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Vection during conflicting multisensory information about the axis, magnitude and direction of self-motion

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Vection during conflicting multisensory information about the axis, magnitude and direction of self-motion

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We examined the vection induced by consistent and conflicting multisensory information about self-motion. Observers viewed displays simulating constant-velocity self-motion in depth while physically oscillating their heads left ^ right or back ^ forth in time with a metronome. Their tracked head movements were either ignored or incorporated directly into the self-motion display (as an added simulated self-acceleration). When this head oscillation was updated into displays, sensory conflict was generated by simulating oscillation along: (i) an orthogonal axis to the head movement; or (ii) the same axis, but in a non-ecological direction. Simulated head oscillation always produced stronger vection than `no display oscillation' even when the axis/direction of this display motion was inconsistent with the physical head motion. When head-and-display oscillation occurred along the same axis: (i) consistent (in-phase) horizontal display oscillation produced stronger vection than conflicting (out-of-phase) horizontal display oscillation; however, (ii) consistent and conflicting depth oscillation conditions did not induce significantly different vection. Overall, orthogonal-axis oscillation was found to produce very similar vection to same-axis oscillation. Thus, we conclude that while vection appears to be very robust to sensory conflict, there are situations where sensory consistency improves vection.

Keywords

vection, conflicting, during, multisensory, information, about, axis, magnitude, direction, self, motion

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**VECTION DURING CONFLICTING MULTISENSORY INFORMATION ABOUT THE AXIS,
MAGNITUDE AND DIRECTION OF SELF-MOTION**

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KEYWORDS: Vection, Vision, Vestibular, Optic flow, Sensory Conflict

Abstract

We examined the vection induced by consistent and conflicting multisensory information about self-motion. Observers viewed displays simulating constant velocity self-motion in depth while physically oscillating their heads left-right or back-forth (in time with a metronome). Their tracked head movements were either ignored or incorporated directly into the self-motion display (as an added simulated self-acceleration). When this head oscillation was updated into displays, sensory conflict was generated by simulating oscillation along: (i) an orthogonal-axis to the head movement; or (ii) the same-axis, but in a non-ecological direction. Simulated head oscillation always produced stronger vection than 'no display oscillation' – even when the axis/direction of this display motion was inconsistent with the physical head motion. When head-and-display oscillation occurred along the same axis: (i) consistent (in-phase) horizontal display oscillation produced stronger vection than conflicting (out-of-phase) horizontal display oscillation; however (ii) consistent and conflicting depth oscillation conditions did not induce significantly different vection. Overall, orthogonal-axis oscillation was found to produce very similar vection to same-axis oscillation. Thus, we conclude that while vection appears to be very robust to sensory conflict, there are situations where sensory consistency improves vection.

1 Introduction

Vection (or the visually induced illusion of self-motion) has often been used to investigate how the senses interact during different situations of self-motion (Fischer and Kornmüller 1930). The 'train illusion' is possibly the best known example of vection. This is the illusion of self-motion experienced when one sits on a stationary train and observes the train on the next track pulling out of the station. Since such illusions of self-motion can be induced by visual information alone, the visual system is often thought to play a particularly important role in the perception of self-motion (Dichgans and Brandt 1978; Johansson 1977; Lee and Lishman 1975; Lishman and Lee 1973). However, there are also a number of non-visual senses that can contribute to the perception of self-motion (especially during active self-motions). These include the vestibular, somatosensory and proprioceptive systems (Benson 1990; Johansson 1977; Siegler et al 2000). In particular, the vestibular system is often thought to provide important information about linear and angular self-acceleration, even though it is unable to distinguish between the observer travelling at a constant linear velocity and remaining stationary (Benson 1990; Lishman and Lee 1973).

While these different senses are thought to provide consistent/redundant information about self-motion in many situations, information in other situations is often non-redundant (Stoffregen and Riccio, 1991), which may lead to so-called 'sensory conflict' (Reason, 1978). Unresolved sensory conflicts are thought by many to be responsible for a number of unpleasant physical symptoms (such as nausea, disorientation, postural instability and other symptoms commonly associated with motion sickness – Bles, Bos de Graaf et al, 1998; Bubka and Bonato, 2003; Palmisano et al 2007) and impair task performance (Bos et al 2005).

Over the years, vection studies have examined self-motion perception in a variety of so-called situations of sensory conflict (see Palmisano et al 2011 for a recent review). Recent studies have shown that not only is the vection experienced by *stationary observers* surprisingly robust to visually simulated self-acceleration, it actually appears to be enhanced by them (compared to displays which only simulate constant velocity self-motions – Nakamura 2010; Palmisano et al, 2000; 2003; 2007; 2008; 2009; 2011). Adding simulated horizontal/vertical viewpoint jitter and oscillation to radial flow displays simulating constant velocity self-motion in depth, has been shown to improve vection strength ratings, reduce vection onset times and increase vection durations. These viewpoint jitter and oscillation advantages for vection are found despite the fact that this visually simulated self-acceleration is expected to dramatically increase the level of visual-vestibular conflict.

Recent research has also examined the vection induced in *active, physically moving observers*. These studies have shown that conflicts between visually simulated and physical self-motion often do not impair vection (Ash, Palmisano and Kim, 2011; Kim and Palmisano, 2008; 2010). In these studies, seated subjects actively oscillated their heads from either from side-to-side or back-and-forth. As a result, self-motion displays typically had two optic flow components, an oscillating component based on the observer's tracked head movement and a constant component representing forwards self-motion in depth. Interestingly, Kim and Palmisano (2008) found no difference between the vection induced by horizontal display oscillation in the same or opposite direction to the observer's head movements (despite the expectation that the former non-ecological condition would generate substantial sensory conflict and the latter ecological condition would generate minimal sensory conflict). Similarly, Ash and colleagues (2011) found no difference between the vection induced by back-and-forth

display oscillation in the same or the opposite direction to the observer's head movements.

From the above findings it appears that vection is remarkably tolerant to a number of situations of expected sensory conflict. However, the visual system is not always successful at overriding/downplaying conflicting non-visual information about self-motion. For example, a recent study by Ash, Palmisano, Govan and Kim (2011) found that vection strength could be reduced by introducing lag between the observer's actual head movement and the incorporation of this head movement information into the visual display.

In the above studies, both the physical and the visually simulated self-acceleration were always along the same-axis. The aim of the current study was to examine vection induced when the visually simulated self-acceleration occurs along an orthogonal-axis to the physical self-acceleration. Four different experimental conditions were examined: (1) both physical and simulated head oscillation along the horizontal axis, (2) both physical and simulated head oscillation along the depth axis, (3) physical head oscillation along the depth axis paired with simulated head oscillation along the horizontal axis, and (4) physical head oscillation along the horizontal axis paired with simulated head oscillation along the depth axis. The gain of the display motion (relative to the head motion) in all four conditions varied from trial to trial (that is, physical head oscillation was either not updated into the display, or updated at the same or twice the amplitude as the observer's head movements). When physical and simulated head motions occurred along the same-axis, we also re-examined the effect of sensory conflicts based on the simulated direction of self-motion¹ (i.e. the simulated

¹ It should be noted that there have been reports of vection differences in stationary, upright observers based simply on the simulated direction of self-motion. For example, Bubka, Bonato and Palmisano (2008) showed a vection advantage for visually simulated backwards, as opposed to forwards, self-

head oscillation moved either in the same or the opposite direction to the observer's physical head movements). Thus, by varying the axis, direction and gain of the display motion (relative to the physical head motion) we were able to systematically examine vection under a variety of sensory conflict conditions (ranging from "little/no" to "extreme" expected conflicts).

