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Coherent perspective jitter induces visual illusions of self-motion

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Abstract. Palmisano et al (2000 *Perception* **29** 57 – 67) found that adding coherent perspective jitter to constant-velocity radial flow improved visually induced illusions of self-motion (vection). This was a surprising finding, because unlike pure radial flow, this jittering radial flow should have generated sustained visual – vestibular conflicts — previously thought to always reduce/impair vection. We attempted to ascertain the essential stimulus features for this jitter advantage for vection by examining three novel types of jitter display. While adding incoherent jitter to radial flow was found to impair vection, adding coherent non-perspective jitter had little effect on this subjective experience (contrary to the notion that jitter improves vection by reducing adaptation to radial flow). Importantly, we found that coherent perspective jitter not only improves the vection induced by radial flow, but it also appears to induce modest vection by itself (demonstrating that vection can still occur when there is an extreme mismatch between actual and expected vestibular activity). These results suggest that the previously demonstrated advantage for coherent perspective jitter was due (in part at least) to jittering vection combining with forwards vection in depth to produce a more compelling overall vection experience.

1 Introduction

Research has shown that the visual and vestibular systems play particularly important roles in the perception of self-motion (Dichgans and Brandt 1978; Howard 1982). The visual system can detect any type of self-motion (active or passive, linear or rotary, constant-velocity, or accelerating) from the optic flow presented to the moving observer (Brandt et al 1973; Johansson 1977; Lishman and Lee 1973). However, the vestibular system of the inner ear can only detect accelerations of the head [based on the inertia of the fluid in the semicircular canals and the otoconia of the otolith organs (Benson 1990; Brandt and Dieterich 1999; Howard 1986; Lishman and Lee 1973)]. The prevailing explanation of how these two sensory systems interact to produce the perception of self-motion will be referred to henceforth as 'visual – vestibular conflict' theory (eg Zacharias and Young 1981).(1) According to this theory, when stationary observers view a motion-picture taken inside a car accelerating from rest up to a constant velocity, they should initially feel that they are stationary owing to the following visual – vestibular conflict: their optic flow indicates self-acceleration but the vestibular activity that normally accompanies this type of self-acceleration is absent. A visually induced illusion of self-motion (referred to as vection) should only occur later, during the motion-picture segment representing constant-velocity linear self-motion, since vestibular activity would not be expected to accompany this type of optic flow.

According to Zacharias and Young's theory: (i) visual – vestibular conflict (eg the absence of expected vestibular activity for a particular optic-flow pattern) should always

(1) This visual – vestibular conflict theory is not accepted by all researchers. For example, Riccio and Stoffregen (1991) argue that there are no situations of sensory conflict, only situations of 'nonredundancy'. They propose each (redundant/nonredundant) pattern of multimodal stimulation specifies a specific self-motion. For example, a nonredundant pattern of multisensory stimulation, containing only visual information that the observer is swaying, could specify sway on a nonrigid surface.

reduce/impair vection; and (ii) the degree of vection impairment should increase with the discrepancy between the actual and expected vestibular activity. Consistent with these predictions, research has shown that circular vection onset latencies are reduced when visual and vestibular inputs are initially consistent (Brandt et al 1974; Melcher and Henn 1981; Wong and Frost 1981), and that providing conflicting vestibular input during saturated circular vection can destroy this experience (Teixeira and Lackner 1979; Young et al 1973). Similarly, in a more recent study, Giannopulu and Lepecq (1998) argued that linear vection in depth should generate more salient visual – vestibular conflicts than linear vection along the vertical axis, since vestibular sensitivities for self-motion in depth tend to be higher than those for vertical self-motion. Consistent with visual – vestibular conflict theory, they found that it took significantly longer to induce linear vection in depth than linear vection along the vertical axis. In a follow-up study, Lepecq and colleagues (1999) directly compared participants' vestibular thresholds for detecting real vertical self-motions to their onset latencies for vertical vection. They found that participants with higher vestibular sensitivities (ie those who were presumably more prone to experience visual – vestibular conflicts) were more likely to have longer vertical-vection onset latencies.

While there is much support for the visual – vestibular conflict theory, the recent findings of a study by Palmisano et al (2000) provide an interesting challenge to this theory in its current form. In this study, stationary observers were shown computer-generated displays of either (i) pure radial flow—simulating constant-velocity forwards self-motion in depth (expected to produce minimal/transient visual – vestibular conflict); or (ii) radial flow with added coherent perspective jitter—simulating constant-velocity forwards self-motion combined with continuous, random horizontal and/or vertical impulse self-accelerations (expected to produce significant and sustained visual – vestibular conflict). Contrary to the notion that visual – vestibular conflict always impairs vection, jittering radial flow was found to induce vection that started sooner and lasted longer than the vection produced by non-jittering radial flow, even though the vestibular stimulation corresponding to the jitter was absent. Furthermore, jittering displays thought to produce more salient visual – vestibular conflicts were found to produce vection that was at least as compelling as those thought to produce lesser visual – vestibular conflicts. For example, displays where jitter occurred along both the horizontal and vertical dimensions did not induce significantly different vection onsets or durations to displays where jitter occurred along only one of these dimensions. This study was, however, unable to determine the manner in which coherent perspective jitter improved the experience of self-motion. The jitter advantage for vection was found to be very robust to manipulations of jitter axes (horizontal/vertical), jitter magnitudes (ranging from 0 to either $\frac{1}{3}$, $\frac{1}{4}$, or $\frac{1}{5}$ of the simulated forwards displacement of 4 m s^{-1}), and jitter update rates (1 – 30 Hz). However, since reducing the magnitudes and the update rates of the random jitter both resulted in a diminished jitter advantage, it was concluded that jittering displays could not have been improving vection by mimicking the optic-flow patterns produced by naturally occurring self-motions.(2)

The original study provided little insight into the cause of the jitter advantage for vection (coherent perspective jitter was always found to improve the vection induced by radial flow). The current study was aimed at identifying which features of the coherent perspective jitter were responsible for these improvements. In separate experiments we examined whether the jitter advantage was restricted to optic-flow patterns with coherent

(2) Walking, running, and even passive transportation usually produce additional random and oscillatory components in the retinal flow—especially when the terrain is uneven (Cutting et al 1992). However, the jitter examined in these experiments typically had larger magnitudes and was updated more frequently than the random and oscillatory flow components produced by most common self-motions.

