E and F highlight the different conditions. In E participants kept their eyes fixed in their heads, moving all as one. In F, participants kept their eyes fixed on the unmoving red fixation target in the center of the field of view.

2.3. *Conflict Detection Task*

During normal use of an HMD, the view on the visual environment is updated based on head movement, resulting in movement of the visual scene that is equal and opposite the head motion, consistent with a stationary, earth-fixed environment. However, in this task, the visual speed was modified to be either faster or slower than the head movement, and participants were asked to judge if the visual motion was too fast or too slow compared to their head movement. In other words, they were asked to detect the conflict between visual motion and head motion. The goal of the experiment was to measure the threshold for detection of this conflict.

The exact timecourse of an individual trial is illustrated in Fig. 1. Participants initiated each trial by adjusting their head position to the designated central position. This was achieved by making small head movements to align a head-fixed target (rendered 300cm in front of the cyclopean eye) with a central, scene-fixed target in an otherwise black, featureless environment. Once aligned, one of the red targets vanished, and a yellow target flashed (0.1s duration) within the participants' left or right near-peripheral vision at an eccentricity of 15°. Then a randomly generated 3D starfield appeared and the participant performed a head rotation to point the head to where the yellow rotation target had flashed. The starfield consisted of 8000 randomly distributed white spheres (radius = 33cm), at a minimum distance of 1000cm, and average distance of 5000cm from the participant's position. After the head rotation, the starfield disappeared, and an audible beep and text on the screen prompted the participant to indicate via keypress if they perceived the visual scene as moving with or against their head motion. If the visual scene moves too slowly, it is perceived to move with the head movement, and if it moves to quickly, it is perceived to move against the head movement. After the response, the next trial was initiated.

Because head movements were actively generated, care was taken to ensure consistency of head movements across trials. Specifically, the duration and speed of head movement was monitored and if duration was too short or long ($0.75s \leq dur \leq 2.78s$), or speed was too slow or fast ($5.4°/s \leq speed \leq 20°/s$), the trial was rejected and the participant received feedback in the form of a metal clang sound and a warning corresponding to the nature of the fault (e.g. too fast, or too slow). Parameters for acceptable head movements were identified in a pre-experiment pilot study. To maintain consistency and encourage a smooth flow through the experiment, the starfield disappeared as before, and the participants were still presented with the same forced choice task. Responses on these trials were recorded, but they did not affect the adaptive psychophysical procedure and were not used to calculate thresholds. There was an average of 7.8 unacceptable trials per block.

Each experimental block consisted of 150 trials with acceptable head movement profiles. The stimulus for a given trial was generated using two interleaved adaptive staircases (2up1down, 1up2down) of 75 trials each (Fig.2). New staircases were initiated in subsequent blocks.

There were two conditions, and participants completed three blocks for a total of 450 trials in each. The conditions were distinguished based on fixation behavior during the active head turn. In the head-fixed fixation condition, after head- and scene-fixed targets were aligned (Fig. 1), the scene-fixed target disappeared, and participants were left to fixate the target that moved with the head (Fig. 1). This behavior maximized retinal image motion (optic flow), while minimizing eye movement. In the scene-fixed fixation condition, the head-fixed target disappeared, and participants were left to fixate the scene-fixed target during the head movement (Fig. 1). This behavior maximized eye movement, while minimizing optic flow.