2. Experiment 1. Effects of conflicting head and display motion on vection in depth

In this experiment, observers viewed displays simulating constant velocity self-motion in depth while physically oscillating their heads left-right or back-forth (in time with a metronome). In some trials, their tracked head movements were incorporated directly into the self-motion display along either: (i) the same axis as the head motion in an ecological direction, (ii) the same axis in a non-ecological direction, or (iii) an orthogonal axis. In other trials, these tracked head movements were ignored (not updated into the display). Observers were asked to report only on the strength of the component of vection along the depth axis.

2.1 Method

2.1.1 Subjects. Twenty-five undergraduate psychology students (19 females and 6 males; mean age = 20.88, SD = 0.75) at the University of Wollongong received course credit for their participation in this experiment. All had normal or corrected-to-normal vision and no existing vestibular or neurological impairments. The Wollongong Ethics Committee approved the study in advance. Each subject provided written informed consent before participating in the experiment.

motion. However, other studies have reported no vection asymmetry between the opposite directions of simulated self-motion (Nakamura and Shimojo, 1998; Palmisano, Pinniger, Ash & Steele, 2009).

2.1.2 Apparatus. A Mitsubishi Electric (Model XD400U) colour data projector (1024 (horizontal) x 768 (vertical) pixel resolution; the update rate was 30Hz) was used to rear project computer-generated displays onto a flat projection screen (1.48 m wide x 1.20 m high). Subjects viewed displays from a fixation distance of approximately 2.2 m away from the screen. They were asked to move their heads from either side-to-side or back-and-forth in time with a computer-generated metronome.

A ceiling mounted camera (FIREFLY-MV, Point Grey Research) was used to track the subject's head position and these movements were then incorporated into the display in real-time and/or recorded for the purpose of checking inter-subject consistency in terms of the frequency and amplitude of their active head movements. Specifically, this digital firewire camera acquired images of a small plastic dome headset fitted to the top of the participant's head at 120 fps. Five LEDs were arranged in a square on the surface of this headset and their coordinates were acquired by a local PC running Windows XP. Real-time analysis of these coordinates was performed using custom software written in Visual C++ 6.0 to obtain the inter-aural head position in pixels. Simple algorithms introduced in the head tracking procedure were applied to linearise the inter-aural resolution of the system across different depths from the camera lens. A pixels-to-centimetres conversion factor was used to ascertain the 3D position of the head in space (please see Kim & Palmisano, 2008, for more details about the head tracking).

At the end of each trial, the subject moved a linear throttle (Pro Throttle USB) along a sliding scale (that ranged from 0-100) to represent the perceived strength of their vection in depth. A rating of 0 indicated no experience of self-motion (display motion was attributed solely to object motion – i.e. stationary observer) and a rating of 100 indicated maximum vection (display motion was attributed solely to self-motion –

i.e. stationary surround). The subject made these ratings compared to a standard reference stimulus that they were told represented a self-motion in depth strength rating of 50. This reference stimulus was a non-oscillating pattern of radially expanding optic flow (i.e. 0 gain). It simulated constant velocity forwards self-motion in depth and was viewed prior to the experimental trials while the subject was stationary.

2.1.3 Visual Displays. Visual displays simulated an optic flow pattern consisting of 2592 randomly placed blue square objects (1.8 cd/m²) on a black background (0.04 cd/m²). These objects were uniformly distributed within a simulated 3-D environment, which was 12 units wide by 12 units high and 18 units deep (object density was one dot per cube unit). Each optic flow display also had a green fixation dot (20 cd/m²) that was located in the centre of the display screen at an intermediate distance in the depth plane. Subjects were asked to fixate on this stationary green dot for the duration of each 30 s trial.

All optic flow displays simulated the same constant velocity (11.25 units/s) forward self-motion in depth (i.e. all displays had the same radially expanding flow component). Subjects were asked to oscillate their head either left-to-right or back-and-forth and information about their changing head position was updated into the visual display in real-time. This visually simulated head oscillation was applied along either the *same-axis* or the *orthogonal-axis* to the subject's actual head-motion. For same axis self-motion conditions, there were 5 combinations of display phase and gain for both axis types: "+2", "+1", "0", "-1" or "-2". During *in-phase conditions* (indicated by a "+" sign), the visual display always moved in the opposite direction to the subject's physical head movements, providing consistent visual-vestibular information about self-acceleration. By contrast, in *out-of-phase conditions* (indicated by "-" sign), the visual

display always moved in the same direction as the subject's physical head movements, providing inconsistent visual-vestibular information about self-acceleration. Finally, in *no visual oscillation conditions* ("0" gain), the subject's physical head movements were simply ignored – which should also have provided inconsistent visual-vestibular information about self-acceleration. The gain of the additional horizontal display motion (with respect to the subject's head movement) was twice as large in the "+2" and "-2" conditions as in "+1" and "-1" conditions.

It should be noted that there was no reason to examine the directional component (i.e. the phase) of the visual display for orthogonal axis conditions, as displays simulated a completely different axis to the subject's physical self-motion (for example, fore-aft head oscillation would be updated as horizontal display oscillation). These displays only varied in terms of amplitude, and not phase (i.e. phase was ignored in these self-motion conditions). Similar to consistent self-motion axis conditions, displays moved at either twice the amplitude as the physical lateral head movements, at the same amplitude as these physical head movements, or were simply ignored (i.e. were not updated into the self-motion display).

2.1.4 Procedure. The subject was first briefed on the experimental instructions and requirements. *Head oscillation type* (horizontal vs. back-and-forth), *display motion axis* (same vs. orthogonal) and *display motion gain* (+/-2, +/-1, 0) all varied as within subjects' variables. Prior to the experiment, subjects were run through two practice trials (they made horizontal head movements in one, and back-and-forth head movements in the other) and given feedback about the frequency and amplitude of their head movements. They were told to oscillate their heads from left-to-right or back-and-forth by: (i) oscillating at the waist, rather than the neck, to avoid discomfort and/or

injury; and (ii) timing their oscillations to a computer-generated auditory tone that sounded at 0.5 s intervals (with the aim being to produce a physical head oscillation frequency of approximately ~ 0.5 Hz).

Subjects were run through each of the following 4 experimental blocks of trials (1) horizontal head oscillation updated as horizontal display oscillation, (2) horizontal head oscillation updated as display oscillation in depth, (3) head oscillation in depth updated as display oscillation in depth, and (4) head oscillation in depth updated as horizontal display oscillation. There were 10 trials in each block (2 repetitions of each of the 5 levels of phase and gain), with each trial lasting 30 secs. Vection in depth strength ratings were averaged across experimental repeats.