(as opposed to incoherent) jitter, perspective (as opposed to non-perspective) jitter, and both radial and jittering components (as opposed to just the jittering component alone). Experiments 1 and 2 were designed to examine the vection produced by adding three different types of global jitter to radial flow: (i) incoherent jitter—where the objects jittered independently of each other by different amounts and in different directions; (ii) coherent perspective jitter—where all of the objects jittered together, but objects which were further away jittered less [identical to the jitter condition used in the Palmisano et al (2000) study]; and (iii) non-perspective jitter—where all of the objects were jittered by identical amounts irrespective of their simulated location in depth.[3] In addition, experiment 3 was carried out to examine whether coherent perspective jitter was sufficient to induce vection when it was presented without radial flow (a potentially important control condition which was not examined in the original jitter study). As in the earlier study, the vection onsets and durations produced by these different jittering displays were compared to the baseline vection produced by non-jittering radial flow (figure 1 provides a graphical representation of the stimuli used in experiments 1 and 2).

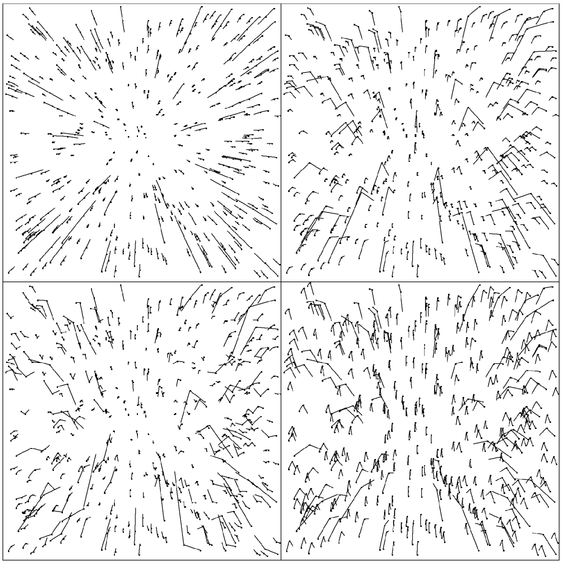

Figure 1. Velocity-field representations of the jittering and non-jittering optic flow used in experiments 1 and 2. The top-left diagram represents a non-jittering pattern of radially expanding flow—consistent with forwards self-motion in depth through a 3-D cloud of randomly positioned objects. The remaining diagrams were all based on this same radially expanding flow pattern with one of three different types of jitter added: (i) coherent perspective jitter (top right); (ii) incoherent jitter (bottom left); and (iii) coherent non-perspective jitter (bottom right).

2 Experiment 1: Effect of incoherent jitter on vection in depth

In experiment 1, we compared the vection induced by radial flow either with no jitter, coherent perspective jitter, or incoherent jitter. As in the previous study, displays with coherent perspective jitter simulated constant-velocity forwards self-motion combined with continuous, random horizontal and/or vertical impulse self-accelerations. Conversely, incoherent jittering displays approximated the optic flow produced by constant-velocity forwards self-motion through a snowstorm/sandstorm. While the addition of coherent jitter to radial flow should produce a situation of sustained visual–vestibular conflict, we predicted that incoherent jitter would result in little sensory conflict—on the assumption that horizontal/vertical impulse accelerations would be attributed to self-motion in the coherent jittering displays and object motion in the

[3] Pilot studies and subject debriefing following the experiments confirmed that radial flow with coherent perspective jitter produced illusory self-motion along all three body axes (horizontal, vertical, and depth). Many subjects spontaneously reported that experiences of self-motion induced by: (i) radial flow with coherent perspective jitter were similar to walking under the influence of alcohol; (ii) radial flow with incoherent jitter were similar to driving through a sandstorm/snowstorm; and (iii) radial flow with coherent non-perspective jitter were similar to driving over an unsealed road.

incoherent jittering displays. However, despite the predicted absence of visual–vestibular conflict in incoherent jittering displays, incoherent jitter was expected to impair vection because: (i) it might cause difficulties extracting the radial component of the flow (which depicted both the self-motion in depth and the 3-D layout of the environment); and/or (ii) the local/independent object motions in these displays might bias observers to perceive the flow as being due to object motion, rather than self-motion.

2.1 *Method*

2.1.1 *Participants.* Nine male and eight female undergraduate psychology students (aged between 17 and 34 years) participated in this experiment. All had normal or corrected-to-normal vision and had not previously experienced illusions of self-motion in the laboratory. Two additional participants discontinued the experiment after experiencing discomfort/disorientation during testing.