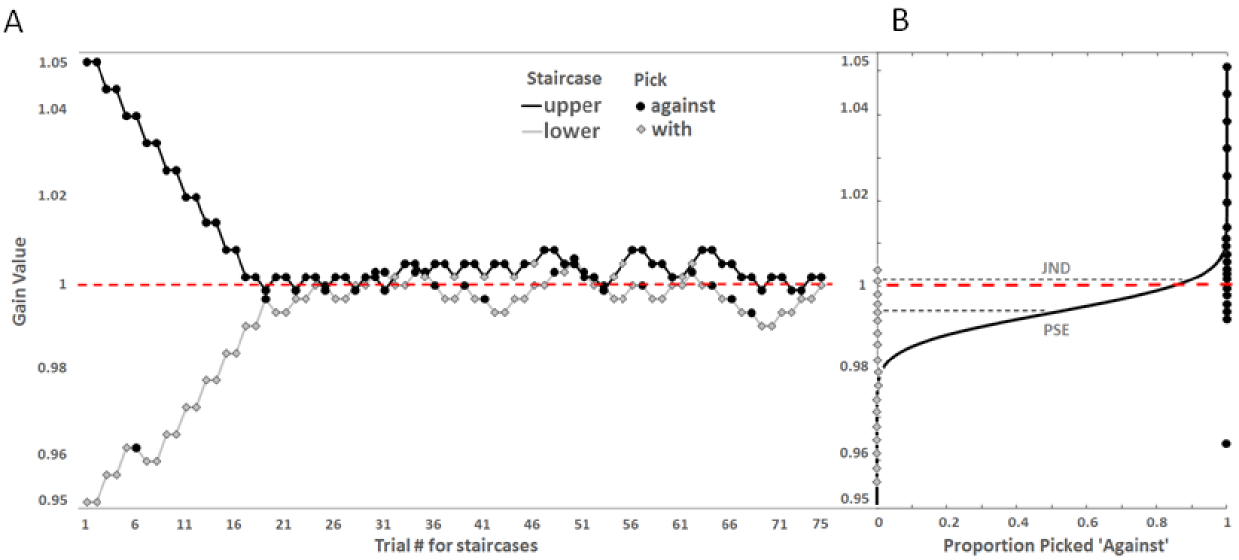

Figure 2. Psychophysics. Here we illustrate how the stimuli presented to a single participant are modulated and show how their two-forced-choice selections define the subsequent fit to a cumulative Gaussian psychometric function. A demonstrates how two interleaving adaptive staircases combine to create a block of 150 trials. B highlights how participants answers of *with* or *against* determine the resulting shape of the psychometric function, values for the mean μ of the curve (point of subjective equality), and the standard deviation σ or steepness of the curve (just noticeable difference).

2.4. Visual Speed-discrimination Task

In this task, participants kept their heads still and were presented with full-field visual motion similar to the optic flow presented during the conflict detection task. Two consecutive motion intervals of 1.0 secs were presented on each trial. One motion interval was the standard stimulus with an average speed of 12.8°/s and a peak velocity of 29.5°/s. Participants then responded which interval contained the faster movement (Fig. 1). Motions were in the same direction in both intervals, and participants completed 150 trails in each block. There were two conditions, head-fixed and scene-fixed, similar to those described above.

2.5. *Training and order of experiments*

Experimentation was split over five sessions, each separated by 24 hours or more. These sessions always began with a thorough training session to ensure that participants understood the task. The training protocol explained and demonstrated each element of the required movement step-by-step. Participants performed each component part numerous times, before they finally executed 20 practice trails. The training was implemented to elicit consistent head-turning behavior within and across participants; training is often required when movements are generated actively rather than presented passively [15, 16]. After the training, participants completed a maximum of two experimental blocks of 150 trials each per session. All blocks for a given condition were completed in sequence, but the order of conditions was counterbalanced across subjects To encourage focus/attentiveness within each session, mandatory breaks of 30 seconds were implemented after 50 and 100 trials. Longer breaks of 4 - 5 minutes were enforced between blocks. During this time participants removed the HMD and the light was turned on. Participants sat comfortably, stretched, or walked around before beginning the next block of trials. Each session was performed with an average running time of 25 minutes.

2.6. *Statistical Analysis*

Analyses were conducted using Matlab R2016a together with the Palamedes toolbox package developed by Kingdom & Prins [17]. PAL_PFML (Palamedes psychometric function: maximum likelihood) functions enabled us to fit a participant's response data to a cumulative Gaussian (Fig.2). We refer to the mean parameter of the fit as the point of subjective equality (PSE), and standard deviation parameter as the just noticeable difference (JND).

Paired t-tests were carried out using participants' JNDs across conditions. We additionally conducted one-sample t-tests to examine whether PSE values differed significantly from a gain value of 1 (1 represents the point where the visual stimuli has not been manipulated and matches the physical head motion). We analyzed VR sickness ratings using factorial ANOVAs examining possible effects of Task (Conflict, Visual), Fixation (Head-fixed, Scene-fixed) and Gender (Male, Female). We set $\alpha = 0.05$ for all statistical tests.

3. Results

Modern day virtual reality head-mounted displays possess refresh rates capable of inducing highly immersive experiences in the user. Refresh rates in the displays are at an all time high as are the frame rates of the underlying hardware (which renders the images). Latency, however, can still be an issue and has been suggested as one of the factors mediating VR sickness [1].