2.2 Results

2.2.1 Horizontal Physical Head Oscillation Data

2.2.1.2 Horizontal Head and Display Motion (Condition 1)

We performed Bonferroni-planned contrasts on this same-axis data (controlling the family-wise error rate at 0.05). Consistent with previous research, we found that both in-phase ($F(1, 24) = 42.17, p = .00$) and out-of-phase ($F(1, 24) = 32.25, p = .00$) horizontal display oscillation conditions both produced significantly stronger vection in depth ratings than no display oscillation conditions (where displays simulated constant velocity forward self-motion and were not altered by the subject's physical head movements - see Figure 1). No significant difference in vection in depth was found between horizontal in-phase and horizontal out-of-phase display oscillation ($F(1, 24) = 2.77, p > .05$). However, when this display oscillation was simulated at twice the amplitude of subjects' head movements, we found that horizontal in-phase display oscillation resulted in significantly stronger vection in depth ratings compared to

horizontal out-of-phase display oscillation ($F(1, 24) = 7.83, p = .05$). Furthermore, for our horizontal in-phase display oscillation conditions, we found a significant effect of display gain (with larger display gains resulting in significantly stronger vection in depth ratings - $F(1, 24) = 19.42, p = .00$). This was not found to be the case for our horizontal out-of-phase display oscillation conditions (there was no significant difference in vection between large and small gains for these conditions - $F(1, 24) = 1.42, p > .05$).

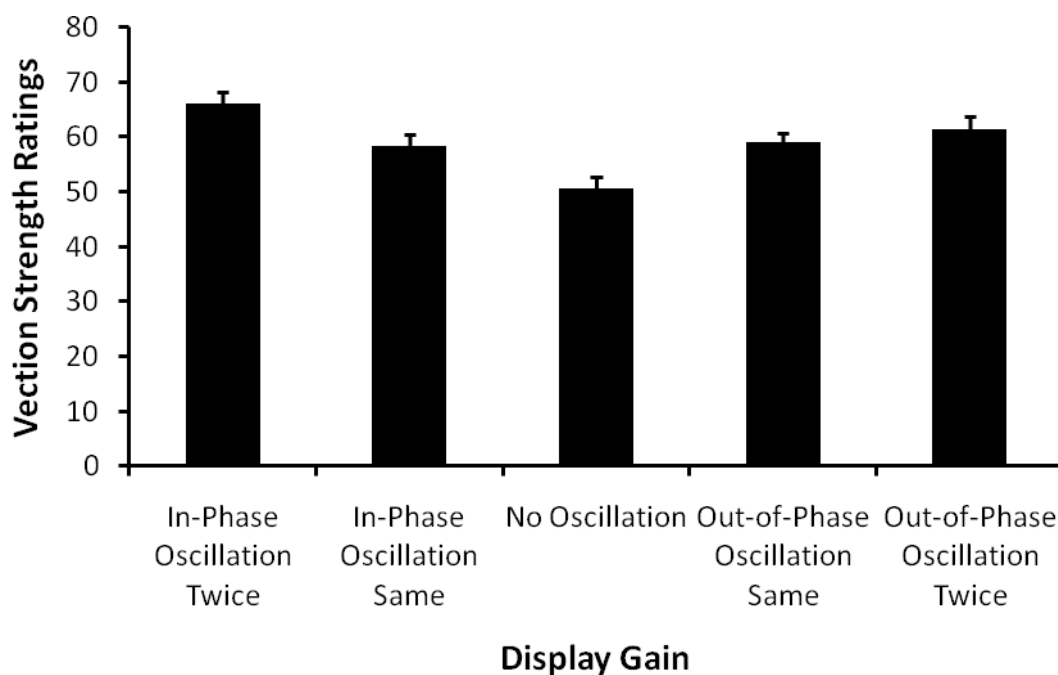


Figure 1. Effect of combined horizontal head and horizontal display oscillation on vection in depth strength ratings as a function of both display gain (either at the same or twice the amplitude expected from the subject's head movements) and phase (either in-phase with, out-of-phase with, or unaffected by, the subject's head movements). Error bars depict the standard error of the mean.

2.2.1.3 Horizontal Head and Depth Axis Display Motion (Condition 2)

We also performed Bonferroni-planned contrasts on this orthogonal self-motion axis data (controlling the family-wise error rate at 0.05). Similar to our same self-motion axis data, we found a significant effect of display oscillation (see Figure 2). That is, oscillating displays were shown to improve vection in depth compared to non-oscillating displays ($F(1, 24) = 55.19, p = .00$). There was a trend toward larger display gains (i.e. 2) producing stronger vection in depth ratings than smaller display gains (i.e. 1). However, this trend did not reach significance - $F(1, 24) = 16.02, p = .00$.

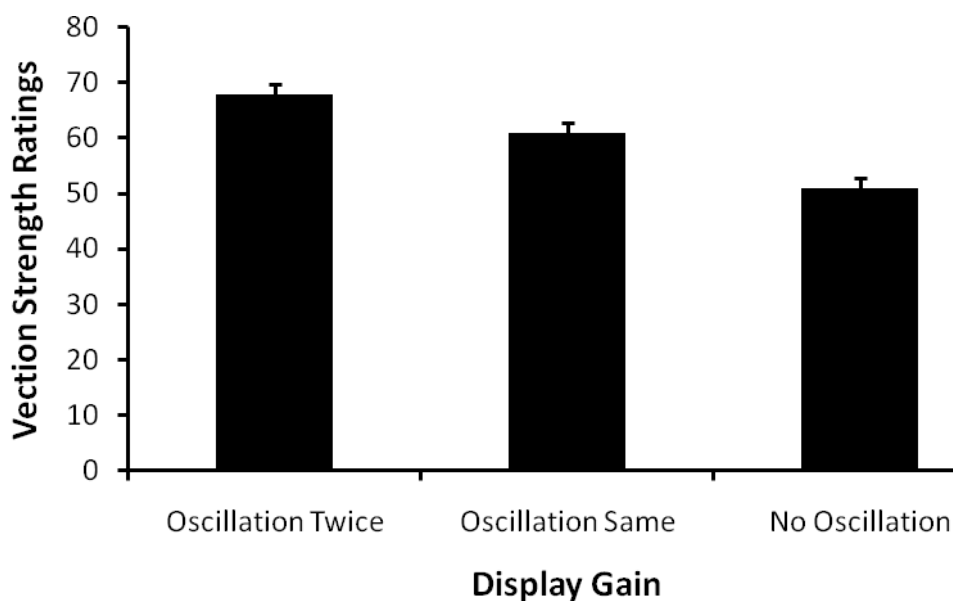


Figure 2. Effect of horizontal head oscillation coupled with depth display oscillation on vection in depth strength ratings as a function of display gain (either at the same or twice the amplitude expected from the subject's head movements). Error bars depict the standard error of the mean.

2.2.1.4 Comparison of Same and Orthogonal Self-motion Axis Data (Horizontal Head Motion)

Finally, for our physical horizontal head oscillation data, we performed Bonferroni-planned contrasts to compare the vection in depth induced by same-axis

and orthogonal-axis display oscillation (controlling the family-wise error rate at 0.05). Same-axis display oscillation did not produce significantly different vection in depth to orthogonal-axis display oscillation, when the display oscillation was in-phase ($F(1, 14) = 2.61, p > .05$). However, same-axis display oscillation produced significantly weaker vection in depth than orthogonal-axis display oscillation when it was out-of-phase ($F(1, 24) = 7.54, p = .03$). In fact, this vection advantage for orthogonal-axis conditions compared to out-of-phase same-axis conditions increased when head oscillation was simulated at twice the amplitude of as the actual self-motion ($F(1, 24) = 12.21, p = .01$). This suggests that same-axis directional conflicts were more important than orthogonal-axis conflicts during our horizontal head motion conditions.