2.1.2 *Design.* Two independent variables were manipulated in this experiment: (i) Jitter type—displays were radially expanding patterns of optic flow with either no jitter, coherent jitter, incoherent-magnitude jitter, or incoherent-magnitude-direction jitter. (ii) Jitter direction—when present, jitter occurred along either the horizontal axis, the vertical axis, or both the horizontal and vertical axes. The simulated forwards speed of self-motion was always 4 m s^{-1} and jitter magnitudes ranged from 0 to $\frac{1}{3}$ of this forwards speed. The coherent and incoherent jitter were both updated 30 times per second (as opposed to the radial component of the flow which was updated 70 times per second). While this jitter occurred at a higher frequency than is typically encountered during normal observer motion, there are instances where such high-frequency vibrations might occur [eg transport in vehicles (Guignard 1960; Martin et al 1984; Wells and Griffin 1984)]. Since the sign and magnitude of this jitter varied randomly from one jitter frame to the next, it is best represented by a range of frequencies (both high and low) limited by the 30 Hz update rate. All displays simulated self-motion through a 3-D cloud of 400 randomly positioned objects.

Two dependent variables were measured for each trial: (i) the latency to vection onset; and (ii) the total vection duration. As in previous vection studies (Andersen and Braunstein 1985; Telford et al 1992; Telford and Frost 1993), trials which did not induce vection were assigned a vection latency equal to the total trial length and a vection duration of zero. Although the inclusion of these no-vection trials would have inflated the latencies and deflated the durations obtained for weaker vection stimuli, they were necessary to determine the relative effectiveness of the different jitter conditions for inducing vection. Re-analysis of the data with the no-vection trials excluded showed that this manipulation had little effect on the overall patterns of significance for the onset and duration data.(4)

2.1.3 *Apparatus.* Displays were generated on Macintosh G4 personal computer and projected onto a mylar screen by a Sanyo XGA 2200 projector (resolution, in pixels, was 1280 horizontal × 1024 vertical). This screen subtended a visual angle of 64 deg horizontal × 64 deg vertical when viewed through a large, cylindrical viewing tube attached to the head-and-chin rest 1.75 m distant (the tube blocked the observer's view of his/her stationary surroundings—which included the screen frame). Stereopsis and occlusion always indicated that the inducing display—seen at the far end of this viewing tube—was in the background [research suggests that optimal vection is produced when the

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(4) Across the three experiments, the same main effects were significant for the duration data, irrespective of whether the no-vection trials were included or not. However, for the onset data, two main effects were altered: (i) the coherent jitter advantage failed to reach significance in experiment 2; and (ii) the advantage of radial flow over jitter alone failed to reach significance in experiment 3.

foreground of the environment is stationary and its background is in motion (Nakamura and Shimojo 1999; Ohmi and Howard 1988)].

2.1.4 *Visual displays.* Both jittering and non-jittering optic flow consisted of moving blue filled-in squares (with a luminance of 3 cd m^{-2}) on a black background (0.03 cd m^{-2}). All displays had a refresh rate of 75 Hz and were symmetrical about both the horizontal and vertical axes. Non-jittering displays simulated a 4 m s^{-1} forwards self-motion in depth through a 3-D cloud of randomly positioned filled-in square objects. This was achieved by increasing the velocity and total area (0.07 deg – 1.21 deg) of each object as it appeared to approach the observer (ie radially expanding optic flow with additional changing-size cues to motion in depth). As objects disappeared off the edge of the screen, they were replaced at the opposite end of space (a simulated distance of 20 m along the depth axis) at the same horizontal and vertical coordinates. To reduce the sensation of their sudden appearance, these objects were initially replaced as dots which were slightly darker (1.6 cd m^{-2}) than the nearer objects.

Coherent and incoherent jittering displays were identical to non-jittering displays, with the sole exception that horizontal and/or vertical jitter was added to the optic flow. As in the original jitter study, coherent jittering displays simulated combined forwards observer motion in depth (4 m s^{-1}) with random horizontal and vertical impulse accelerations. This coherent perspective jitter was created in the following manner. First, the absolute magnitude of horizontal and/or vertical jitter for each jittering frame was randomly selected from a uniform distribution ranging from 0 to $\frac{1}{3}$ of the simulated forwards displacement. Its direction (left/right for horizontal jitter and up/down for vertical jitter) changed randomly from one jitter frame to the next. This signed jitter was then given the appropriate perspective transformation before it was applied to objects at different simulated locations in depth—ie the jitter component was less for more distant objects.

Incoherent jittering displays depicted forwards self-motion in depth (4 m s^{-1}) in the presence of additional horizontal and/or vertical object motions. At any one point in time, each object was assigned a different (as opposed to identical) absolute magnitude of horizontal and/or vertical jitter (as with coherent jitter, this was chosen from within the range from 0 to $\frac{1}{3}$ of the simulated forwards displacement). To ensure that the incoherent jitter range was equivalent to the coherent jitter range, a perspective transformation was also applied to this jitter. While this perspective transformation was not meaningful—since at any one point in time the absolute jitter magnitude was different for each object—it did result in an overall decrease in final jitter magnitude with increasing distance (see figure 1, bottom left). Two types of incoherent jitter were examined: (i) incoherent-magnitude jitter—different objects had different jitter magnitudes but a common jitter direction; (ii) incoherent-magnitude-direction-jitter displays—different objects not only had different jitter magnitudes but also different jitter directions (it proved difficult for participants to distinguish one type of incoherent jitter from the other).

2.1.5 *Procedure.* Subjects were told that they would be shown displays of moving objects and that: "Sometimes the objects may appear to be moving; other times you may feel as if you are moving. Your task is to press the mouse button down when you feel as if you are moving and hold it down as long as the experience continues. If you don't feel that you are moving then don't press the mouse button" (instructions modified from Palmisano et al 2000).(5)

(5) The instructions to participants in the original study were as follows: "Sometimes the objects may appear to be moving towards you; other times you may feel as if you are moving towards the objects." In the modified instructions used for the current experiments, all references to the direction of self-motion or object motion were removed, as the aim of these experiments was to examine whether coherent perspective jitter also induced illusions of horizontal/vertical self-motion as well as illusions of self-motion in depth.