The human brain is very sensitive to lag. Conflicts between what the brain expects, and the information it ultimately receives, lead to disorientation and increased symptoms of VR sickness. It has been suggested that to maximize the potential for immersion and presence, and minimize the probability of nausea, we need to reduce any delay to $\leq 20ms$, and ideally $\leq 7ms$ [18, 19, 20]. While hardware evolution shall inevitably solve the problem advances are somewhat hindered by an inherent trade-off between latency and reliability [21].

Sensory conflict of this nature has not been extensively studied. Prior work, employing passive, full body rotations, indicated fixation as a significant influence on sensitivity. Here we examine whether fixation acts as an equally compelling mediator when movements are self-generated.

3.1. *Conflict Detection Task*

Psychometric fits to the data from each individual subject and condition (e.g. Fig. 2B) provide a measure of the visual gain that is perceived to match the physical head motion (the PSE) as well as the threshold for the change in gain that leads to detection of conflict (the JND). Thresholds in the head-fixed condition (mean=0.032; SD=0.021) were significantly larger (t=2.828, p=0.011) than those in the scene-fixed condition (mean=0.022; SD=0.009). These thresholds are plotted in Fig. 3A. The slope of the blue line is the average ratio of the scene-fixed versus head-fixed

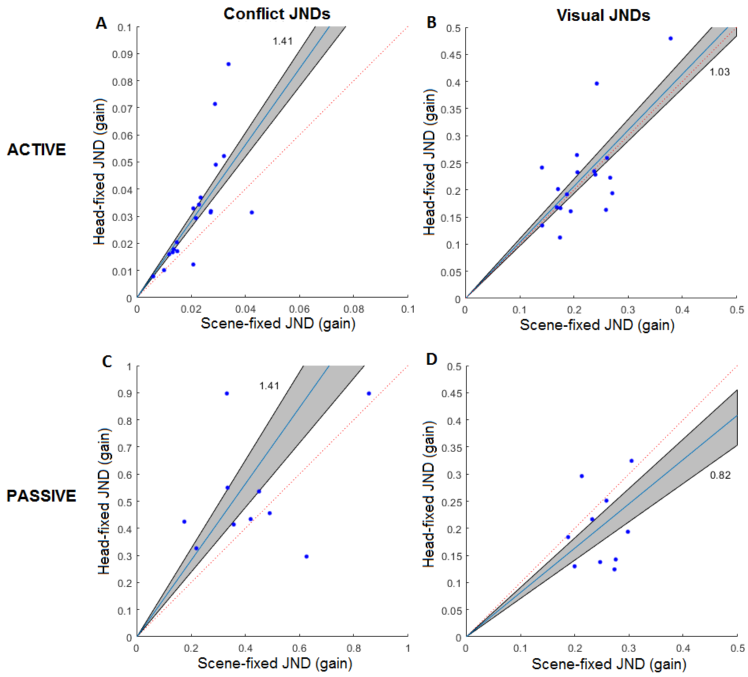

Figure 3. Results. We summarize our main findings in these four graphs. All values represent measurements for perceptual sensitivity to visual gain modulation and correspond to a deviation from gain=1. While the standard error of the head-fixed versus scene-fixed ratio for conflict detection conditions differs between active (0.11) and passive (0.22) head rotations, the ratio itself is exactly the same (1.41). The ratio perfectly coincides despite an order of magnitude improvement in discrimination sensitivity. Such relative replication encourages optimism in the use of HMD while further work may be necessary in order to tease apart exactly what is behind the order of magnitude difference. We observe a small difference in visual tasks between active and passive experiments. While the ratio differs the values are very similar. The difference here may be down to the number of participants (19 vs. 10) as the vast majority of data points in each graph seem perfectly interchangeable. The overwhelming conclusion we may take from examining the graphs alone is that using a virtual reality, head-mounted display set-up to conduct psychophysical experimentation is perfectly valid and provides very similar findings as far more expensive, resource greedy, experimental methodologies.

JND (1.41) and the shaded area represents the standard error of this ratio (0.11). For comparison we have also plotted the thresholds measured in our previous study with passive head movements (Fig. 3C). As in the current study, thresholds in the head-fixed condition were larger than those in the scene-fixed condition. Again, the slope of the blue line is the average ratio of the scene-fixed versus head-fixed JND (1.41) and the shaded area represents the standard error of this ratio (0.22). The relationship between head-fixed and scene-fixed thresholds appears to be independent of whether head movement was active or passive.