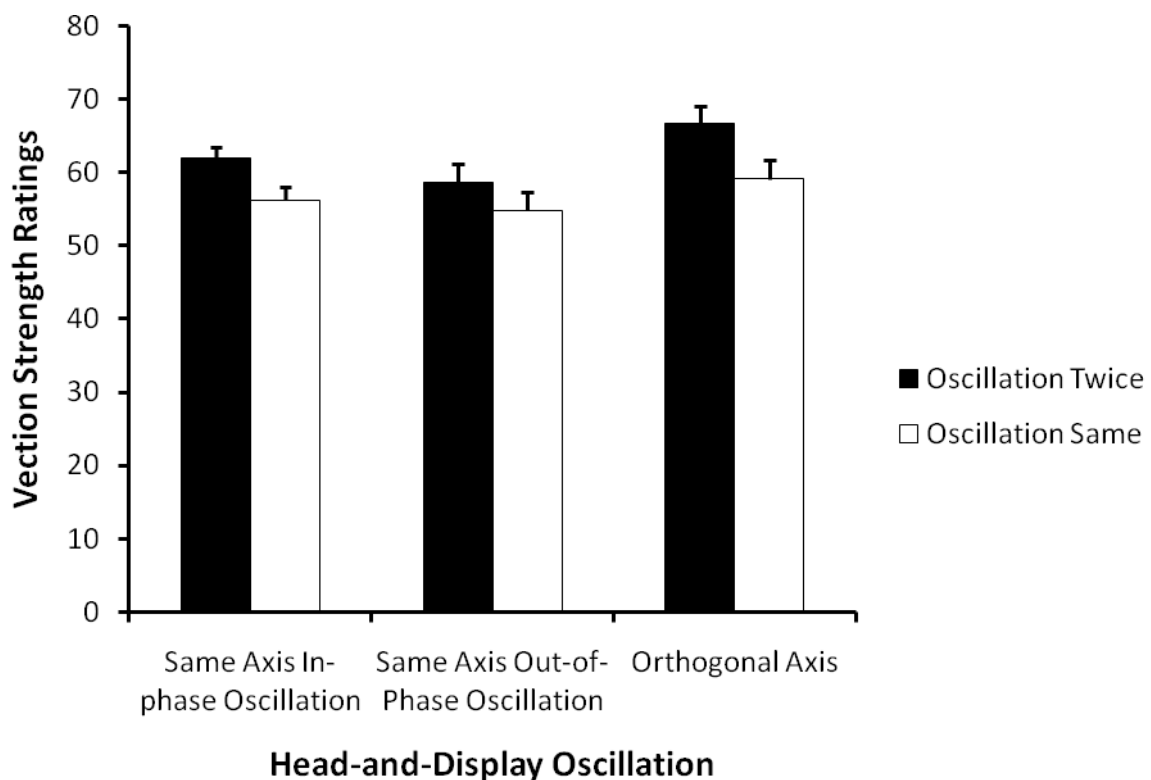


Figure 3. Vection in depth strength ratings for in-phase and out-of-phase same (horizontal head-and-display) axis and orthogonal (horizontal head, depth display) axis conditions as a function of display gain (either at the same or twice the amplitude

expected from the subject's head movements). Error bars depict the standard error of the mean.

2.2.2 Physical Back-and-forth Head Oscillation Data

2.2.2.1.1 *Depth Axis Head and Display Motion (Condition 3)*

Similar to our horizontal same axis data, we performed Bonferroni-planned contrasts on our depth same axis data (controlling for a family-wise error rate of 0.05). In-phase ($F(1, 24) = 28.97, p = .00$) and out-of-phase ($F(1, 24) = 28.51, p = .00$) depth display oscillation conditions were both found to produce significantly stronger vection in depth ratings than no display oscillation conditions (see Figure 4). However, we failed to find a difference in the vection in depth induced by in-phase and out-of-phase depth display oscillation conditions (even when display oscillation was simulated at twice the amplitude of the subject's physical head movements - $F(1, 24) = 0.07, p > .05$). We did find a significant effect of display gain for in-phase oscillation conditions, with larger gains resulting in significantly stronger vection in depth strength ratings ($F(1, 24) = 43.75, p = .00$). We also found a similar significant effect of display gain for our out-of-phase display oscillation conditions ($F(1, 24) = 9.32, p = .03$).

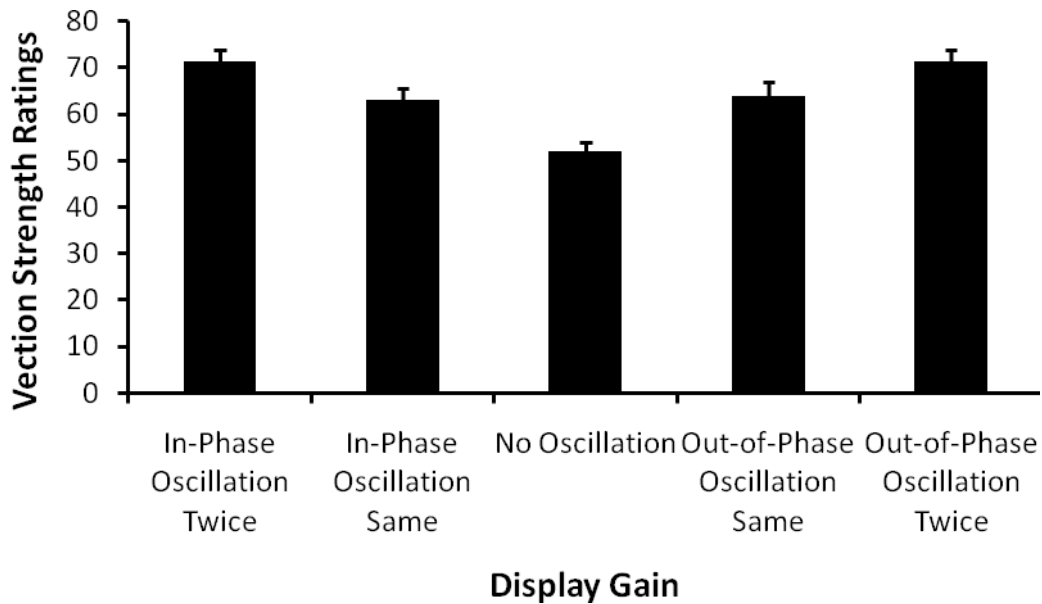


Figure 4. Effect of head-and-display oscillation, both along the depth axis, on vection in depth strength ratings as a function of display gain (either at the same or twice the amplitude expected from the subject’s head movements) and phase (either in-phase with, out-of-phase with, or unaffected by, the subject’s head movements). Error bars depict the standard error of the mean.

2.2.2.2 Depth Axis Head and Horizontal Display Motion (Condition 4)

We also performed Bonferroni-planned contrasts on our depth orthogonal axis conditions (controlling for a family-wise error rate of 0.05). Under these conditions, oscillating displays were again found to produce stronger vection in depth ratings than non-oscillating displays ($F(1, 24) = 35.02, p = .00$). Furthermore, the large amplitude display oscillation (i.e. 2) condition was found to produce stronger vection in depth ratings than the small display oscillation (i.e. 1) condition ($F(1, 24) = 20.34, p = .00$).