Subjects were also informed that each display had a fixed duration of 3 min and an intertrial interval of 20 s. After two practice trials, the experimental displays were presented in a random order.

2.2 *Results*

Vection was reported in 164 of the 204 trials (seventeen subjects responding to twelve stimuli). Of the forty trials where vection was not induced, 4 had non-jittering displays, 17 had displays with incoherent-magnitude jitter, and 19 had displays with incoherent-magnitude-direction jitter (all coherent jitter trials induced vection). Separate repeated-measures ANOVAs were performed on the onset and duration data. A posteriori contrasts were performed when a significant F value was obtained.

Jitter type was found to produce significant main effects for both vection onsets ($F_{3,48} = 17.66$, $p < 0.0001$) and vection durations ($F_{3,48} = 37.17$, $p < 0.0001$). Consistent with the findings of the previous jitter study, displays with coherent jitter were found to produce significantly longer vection durations than displays without jitter ($F_{1,48} = 11.05$, $p < 0.006$) (see figure 2). However, while displays with coherent jitter produced on average shorter vection onsets than those without jitter, this difference failed to reach significance ($F_{1,48} = 1.63$, ns). As predicted, incoherent-magnitude jitter and incoherent-magnitude-direction jitter were both found to significantly impair vection, leading to significantly longer vection onsets ($F_{1,48} = 21.17$, $p < 0.0004$; $F_{1,48} = 18.04$, $p < 0.0009$) and significantly shorter vection durations ($F_{1,48} = 28.69$, $p < 0.0001$; $F_{1,48} = 30.19$, $p < 0.0001$) than coherent jitter and no-jitter displays. The vection onsets and durations found for displays with incoherent-magnitude jitter were not significantly different to those found for incoherent-magnitude-direction jitter ($F_{1,48} = 0.125$, ns; $F_{1,48} = 0.019$, ns).

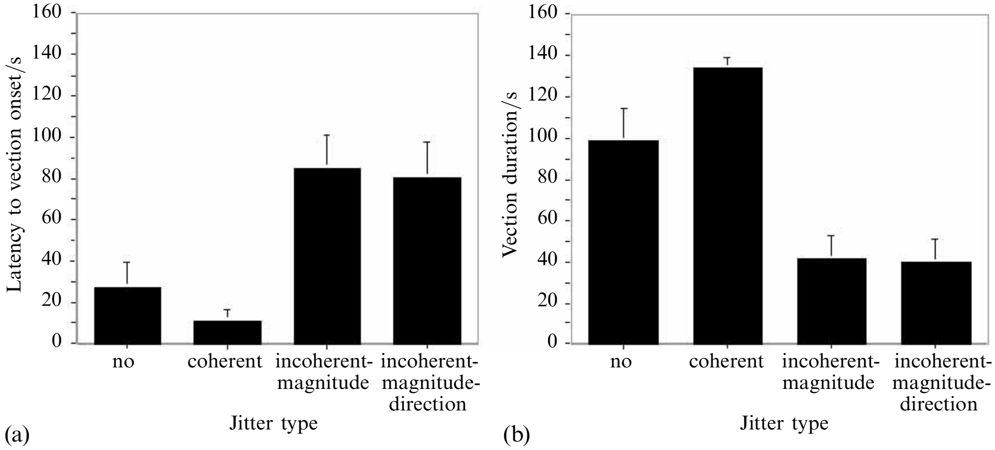

Figure 2. The effect of the type of jitter (no jitter, coherent jitter, incoherent-magnitude jitter, and incoherent-magnitude-direction jitter) on (a) the latency to vection onset and (b) the total vection duration. Error bars represent standard errors of the means.

Significant two-way interactions between jitter type and jitter direction were also found both for vection onsets ($F_{6,96} = 3.24$, $p < 0.0002$) and for vection durations ($F_{6,96} = 4.12$, $p < 0.001$) (see figure 3). Irrespective of the jitter type, displays with horizontal jitter did not produce significantly different vection onsets or durations to displays with vertical jitter (onsets: coherent, $F_{1,96} = 0.069$, ns; incoherent-magnitude, $F_{1,96} = 0.003$, ns; incoherent-magnitude-direction, $F_{1,96} = 1.95$, ns) (durations: coherent, $F_{1,96} = 0.335$, ns; incoherent-magnitude, $F_{1,96} = 0.079$, ns; incoherent-magnitude-direction, $F_{1,96} = 4.00$, ns). However, while displays with horizontal or vertical coherent jitter did not produce significantly different vection onsets ($F_{1,96} = 0.064$, ns)