The most conspicuous difference between results of current and former studies is that conflict detection thresholds were reduced by an order of magnitude when head movement was fast (peak vel.∼29.5°/s) and active rather than slow (peak vel. 10°/s) and passive. Possible reasons for this increased sensitivity are explored in the discussion.

Results of the current study also differ from previous reports because the visual gains perceived as matching head motion (the PSEs) are much closer to unity in the present study. The gain perceived as matching in the head-fixed condition was 0.990 (0.018 SD) which is close to a gain of 1, but significantly different (t=-2,342, p=0.031). The gain perceived as matching in the scene-fixed condition was 0.995 (0.012 SD) which was not significantly different from 1. In contrast with the present results, prior studies consistently report that the visual gain perceived as matching is greater than 1 [22, 23, 24]. Methodological differences may be able to explain this difference in results (see Discussion).

3.2. *Visual speed-discrimination task*

In addition to measuring visual-vestibular conflict detection, we also measured visual speed discrimination thresholds. We did this to examine whether the effect of fixation behavior on conflict detection could simply reflect an effect of fixation on visual speed estimation. For example, more variable visual speed estimation during head-fixed fixation could explain higher conflict detection thresholds. However, results do not support this hypothesis. Discrimination thresholds were approximately equal during head-fixed (mean=0.244, SD=0.119) and scene-fixed (mean=0.239, SD=0.109) fixation (t=0.297, p=0.770), so differences in visual variability alone cannot explain the observed dependence of conflict detection on fixation. Thresholds in the two fixation conditions were not only approximately equal, they were also significantly correlated (r=0.846, p<0.001; Fig. 3B), likely reflecting their dependence on similar underlying visual motion processing mechanisms.

For comparison, we also examined visual speed discrimination thresholds from our prior study which used much slower movements (Fig. 3D). Again, thresholds were not significantly different during scene-fixed fixation compared with head-fixed fixation. Thresholds were similarly correlated, albeit less so. Such similarity of trend which lacking the absolute strength of correlation may be explained by simple differences in the number of data points (n = 19, vs n = 10). Thresholds expressed as a fraction of the pedestal speed were comparable between the current (Fig. 3B) and previous study (Fig. 3D), unlike during conflict detection (Fig. 3A vs. Fig. 3C).

3.3. Simulator Sickness Questionnaire

At the end of each condition, participants completed the SSQ [6]. Responses were analyzed using ANOVA with factors Task (Conflict, Visual), Fixation (Head-fixed, Scene-fixed) and Gender (Male, Female). There was a significant effect of Task ($F=15.343$, $p<0.001$), with more adverse responses reported during the visual discrimination task. This makes sense because in this task, visual optic flow consistent with head motion was presented to stationary observers. We observed a trend (albeit not quite statistically significant) relating to Fixation ($F=3.408$, $p=0.07$), with more adverse response reported during Scene-fixed fixation. Conflict detection thresholds were also lower during scene-fixed fixation; this association is consistent with the hypothesis that conflict detection mechanisms that underlie perceptual reports may be the same as those that can ultimately elicit simulator sickness. Finally, there was a significant effect of Gender ($F=32.695$, $p<0.001$) with more sickness reported by female participants. This is consistent with gender-dependent effect reported previously, but the cause for these effects remains unknown.

4. Discussion

In the current study, we examined sensitivity to visual gain modulation during active head-on-body rotation using an HMD. This work builds on our prior study[anon] in which we measured this sensitivity during slow, passive full-body rotation. We found that conflict detection depends similarly on fixation behavior, regardless of whether head movements were actively or passively generated. This effect of fixation cannot be explained based on the variability of the visual self-motion estimates, because visual discrimination thresholds do not depend strongly on fixation behavior. Instead, we hypothesize that cue comparison mechanisms operate differently depending on oculomotor behavior, regardless of whether movements are active are passive. We also found that conflict detection thresholds were an order of magnitude lower during active compared to passive head rotation. These differences could be due to additional non-visual cues to head motion in form of efference copy and proprioception. Alternatively, these differences could be a consequence of faster velocities of head movement used during active compared to passive conflict detection studies. Examining the basis of this active/passive difference, and also the relation between conflict sensitivity and simulator sickness, are important areas for future study.

4.1. Visual-vestibular conflict detection during active head movements

The prior work which we extend in this study explicitly examined visual-vestibular conflict detection. Passive full-body movements were generated by motion platform and thus no proprioceptive or motor signals (such as efference copy) were evoked. In sharp contrast, this active (self-generated) movement methodology necessarily stimulated motor signals. As such, we cannot strictly define the conflict detection task in simple bimodal discrimination terms.