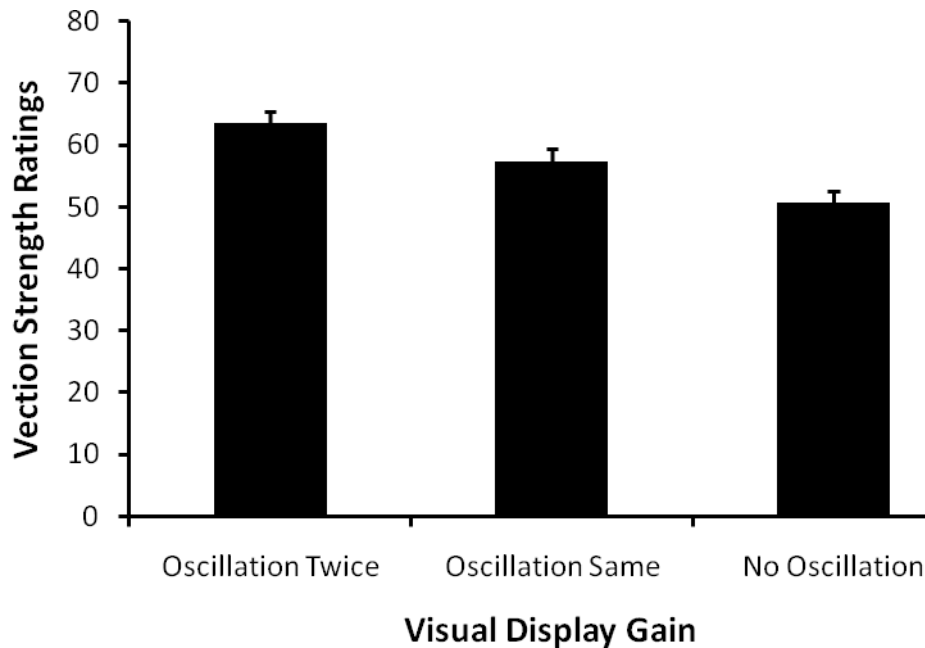


Figure 5. Effect of physical depth head oscillation coupled with horizontal display oscillation on vection in depth strength ratings as a function of display gain (either at the same or twice the amplitude expected from the subject's head movements). Error bars depict the standard error of the mean.

2.2.2.3 Comparison between Same and Orthogonal Self-motion Axis Data (Depth Axis Head Motion)

Finally, we performed Bonferroni-planned contrasts to compared depth same and orthogonal axis conditions (controlling for a family-wise error rate of 0.05). During depth axis head motions, we found trends for same-axis display oscillation to produce stronger vection in depth ratings than orthogonal-axis display oscillation - for both in-phase ($F(1, 24) = 5.19, p = .06$) and out-of-phase ($F(1, 24) = 5.33, p = .06$) conditions. However, when this display oscillation was simulated at twice one's physical head movements, we found that both in-phase ($F(1, 24) = 6.76, p = .03$) and out-of-phase (F

(1, 24) = 6.12, $p = .04$) same-axis conditions resulted in significantly stronger vection in depth strength ratings compared to the corresponding orthogonal-axis condition.

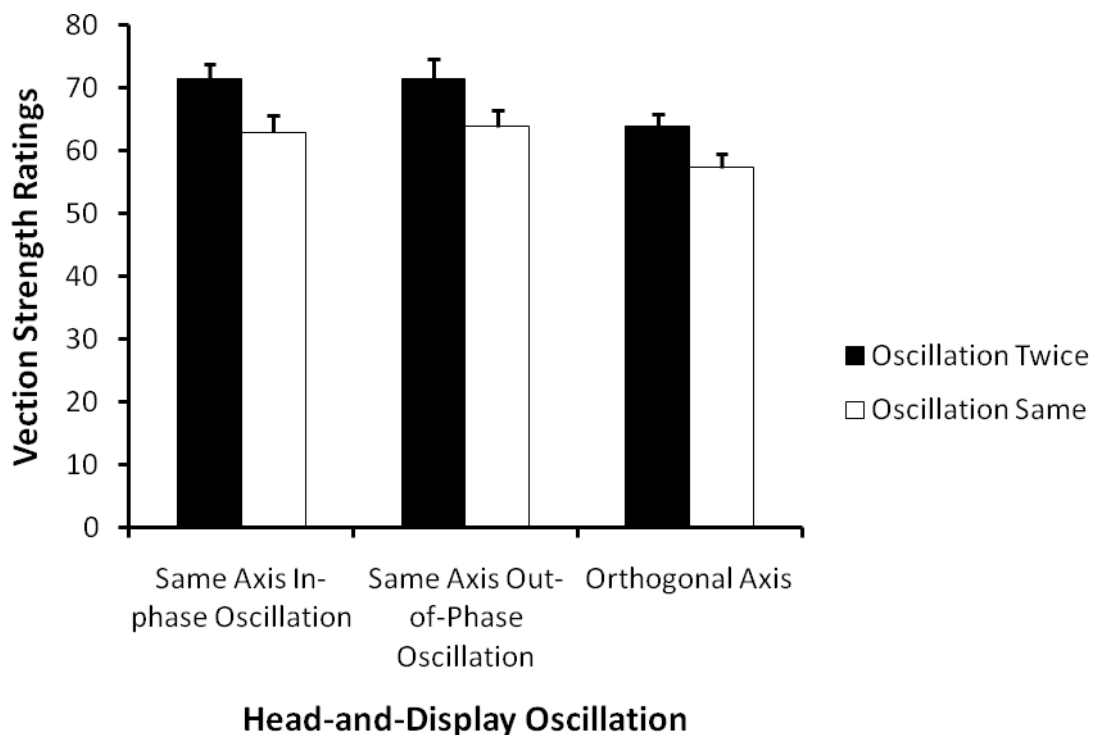


Figure 6. Vection in depth strength ratings for in-phase and out-of-phase same (depth head and display) axis and orthogonal (depth head and horizontal display) self-motion axis conditions as a function of display gain (either at the same or twice the amplitude expected from the subject's head movements). Error bars depict the standard error of the mean.

2.2.3 Head Movement Data

Subjects were found to oscillate their heads at a similar frequency for all conditions tested (~ 0.64 Hz on average). Physical head oscillation frequencies were similar for: (i) our horizontal-head-and-display and our depth-head-and-display oscillation conditions ($t(24) = 1.32, p = .2$), (ii) our horizontal-head-and-display and our horizontal-head-and-depth-display oscillation conditions ($t(24) = -1.01, p = .32$); and

(iii) our depth-head-and-display and our depth-head-and-horizontal-display oscillation conditions ($t(23) = 1.77, p = .09$).

Head movement amplitudes were similar for our depth-head-and-display ($M = 5.99$ cm) and our horizontal-head-and-display ($M = 5.98$ cm) oscillation conditions ($t(24) = .02, p = .99$). They were also similar for our horizontal-head-and-display ($M = 5.98$ cm) and horizontal-head-and-depth-display ($M = 5.42$ cm) oscillation conditions ($t(23) = 1.16, p = .19$). However, we did find a significant difference in head oscillation amplitude between our depth-head-and-display ($M = 5.99$ cm) and our depth-head-and-horizontal-display ($M = 6.88$ cm) oscillation conditions ($t(24) = -2.46, p = .02$). It is possible that this difference in head amplitudes might explain the differences in vection strength ratings found for these two types of conditions (in Figure 7).

