Accelerating self-motion displays produce more compelling vection in depth

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Received 20 November 2006, in revised form 15 March 2007; published online 28 January 2008

Abstract. We examined the vection in depth induced when simulated random self-accelerations (jitter) and periodic self-accelerations (oscillation) were added to radial expanding optic flow (simulating constant-velocity forward self-motion). Contrary to the predictions of sensory-conflict theory frontal-plane jitter and oscillation were both found to significantly decrease the onsets and increase the speeds of vection in depth. Depth jitter and oscillation had lesser, but still significant, effects on the speed of vection in depth. A control experiment demonstrated that adding global perspective motion which simulated a constant-velocity frontal-plane self-motion had no significant effect on vection in depth induced by the radial component of the optic flow. These results are incompatible with the notion that constant-velocity displays produce optimal vection. Rather, they indicate that displays simulating self-acceleration can often produce more compelling experiences of self-motion in depth.

1 Introduction

While a number of senses are known to be involved in self-motion perception, visual and vestibular information appear to dominate this experience (eg Dichgans and Brandt 1978). Unlike vision, which can detect any type of self-motion[1] on the basis of the observer's optic flow, the vestibular system can detect only accelerating self-motions from the inertia of the fluid in the semicircular canals and otoliths (Benson 1990). As a result, the vestibular system is unable to distinguish between travelling at a constant linear velocity and remaining stationary (Lishman and Lee 1973). Many studies of visual illusions of self-motion (vection) have used this limitation of the vestibular system to minimise the visual – vestibular conflicts experienced by their stationary observers (eg Andersen and Braunstein 1985; Palmisano 1996, 2002; Telford and Frost 1993; Telford et al 1992). These studies all used displays that simulated constant-velocity linear self-motions. The logic that underlies this choice of inducing display is formalised by visual – vestibular conflict theory (eg Zacharias and Young 1981).

According to this theory, when stationary observers are first presented with optic flow simulating self-motion, they initially feel that they are stationary owing to the following sensory conflict—their visual input is consistent with self-motion, but they have not yet received vestibular input to indicate that they have accelerated up from rest. If their optic flow simulates large and frequent changes to the direction/magnitude of the self-motion, then this sensory conflict will persist and prevent the induction of compelling vection (as significant and sustained vestibular activity would always be expected for this type of optic flow). However, if this optic flow simulates constant-velocity linear self-motion, then the initial sensory conflict will fade quickly, resulting in a rapid transition from object motion perception, to combined object motion perception and vection, and finally to exclusive (and potentially compelling) vection.

Consistent with this visual – vestibular conflict account of vection, research has shown that circular vection onsets can be decreased when observers are given a brief

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[1] The visual system can detect self-motions that are active and passive, linear and rotary, accelerating and constant velocity. It does, however, have the limitation that it is primarily sensitive to low temporal frequencies.

physical acceleration in the simulated direction of the self-rotation (Brandt et al 1974; Melcher and Henn 1981; Wong and Frost 1981). Also consistent with this notion, others have found that circular vection can be destroyed by sudden physical acceleration in the opposite direction to the simulated self-rotation (Teixera and Lackner 1979; Young et al 1973). However, while visual–vestibular conflicts can sometimes impair vection, it is worth noting that compelling visual illusions of self-motion can still be induced in situations thought to induce substantial sensory conflicts. For example, most stationary observers (60%–92%) experience complete (360°) illusions of self-rotation when placed inside a large, fully furnished room rotating about their roll axis—despite salient visual conflicts with vestibular, somatosensory, and proprioceptive inputs (Allison et al 1999; Palmisano et al 2006).