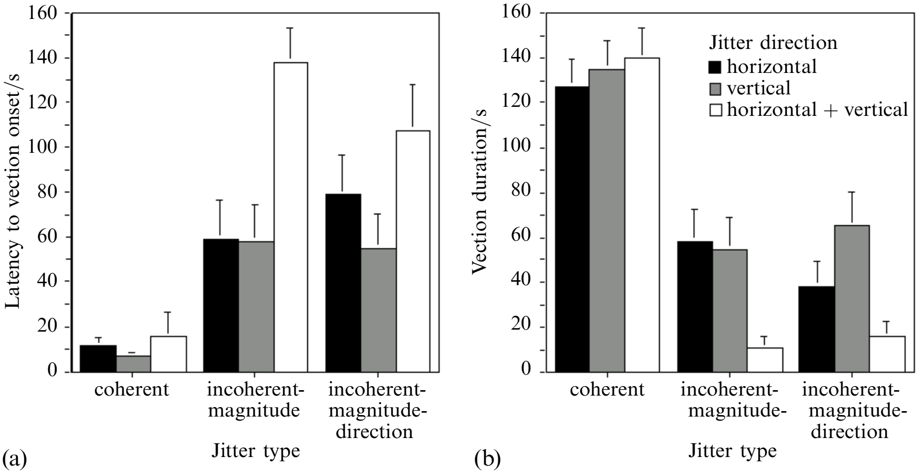

Figure 3. The effects of both the type of jitter and the direction of jitter (horizontal, vertical, or both horizontal and vertical) on (a) the latency to vection onsets and (b) the total vection duration. Error bars represent the standard errors of the means.

or durations ($F_{1,96} = 0.575$, ns) to combined horizontal and vertical coherent jitter, displays with combined horizontal and vertical incoherent-magnitude jitter produced longer vection onsets ($F_{1,96} = 27.65$, $p < 0.0001$) and shorter vection durations ($F_{1,96} = 15.18$, $p < 0.001$) than those with incoherent-magnitude jitter along only one dimension. Similarly, displays with combined horizontal and vertical incoherent-magnitude-direction jitter produced longer vection onsets ($F_{1,96} = 7.198$, $p < 0.02$) and shorter vection durations ($F_{1,96} = 9.55$, $p < 0.009$) than those with incoherent-magnitude-direction jitter along only one dimension.

2.3 *Discussion*

Consistent with ecology, only coherent jitter was found to improve the vection induced by radially expanding optic flow. Conversely, adding equivalent magnitudes of incoherent jitter to radial flow was found to significantly impair vection. Interestingly, displays with combined horizontal and vertical incoherent jitter were found to impair vection to a greater degree than those with incoherent jitter in only one dimension. This finding suggests that the vection impairments produced by incoherent jitter were due (in part at least) to this jitter acting as noise, which obscured the radial component of the flow (the signal required to induce vection in depth and to perceive the 3-D environment). Since displays where incoherent jitter occurred simultaneously along both dimensions would have had lower signal-to-noise ratios than displays with incoherent jitter along only one dimension, it would have been more difficult to extract the radial component from these horizontal and vertical jittering displays. However, it was also possible that incoherent jitter impaired vection by biasing the observer to perceive object motion (as opposed to self-motion). While coherent jitter was consistent with an accelerating horizontal/vertical self-motion by itself (hence producing the visual – vestibular conflict in these displays), incoherent jitter was incompatible with any type of self-motion—rather the random, independent motions it provided could only be consistent with object motion. Thus, independent object motion along two dimensions might have been more likely to bias the observer away from self-motion perception than object motion along only one dimension. Interestingly, the disruptive effects of incoherent-magnitude jitter on vection in depth were very similar to those of incoherent-magnitude-direction jitter. This finding suggests the large differences in jitter magnitude between different objects at any one point in time obscured the presence of jitter direction differences.

3 Experiment 2: Effect of non-perspective jitter on vection in depth

Experiment 1 demonstrated that global jitter has to be coherent if it is to improve vection in depth. In this experiment, we examined whether the jitter advantage for vection also requires that the coherent jitter be altered according to perspective (so that the image motion due to the jittering component of the flow is less for more distant objects). While the coherent perspective jitter used previously was similar to 'camera shake', the coherent non-perspective jitter used in this experiment was similar to 'TV shake'—all objects were displaced horizontally/vertically by identical amounts (the only perspective displacements were provided by the radial component of the flow, which represented forwards self-motion in depth). In principle, both coherent perspective jitter and coherent non-perspective jitter might improve vection by reducing adaptation to the optic flow. Consider the time course of the vection induced by a non-jittering pattern of radial flow. As the observer adapts to this repetitive and unchanging optic flow, his/her impression of self-motion in depth should continually diminish in magnitude (Denton 1980; Schmidt and Tiffin 1969). However, if a reasonable amount of global jitter (either perspective or non-perspective) is added to the radial flow, it should become more difficult to adapt to this combined flow and hence there might be little or no decline in vection over time.

3.1 *Method*

The apparatus and procedure were identical to those of experiment 1, with the sole exception that display durations were reduced from 3 min down to 1 min (to allow more replications of each of the experimental conditions).

3.1.1 *Participants.* Six male and nine female undergraduate psychology students (aged between 18 and 31 years) participated in this experiment. All had normal or corrected-to-normal vision and had not previously experienced illusions of self-motion in the laboratory. Three additional participants discontinued the experiment after experiencing motion sickness.

3.1.2 *Design.* Two independent variables were manipulated in this experiment: (i) Jitter type—displays were radially expanding patterns of optic flow with either no jitter, coherent perspective jitter, or coherent non-perspective jitter. (ii) Jitter direction—when present, jitter occurred along either the horizontal axis, the vertical axis, or both the horizontal and vertical axes. Unlike experiment 1, this jitter was always coherent.