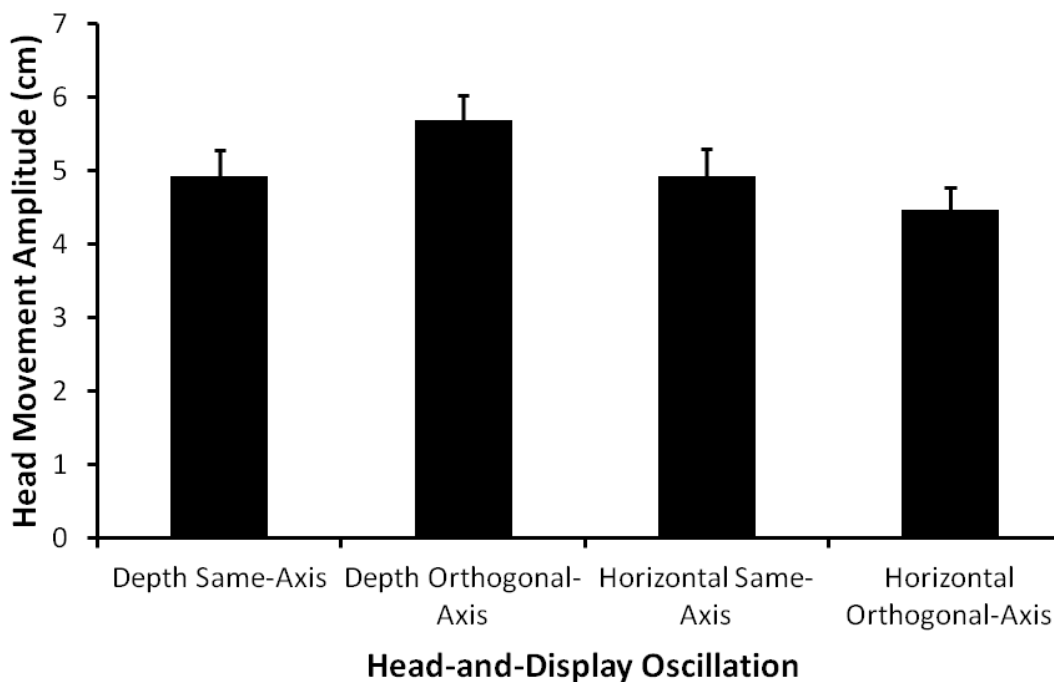


Figure 7. Average physical head movement amplitudes (cm) for same- and orthogonal-axis horizontal and depth head-and-display oscillation conditions. Error bars depict the standard error of the mean.

We performed regression-based analyses to determine whether physical head movement amplitude predicts vection strength ratings. These regression-based analyses utilised all data (i.e. each vection strength rating was paired with the appropriate head oscillation amplitude for the trial) following Lorch and Myers (1990) suggested method for Repeated Measures designs². To avoid averaging across individual subjects, we calculated separate regression equations for each of our 25 subjects using measurements from each condition. We then performed a one sample t-test on the β coefficients for these different equations, and found that these were not significantly different from zero ($t(24) = -.4, p = .7$ – see Table 1). Thus, our subjects' head movement amplitudes were not found to significantly predict their vection in depth strength ratings.

2.3 Discussion

Overall, there was surprisingly little evidence of vection in depth impairment in the orthogonal-axis head-and-display motion conditions. The vection in depth induced in horizontal head motion conditions with depth display oscillation was similar to that induced in ecological conditions (where both the head and display oscillated in-phase along the horizontal axis). However, interestingly, we did find a modest vection impairment in depth head motion conditions when this head oscillation was updated as horizontal display oscillation (compared to ecological conditions where both the head and display oscillated in-phase along the depth axis).

As in previous studies, vection in depth was also found to be remarkably tolerant to same-axis conflicts. While vection was found to be similar for in-phase and out-of-

² Since our experiment had a Repeated Measures design, the raw data did not represent independent samples. In this situation, Lorch and Myers' (1990) recommend that: (i) individual regression equations should be calculated for each subject; and then (ii) a t-test should be performed to determine whether regression coefficients are significantly different from zero.

phase same axis conditions during depth head motion, we did find a modest vection impairment when the inducing display was out-of-phase with the subject's horizontal head motion. Specifically, when large amplitude horizontal display oscillation was used, in-phase head-and-display oscillation produced significantly stronger vection in depth strength ratings than out-of-phase head-and-display oscillation. This latter result is consistent with recent findings of Ash et al (2011) that consistent multi-sensory information about horizontal self-motion can improve vection.

Our failure to find dramatic vection impairments in the above 'sensory conflict' conditions is highly consistent with the findings of several experimental (Berthoz et al 1975; Wong and Frost 1981) and neurophysiological imaging (Brandt et al 1998; Kleinschmidt et al 2002) studies. Taken together, these studies suggest that there may be a reciprocal inhibitory interaction between the visual and vestibular systems during vection. We believe that these current psychophysical and past neurophysiological findings are all consistent with the notion that vision may downplay or override conflicting vestibular information about self-motion during situations of sensory conflict (particularly in situations of extreme sensory conflict). However, if the visual system was overriding or downplaying vestibular information in extreme sensory conflict situations, why did we find a vection impairment in depth-head-and-horizontal-display oscillation conditions (compared to ecological head-and-display motion conditions)?

One possible explanation was that depth-head-and-horizontal-display-oscillation conditions produced larger head oscillation amplitudes than the other three types of experimental conditions (depth-head-and-display-oscillation, horizontal-head-and-display-oscillation, horizontal-head-and-depth-display-oscillation). However, when we performed a regression analysis on these data, we found that head movement

amplitudes did not significantly predict vection in depth strength ratings. Therefore, we believe that differences in physical head movement amplitudes cannot explain this particular vection strength finding (or in fact any of our other vection strength effects).

Alternatively, it was possible that depth-head-and-horizontal-display oscillation generated weaker ratings of vection in depth than depth-head-and-display oscillation because it provided less visual information about self-motion in depth (since subjects were only asked to rate the motion in depth component of their vection – not their sideways or their overall vection). We tested this possibility in the control experiment described below.

3. 2. Experiment 2. Effects of conflicting head and display motion on sideways vection

This control experiment was identical to Experiment 1, with only one exception: subjects rated their perceived sideways self-motion, rather than their perceived self-motion in depth. Thus, we measured the sideways vection induced by our displays during depth-head-and-display-oscillation, depth-head-and-horizontal-display oscillation, horizontal-head-and-display oscillation and horizontal-head-and-display oscillation.

3.1 Method

3.1.2 Subjects. Eight naïve psychology students (3 male and 5 female; mean age = 24.8, SD = 3.79) at the University of Wollongong participated in this experiment. All subjects met the same selection criteria as Experiment 1.

3.2 Results

As in Experiment 1, we again performed Bonferroni-corrected planned contrasts on our sideways vection data (controlling for the family-wise error rate at 0.05).

3.2.1. Depth Axis Head Oscillation Conditions

We found that both in-phase ($F(1, 7) = 10.76, p = .05$) and out-of-phase ($F(1, 7) = 12, p = .04$) depth-head-and-display oscillation resulted in significantly weaker sideways vection ratings than depth-head-and-horizontal-display oscillation.