We observed an order of magnitude reduction in threshold for this multimodal conflict detection compared to the passive visual-vestibular methodology. In addition to the extra sensory cues, this condition differed in the peak velocity of head movements (~29.5°/s vs. 10°/s), and the display medium (HMD vs. 3D monitor). We may rule out differences in visual variability as results from the visual speed-discrimination task closely mirrored those previously observed. We additionally saw an almost perfect replication in the effect of fixation.

Such consistency in the findings (active vs. passive) allows us to rule out a number of possible explanations and focus in on potential causes. The extra sensory cues are an obvious candidate. Intuitively, extra information flows should reduce uncertainty, and allow for a more accurate decision of where any conflict has arisen. Indeed, several previous studies [25, 26, 27, 28, 29] have shown greater precision of responses when all modalities (vestibular, proprioception, efference copy) signaled a rotation [16].

Much remains unknown regarding the underlying mechanisms mediating when and how the different cues are compared and combined. Forced fusion has been proposed in modeling visual-vestibular [30, 31, 32] and vestibular-proprioceptive [33] integration and conflict detection. Evidence points towards greater variability in vestibular signals than those of proprioception and efference copy [16]. While these factors must be considered we must also acknowledge that evidence also exists for limits on discrimination performance relating to the sum of the single cue variabilities [34, 30].

With little consensus regarding the effect of additional cues, and a magnitude improvement in sensitivity to explain, we must also consider the three-fold increase in peak velocity for the active case. Previous studies on the detection of latency in HMDs (conflict detection) have revealed significant improvements in sensitivity when peak velocity of rotation is increased [20, 35] The improvements demonstrated are not in line with the magnitude of improvement observed in our study. However, when considered in combination with evidence for greater precision in a multimodal situation, we are perhaps closing in on a feasible explanation.

Follow up experiments shall look at examining exactly how much of the variation between active and passive sensitivities can be explained by the two factors described. We shall initially repeat our HMD with high peak velocity conditions using the motion platform. Negating the effects of proprioception and efference copy shall reveal exactly how much velocity effects sensitivity. Subsequent experiments shall attempt to tease apart vestibular signals from proprioception and efference copy. By utilizing a rotation chair we may negate the vestibular signal by countering the active head rotation.

4.2. Visual gain perceived as matching is very close to 1

Previous work has generally demonstrated that the visual gain necessary to match a physical head rotation is significantly greater than 1 [23, 22, 24]. We instead observed very little difference from a gain of 1, with values marginally under. While this disparity demands closer inspection we may find that such variation can be explained by mere experimental differences. Examining the previous literature in greater detail we observe that while an average visual gain greater that 1 may best fit rotation movements in general, yaw tends to require less deviation from unity [22, 24]. Additionally, we see that a wide spread of gains (0.8 to 1.4) that are in fact accepted as stable [22].

Size and depth cues influence self-motion perception [36]. We may consider manipulating size and distance attributes of the starfield in order to examine how this may effect the matching visual gain. Modulation in visual dominance can occur due to the influence of proprioceptive and efference copy cues. If we consider the forced fusion models previously discussed we may posit a tighter coupling of priors for vestibular-proprioception, vestibular-efference copy, and proprioception-efference copy, than those relating to vision. Such cue reweighting is well documented [37] and demonstrates a dynamic situation highly dependent on situation, and mode of movement (active vs. passive) [38, 39, 40].

4.3. Sickness and relation to conflict detection

We observed far greater reporting of simulator sickness symptoms in the visual speed-discrimination task than in conflict detection. Additionally, in the conflict detection task we saw exactly the same level for scene-fixed and head-fixed conditions. While the ability to detect conflict differed significantly across the two conditions this did not translate into similar differences in sickness symptoms.

The conflict detection task included active head rotations by participants. We posit that this motor activation mitigates the effects of conflict due to agency or control [41]. Previous studies have shown how postural instability [42, 43] and control and the resulting expectations [44, 41] mediate motion sickness. An active participant necessarily has far greater control and increased postural stability which may account for the reduction in symptoms.

We observed a gender bias similar to several previous studies. With so many contradictory findings in existence this additional result does little to swing the balance of evidence either way. Far more work is necessary in this arena before any definite conclusions can be made.

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