3.1.3 *Visual displays.* Displays both with and without coherent perspective jitter were identical to the coherent jittering and non-jittering displays used in experiment 1. Displays with coherent non-perspective jitter had identical radial-flow components to these displays. The coherent non-perspective jitter was created in the following manner. As with coherent perspective jitter, the absolute magnitude of the horizontal and/or vertical jitter for each jittering frame was randomly selected from within the range from 0 to $\frac{1}{3}$ of the simulated forwards displacement. However, instead of applying the appropriate perspective transformation to the jitter for objects at different simulated depths (so that objects which appeared to be further away jittered less), the same inappropriate perspective transformation was applied to the jitter for all objects. On each jittering frame, the jitter magnitude for each object was divided by the same value. This artificial common 'depth' value changed continually throughout the display—each one was randomly chosen from within the range of 1 m to 20 m (ie the extent of the simulated environment along the depth axis). The aim of this manipulation was to produce coherent non-perspective jitter that had (on average) a similar magnitude to the coherent perspective jitter.

3.2 *Results*

Vection was reported in 256 of the 270 trials (fifteen subjects responding to nine stimuli with two replications). Of the 14 trials where vection was not induced, 6 had non-jittering displays and the remaining 8 had displays with non-perspective jitter (all perspective jitter trials induced vection). Separate repeated-measures ANOVAs were performed on both the onset and duration data (the means are shown in figures 4a and 4b). A posteriori contrasts were performed when a significant F value was obtained.

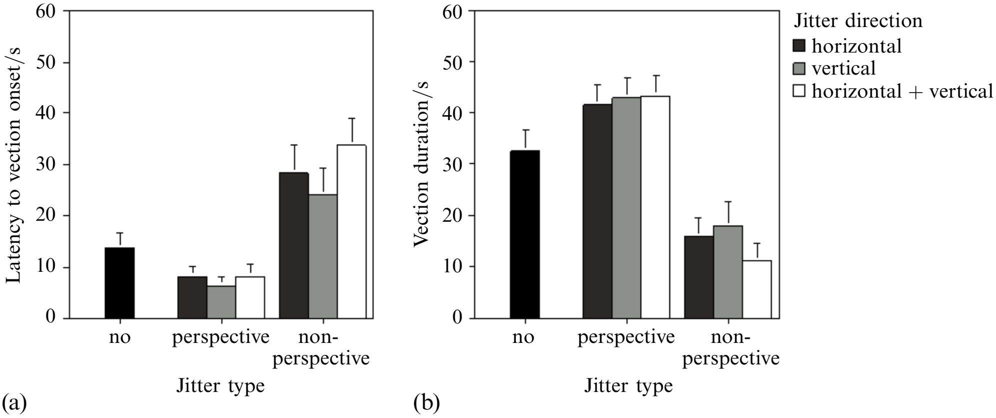

Figure 4. The effect of the type of jitter (no jitter, perspective jitter, and non-perspective jitter) on (a) the latency to vection onset and (b) the total vection duration. When present, jitter occurred in either the horizontal, vertical, or both the horizontal and vertical directions. Error bars represent standard errors of the means.

As predicted, jitter type was found to produce significant main effects both for vection onsets ($F_{2,28} = 5.30$, $p < 0.01$) and for vection durations ($F_{2,28} = 5.82$, $p < 0.007$). While perspective jitter was found to produce significantly shorter vection onsets ($F_{1,28} = 7.26$, $p < 0.02$) and significantly longer vection durations ($F_{1,28} = 7.01$, $p < 0.02$) than non-jittering displays, non-perspective jitter was not found to produce significantly different vection onsets ($F_{1,28} = 0.057$, ns) or durations ($F_{1,28} = 0.291$, ns) from non-jittering displays. Jitter direction was not found to produce significant main effects for either vection onsets ($F_{2,28} = 3.102$, ns) or vection durations ($F_{2,28} = 0.892$, ns). No two-way interactions (ie between jitter type and jitter direction) reached significance in this experiment.

3.3 *Discussion*

Only coherent perspective jitter was found to improve vection above the levels produced by pure radial flow. Since non-perspective jitter did not significantly improve vection (relative to that induced by the non-jittering control), it seems unlikely that the perspective jitter advantage for vection was due to jitter reducing/preventing adaptation to the radial component of the flow. If this explanation was valid, then both coherent perspective and coherent non-perspective jitter should have improved vection (although not necessarily by similar amounts). It was also interesting to note that non-perspective jitter did not impair vection in depth—vection onsets and durations for displays with non-perspective jitter were not significantly different from those produced by non-jittering displays. So, unlike the incoherent jitter examined in experiment 1, non-perspective jitter did not appear to obscure the radial component of the combined flow. Rather, the radial component of the flow was extracted as accurately with non-perspective jitter as it was without.

Even though the coherent non-perspective jitter used in this experiment could have been consistent with a self-motion if it was presented alone (ie horizontal/vertical self-motion relative to a 2-D frontal-plane environment), it was incompatible with both the self-motion and the environment depicted by the radial component of the flow (forwards self-motion in depth relative to a 3-D cloud of objects). It appears that the inconsistent self-motion/layout information provided by the coherent non-perspective jitter was ignored by the visual system in favour of the dominant information about self-motion in depth provided by the radial component of the flow. However, it was possible that the consistent self-motion/layout information provided by coherent perspective jitter produced additional illusory horizontal/vertical self-motions, which enhanced the overall vection experience.

4 Experiment 3: Effect of jitter alone on vection

Experiments 1 and 2 have shown that adding coherent perspective jitter to radial flow shortens vection onsets and lengthens vection durations. This raises the following question: Are these vection improvements due to coherent perspective jitter enhancing the vection in depth induced by radial flow or are they due to coherent perspective jitter inducing additional horizontal/vertical vection? According to the latter possibility, if both the radial and jittering components induced vection, then their effects might be additive (eg resulting in shorter onsets and longer overall durations of vection). In experiment 3 we examined this possibility by comparing the vection induced by coherent perspective jitter alone to that induced by either pure radial flow or combined radial flow and coherent perspective jitter.