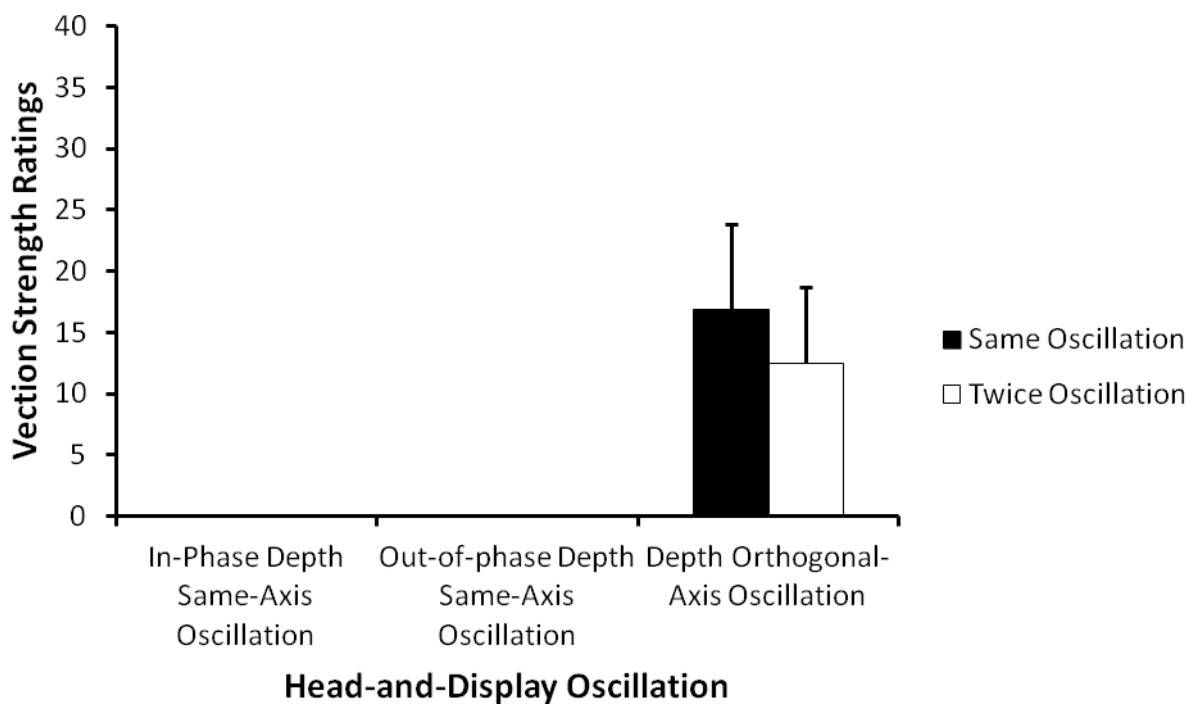


Figure 8. Effect of in-phase depth same-axis, out-of-phase depth same-axis and depth orthogonal-axis oscillation on the strength of sideways vection (0-100) as a function of gain (either same or twice the amplitude expected from the subjects head movements). Note that the depth-head-and-display conditions generated no sideways vection. Error bars depict the standard error of the mean.

3.2.2 Horizontal Axis Head Oscillation Conditions

We also found that both in-phase ($F(1, 7) = 13.12, p = .03$) and out-of-phase ($F(1, 7) = 12.85, p = .04$) horizontal-head-and-display-oscillation resulted in significantly stronger sideways vection than horizontal-head-and-depth-display-oscillation. We found no significant difference in sideways vection between in-phase and out-of-phase horizontal-head-and-display oscillation conditions ($F(1, 7) = .028, p > .05$).

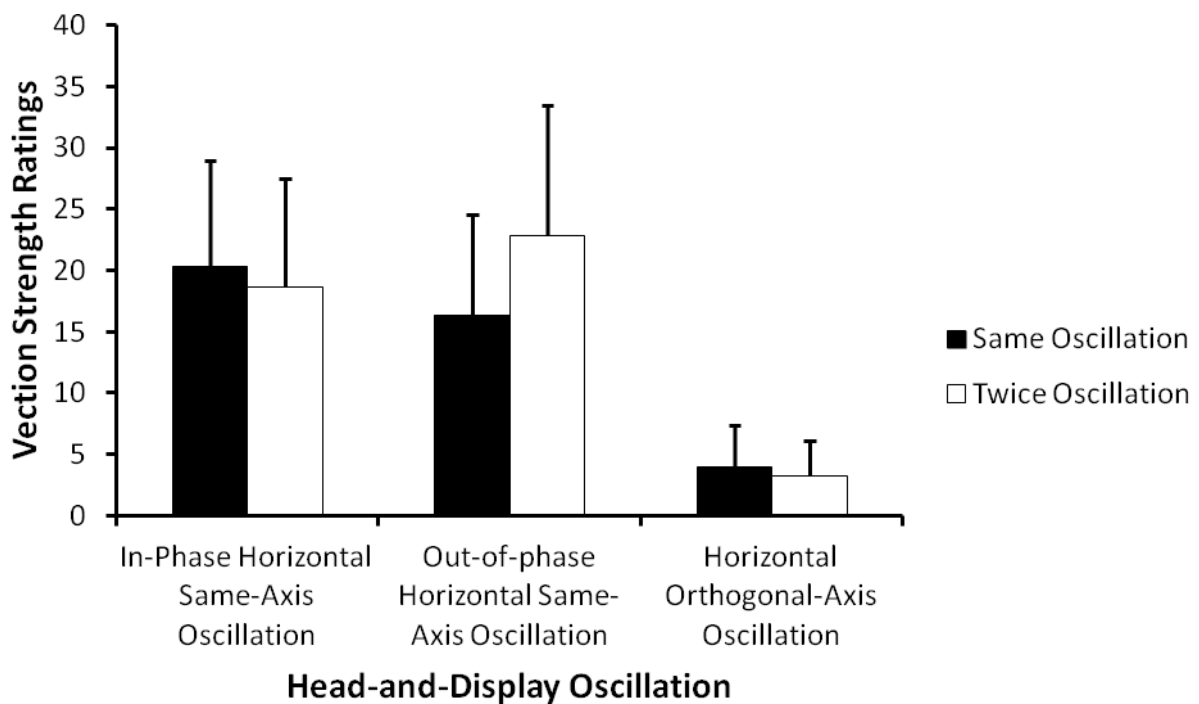


Figure 9. Effect of in-phase horizontal same-axis, out-of-phase horizontal same-axis and horizontal orthogonal-axis oscillation on the strength of sideways vection (0-100) as a function of gain (either same or twice the amplitude expected from the subjects head movements). Error bars depict the standard error of the mean.

3.3 Discussion

In Experiment 1, we found that depth-head-and-display oscillation resulted in stronger vection in depth than depth-head-and-horizontal-display oscillation. It was noted by a reviewer that one potential explanation for this difference was that the former condition provided more visual information about self-motion in depth. Consistent with this notion, the current experiment found that depth-head-and-horizontal-display-oscillation resulted in stronger sideways vection than depth-head-and-display-oscillation. However, inconsistent with this notion, we also found a significant difference in sideways vection between horizontal-head-and-display oscillation (both in- and out-of-phase) and horizontal-head-and-depth-display oscillation conditions. In Experiment 1, no significant difference was found between these two conditions in terms of vection in depth. Furthermore, in Experiment 1, we found a significant difference in vection in depth between in-phase and out-of-phase horizontal-head-and-display oscillation, but no significant difference in sideways vection between these two conditions was found in the current experiment. Therefore, it does not appear that our findings can be simply explained by differences in the degree of simulated depth and/or sideways self-motion.

4. General Discussion

In the current experiments we compared the vection induced by consistent and conflicting patterns of multisensory information about the direction and axis of self-motion. Observers viewed displays simulating self-motion in depth while physically oscillating their heads left-right or back-forth. Sensory conflict was generated by the visual display either moving in a non-ecological direction, or along an orthogonal-axis, or not at all, in response to the subject's physical head motion. Overall, we found that directional and axis based sensory conflicts produced surprisingly little vection

impairment (relative to ecological conditions where all of the available self-motion information was consistent with the display). Below we discuss the rather modest vection impairments produced by some (but not all) of these conditions of (presumed) sensory conflict.