4.1 *Method*

The apparatus, visual displays, and procedure were identical to those of experiment 2, with the following exceptions. First, an additional jitter-only condition was included. Second, the jitter was always altered according to perspective (ie coherent perspective jitter).

4.1.1 *Participants.* Ten male and nine female postgraduate psychology students (aged between 23 and 32 years) participated in this experiment. All had normal or corrected-to-normal vision and had not previously experienced illusions of self-motion in the laboratory.

4.1.2 *Design.* Two independent variables were manipulated in this experiment: (i) Display type—displays consisted of either non-jittering radial flow, combined radial flow and coherent perspective jitter, or coherent perspective jitter alone. (ii) Jitter direction—when present, jitter occurred along either the horizontal axis, the vertical axis, or both the horizontal and vertical axes. For jittering displays, the absolute jitter range was always between 0 and $\frac{1}{3}$ of the forwards speed of 4 m s^{-1} represented by the pure radial flow (even when this radial component of the flow was absent).

4.2 *Results*

Vection was reported in 314 of the 342 trials (nineteen subjects responding to nine stimuli with two replications). All 28 non-vection trials had jitter-only displays. Separate repeated-measures ANOVAs were performed on both the onset and duration data (the means are shown in figures 5a and 5b). A posteriori contrasts were performed when a significant *F* value was obtained. As predicted, display type was found to produce significant main effects both for vection onsets ($F_{2,36} = 10.30$, $p < 0.002$) and for vection durations ($F_{2,36} = 20.48$, $p < 0.0001$). A posteriori contrasts revealed that while jittering radial displays produced longer vection durations than non-jittering radial displays ($F_{1,36} = 6.17$, $p < 0.03$), they did not induce significantly shorter vection

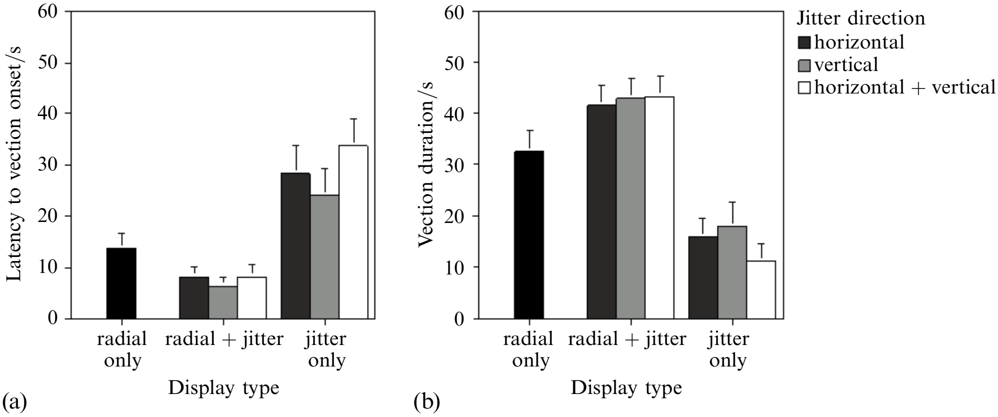

Figure 5. The effect of the display type (radial flow only, radial + jittering flow, and jitter only) on (a) the latency to vection onset and (b) the total vection duration. When present, jitter occurred in either the horizontal, vertical, or both horizontal and vertical directions. Error bars represent standard errors of the means.

onsets than non-jittering radial displays ($F_{1,36} = 1.75$, ns). Jitter-only displays were found to produce significantly longer vection onsets ($F_{1,36} = 9.59$, $p < 0.01$) and significantly shorter vection durations ($F_{1,36} = 14.94$, $p < 0.002$) than non-jittering radial displays. Jitter direction was also found to have a (marginally) significant main effect for vection onsets ($F_{2,36} = 3.35$, $p < 0.046$), but not for vection durations ($F_{2,36} = 0.94$, ns). Specifically, displays which jittered along both horizontal and vertical dimensions appeared to produce longer vection onsets than those which jittered along only one dimension ($F_{1,36} = 4.77$, $p < 0.04$). No two-way interactions (ie between jitter type and jitter direction) reached significance in this experiment.

4.3 *Discussion*

Interestingly, coherent perspective jitter was found to produce some sensation of self-motion on its own—although this horizontal and/or vertical vection(6) started later and was briefer than the vection induced by either jittering or non-jittering radial flow. This finding is consistent with the notion that the coherent perspective jitter advantage for vection is due to jittering vection and forwards vection combining to produce a more compelling vection experience. The finding that coherent perspective jitter alone induced less than optimal vection was not surprising for two reasons. First, since both the direction and magnitude of this vection was continually changing, it should have been difficult for the vection experience to develop to saturation. Second, unlike the non-jittering radial flow, coherent perspective jitter would have produced a visual – vestibular conflict. It is even possible that the sensory conflict produced by the jitter-only condition was more salient than the sensory conflict produced by the jittering-radial-flow-condition, since the former type of display simulated pure self-acceleration (sustained visual – vestibular conflict), while the latter simulated a mixture of both accelerating (sustained visual – vestibular conflict) and constant-velocity self-motion (minimal/transient visual – vestibular conflict).

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(6) Subject debriefing following this experiment confirmed that these jitter-only displays did in fact induce vection along the subject's horizontal/vertical axes. Preliminary research on the effect of coherent perspective jitter on visually induced postural sway appears to confirm this observation. In this study, both 'jittering radial' and 'jitter-only' displays produced greater transitional lateral sway in standing observers than 'non-jittering radial' displays.

5 Conclusions

We examined the effects of three different types of jitter on visually induced illusions of self-motion (coherent perspective jitter, coherent non-perspective jitter, and incoherent jitter). Of these three types of jitter, only coherent perspective jitter was found to improve the visual illusions of self-motion induced by radial flow. Experiment 1 showed that while coherent jitter improved vection in depth, equivalent levels of incoherent jitter impaired vection in depth. This vection impairment could have been due to the noisy jittering component obscuring the radial component of the flow—which in turn, would have made it more difficult for the visual system to accurately extract information about self-motion in depth and the 3-D layout of the environment from the combined flow. Alternatively, the presence of these independent object motions might have biased observers to perceive object motion, rather than self-motion. Experiment 2 showed that, unlike incoherent jitter, non-perspective jitter had little effect on the vection induced by radial flow. This finding was inconsistent with the notion that coherent global jitter was improving vection by preventing adaptation to the radial component of the flow, since this predicts that both perspective and non-perspective jitter should improve vection in depth. One possible explanation for this null finding (no improvement/no impairment) was that, because each object was jittered horizontally and vertically by equal amounts, the radial component of the flow was not obscured by this non-perspective jitter, which allowed the information about self-motion in depth and the 3-D layout of the environment to be accurately extracted from the combined flow.

Experiment 3 showed that coherent perspective jitter was able to induce the sensation of self-motion in the absence of radial flow. While the vection produced by these jitter-only displays was far from optimal—it started later and was briefer than the vection induced by pure radial flow or radial flow combined with coherent perspective jitter—this was an important finding. Previously, vection had only been induced by jittering displays which consisted of two components: a jittering component which simulated accelerating self-motions (vestibular activity was expected throughout the display for this component) and a radial component which simulated constant-velocity self-motion (no vestibular activity was expected for this component after a brief initial period). However, experiment 3 demonstrated that vection could be induced by jittering displays which represented pure self-acceleration (jitter-only displays simulated a situation of pure visual–vestibular conflict, where all of the visual motion should have been accompanied by vestibular activity). Thus, it appears that vection can be induced even when there is an extreme mismatch between the information provided by the visual and vestibular systems.

While the jitter advantage for vection appears inconsistent with much of the previous research on visual–vestibular interaction, the results of a recent psychophysiological study by Brandt and his colleagues (1998) appear to partially reconcile these discrepant findings. They examined the positron emission tomography (PET) activation of observers viewing optic-flow displays that either simulated a constant-velocity self-rotation about the roll axis or equivalent independent object motions. They subtracted the PET images of activated cortical areas obtained during non-vection trials from those obtained during vection, and found that vection activated the medial parieto-occipital visual area, while simultaneously deactivating the parieto-insular vestibular cortex. Brandt and his colleagues concluded that when self-motion perception is dominated by vision (eg driving a car at a constant velocity), vestibular information about self-motion is partially suppressed. Further, they claimed that this deactivation of the vestibular system was adaptive, since the vertical vestibular activity provided by car motions and/or secondary involuntary head accelerations often provide inadequate or misleading information about self-motion.

So the jitter advantage for vection appears to be due (in part at least) to a reduction in the observer's sensitivity to visual – vestibular conflicts during visual self-motion perception. This proposed inhibitory visual – vestibular interaction accounts for our current finding that the visual – vestibular conflicts produced by coherent (perspective/non-perspective) jitter do not significantly impair vection. However, it is unable to explain the vection improvements produced by adding coherent perspective jitter to radial flow. In principle, this jitter advantage could have been produced by horizontal/vertical jitter improving the impression of self-motion in depth and/or the 3-D layout of the environment. For example, it was possible that coherent perspective jitter improved vection by enabling changing-size detectors to extract more accurate information about direction/speed of self-motion in depth (since these inducing displays contained both motion perspective and changing-size cues to motion in depth). Consistent with this notion, Regan and Beverley (1980) have previously shown that estimates of the direction of object motion in depth become more accurate when (8 Hz) frontal-plane jitter was added to these changing-size cues.

However, since the present study has shown that coherent perspective jitter can induce modest vection by itself, it seems likely that the jitter advantage for vection was due (in part at least) to horizontal/vertical jittering vection combining with forwards vection in depth to produce a more compelling overall vection experience. For example, vection onsets could have been shortened if the jittering vection was induced earlier than the vection in depth. Similarly, vection durations might have been lengthened if jittering vection persisted during vection in depth drop-outs (and vice versa). However, if this additive account of the coherent perspective jitter advantage for vection is valid, then the lack of a similar advantage for non-perspective jitter suggests that jittering vection and vection in depth are only combined when they provide compatible information about self-motion and the environmental layout. The visual system appears to ignore the inconsistent self-motion/layout information provided by non-perspective jitter (indicating horizontal/vertical self-motion relative to a *2-D environment*) in favour of the dominant information about forwards self-motion in depth (through a *3-D environment*) provided by the radial component of the flow.

In conclusion, the current experiments have shown that only coherent perspective jitter can improve the vection induced by radial flow—non-perspective jitter had little effect on vection and incoherent jitter impaired this experience. We found little support for the notion that coherent jitter improved vection by reducing adaptation to the radial flow (which predicted that both coherent perspective and coherent non-perspective jitter would improve vection). However, our experiments have shown for the first time that coherent perspective jitter can induce modest vection by itself. This discovery suggests that the vection advantage for coherent perspective jitter is due to the following: (i) an inhibitory visual – vestibular interaction which favours visual self-motion information over conflicting vestibular information; and (ii) the consistent self-motion information in horizontal/vertical jitter combining with the forwards vection in depth to produce a more compelling overall vection experience.

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