Experiment 1 measured ratings of vection in depth during horizontal-head-and-display, horizontal head-and-depth-display, depth-head-and-display, and depth-head-and-horizontal-display oscillation conditions. We found that when subjects moved their heads horizontally, there was a modest impairment in vection in depth ratings during out-of-phase (compared to in-phase) horizontal display oscillation, but no impairment during depth display oscillation. By contrast, when subjects oscillated their heads in depth, we found a modest impairment in vection in depth ratings during horizontal display oscillation, but no significant impairment during out-of-phase depth display oscillation (compared to in-phase depth-head-and-display motion).

A check of our head tracking data confirmed that these differences in vection in depth strength ratings could not be explained by condition-based differences in physical head movement amplitudes. Next, we performed a control experiment to determine whether vection in depth impairments were simply due to some conditions producing less visual information about self-motion in depth than other conditions. However, the sideways vection strength ratings obtained in Experiment 2 (for the same conditions tested in Experiment 1) were also not compatible with this explanation.

In general, the current findings support the notion that vision can downplay or override conflicting vestibular information about self-motion during situations of sensory conflict (See also Berthoz et al 1975; Brandt et al 1998; Kleinschmidt et al 2002; Wong and Frost 1981). Why then did vection appear to be impaired in some sensory conflict conditions but not in others? One potential explanation of the current

findings might be that: (i) when sensory conflict produced by the particular condition was extreme, vestibular information was downplayed and/or ignored and, as a result, vection was often unimpaired (relative to ecological/consistent multisensory conditions); and (ii) when sensory conflict by the condition was only modest, both visual and vestibular self-motion information were utilised and vection was reduced/impaired as a result (compared to ecological/consistent multisensory conditions). We had expected our novel orthogonal-axis head-and-display motion conditions might generate particularly salient sensory conflicts (since even if the vestibular system is unable to determine conflicts in the direction of self-motion given the specific head speeds (~ 0.64 Hz) of the current experiment, it should still be able to readily detect the axis of physical head acceleration)³. Consistent with this notion, we found that horizontal-head-and-depth-display oscillation produced no significant vection impairment (compared to in-phase horizontal-head-and-display oscillation). However, if the visual system was overriding or downplaying vestibular information during orthogonal axis conditions, why did we still find a vection impairment in depth-head-and-horizontal-display oscillation (compared to depth-head-and-display oscillation)?

It is also possible that these (and other) discrepancies in vection strength ratings were due to axis-based differences in vestibular sensitivity. Lepecq and colleagues (Giannopulu and Lepecq 1998; Lepecq et al 1999) have previously proposed that there are differences in vestibular sensitivity for self-motion along the vertical and depth

³ One reviewer suggested that in fact the opposite might have been the case. This reviewer proposed that same-axis out-of-phase conditions might have generated greater sensory conflict than orthogonal-axis out-of-phase conditions – since the angular differences in the directions of the head and display motion in each case were 180 degrees for the former and 90 degrees for the latter conditions respectively. This might explain why we found a vection impairment for out-of-phase horizontal-head-and-display oscillation, but not for horizontal-head-and-depth-display oscillation (relative to in-phase head-and-display oscillation). However, this still does not explain why we found a vection impairment for depth-head-and-horizontal-display oscillation, but not for out-of-phase depth-head-and-display oscillation (relative to in-phase depth-head-and-display oscillation).

axes. According to this notion, the level of visual-vestibular conflict might have differed between the two orthogonal-axis conditions - with the vestibular system being more sensitive to back-forth head motions than to left-right head motions. Similarly, differences in vestibular sensitivity could also underlie the following same-axis condition findings: (i) vection was found to be similar for in-phase and out-of-phase depth-head-and-display oscillation conditions; but (ii) vection was superior for in-phase compared to out-of-phase horizontal-head-and-display oscillation conditions.

Another possible explanation for why depth-head-and-horizontal-display oscillation might have impaired vection in depth was that this condition disrupted the available depth information in the display. Previous studies (Palmisano 1996; 2002; Telford et al 1992) have shown that: (i) depth information can be important for inducing a compelling illusion of self-motion; and (ii) disruptions to this information can impair vection (e.g. Palmisano et al, 2003, found an advantage for coherent perspective jitter compared to incoherent perspective jitter in stationary observers). In the current experiment, when subjects oscillated their heads back-and-forth in the orthogonal-axis conditions, the self-motion display would have only oscillated horizontally (it would not have expanded/contracted in response to these head movements). As a result, the local optical sizes of the individual objects in the display would not have changed by differing amounts consistent with their simulated position in 3-D space, which may have impaired vection (see Palmisano, 1996). By contrast, in the horizontal-head-and-depth-display oscillation conditions, the display expanded and contracted in response to the observer's head movements. Even though these display motions were inconsistent with the observer's physical head movements, the individual objects would have still changed in optical size appropriately for their simulated

positions in 3-D space, which could explain why vection was not impaired in these conditions.

It should be noted that we could only check eye-movements in the current experiments using a monocular eye tracking system⁴ and were, therefore, unable to fully explore the role of compensatory eye movements during our different self-motion conditions. Future studies would benefit from using a binocular eye tracking system to gain a more comprehensive understanding of the role that radial flow vergence eye movements played during orthogonal-axis conditions. Another limitation of the current experiment, as noted by a reviewer, was that we only asked subjects to rate vection in depth. It would have also been useful to have subjects rate their overall vection, rather than getting them to parse this experience into sideways vection and/or vection in depth. Considering there could be an asymmetry in vestibular sensitivity to certain self-motion axes, it may also be important for future research to examine other head oscillation types, such as vertical head oscillation (up and down head movements) updated as either vertical, depth or horizontal oscillation.

In conclusion, the take-home message of this study is that vection appears to be remarkably robust to sensory conflict. In our experiment, only a subset of the expected sensory conflict situations were found to impair vection (compared to conditions which provided consistent multisensory self-motion stimulation). Consistent with previous experimental and neurophysiological studies, we suggest that the visual system often overrides or downplays conflicting vestibular information about self-motion.

⁴ In all of the experimental conditions, subjects were asked to fixate on a green dot in the centre of the display. If subjects accurately maintained fixation on this dot, horizontal head movements should have produced similar (predominantly) horizontal eye-movements in both the same-axis and orthogonal-axis conditions (despite the display moving in depth instead of horizontally in the latter case). Similarly, back-and-forth head movements should have generated similar (predominantly) vertical eye-movements in both same-axis and orthogonal-axis conditions. We tracked the (monocular) eye-movements made by one subject when viewing all of these experimental displays. His horizontal and vertical eye-movement traces were consistent with both of the above predictions.

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Table 1. *Regression coefficients from individual analyses of subjects' head movement amplitude and vection in depth strength data from Experiment 1.*

Subject	β coefficients
1	0.97
2	0.85
3	-0.01
4	-2.52
5	12.17
6	-0.58
7	0.79
8	-4.86
9	-4.68
10	-0.58
11	0.08
12	-0.54
13	-0.38
14	-0.7
15	-2.21
16	1.01
17	-2.62
18	-7.3
19	-0.17
20	-0.7
21	3.62
22	-3.32
23	0.14
24	4.18
25	0.25
<i>M</i>	-0.28
<i>SE</i>	0.73
<i>t</i>	-0.4

Note: Our subjects' head movement amplitudes were not found to significantly predict their vection in depth strength ratings ($p > .05$).