Visual–vestibular conflict theory has also been challenged by findings that visual displays which generate greater sensory conflicts can sometimes produce more compelling vection (Palmisano and Chan 2004; Palmisano et al 2000, 2003). The jittering and non-jittering displays used in these studies contained the same radial-flow component, which simulated constant-velocity self-motion in depth through a 3-D cloud of objects (expected to produce minimal/transient visual–vestibular conflict when viewed by stationary observers). Jittering displays also contained an additional flow component (similar to the effects of camera shake), which represented continuous, random horizontal/vertical impulse self-accelerations (expected to produce significant and sustained visual–vestibular conflict when viewed by stationary observers). Contrary to notions that visual–vestibular conflict always impairs vection, radial-flow displays with global perspective jitter were found to produce illusions of self-motion that started sooner and lasted longer than those produced by non-jittering radial flow.

The goal of the current study was to identify the origin of this previously identified jitter advantage for vection.[2] We were interested in whether this jitter advantage represents a special case of visual self-motion perception, which was produced either by the random nature of the jitter or because this jitter always occurred along an axis that was orthogonal to the main (constant-velocity) component of the simulated self-motion. To address these issues, we compared the vection induced by adding global perspective jitter (random-impulse-simulated self-accelerations) and global perspective oscillation
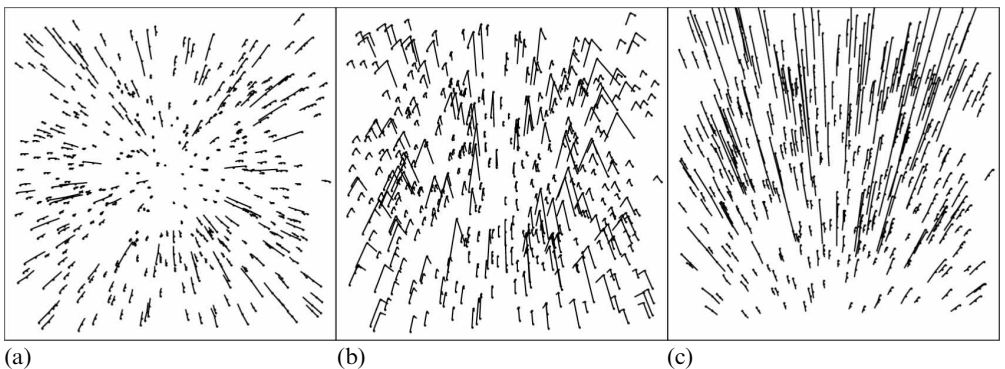

(a)   (b)   (c)

Figure 1. Velocity field representations of the three types of optic flow used in experiment 1: (a) non-accelerating radial flow represents constant-velocity forward self-motion. (b) Jittering radial flow represents constant-velocity forward self-motion combined with random vertical self-acceleration. (c) Oscillating radial flow represents constant-velocity forward self-motion combined with oscillating vertical self-acceleration.

[2] Interestingly, while Kitazaki and Hashimoto (2006) have recently replicated our effects of perspective jitter on vection, they found no significant effect on postural sway. On the basis of these findings, they concluded that the visual processes underlying vection and postural control are "dissociated before the jitter modulates self-motion perception".

(periodic simulated self-accelerations) to radial displays simulating constant-velocity self-motion in depth (see figure 1). We also examined whether adding depth jitter and oscillation to radial displays would improve vection in a similar fashion to adding frontal-plane jitter.

2 Experiment 1. Effect of jitter and oscillation on vection in depth

While the visual system is primarily sensitive to low temporal frequencies (below $1 - 0.5$ Hz) and constant-velocity self-motions (van Asten et al 1988; Berthoz et al 1975, 1979; Dichgans and Brandt 1978; Howard 1986), the vestibular system prefers high-temporal-frequency self-accelerations (ie above 1 Hz—Diener et al 1982; Howard 1986; Melville-Jones and Young 1978). In the current experiments, global perspective jitter simulated random self-motions along either the horizontal, vertical, or depth axis. Since the sign and magnitude of this jitter varied randomly, it is best represented by a range of frequencies (both high and low) limited by the Nyquist rate (15 Hz) specified by the update rate of the data projector (30 Hz). However, global perspective oscillation simulated periodic, low-frequency self-motions (0.3 Hz or 0.14 Hz). On the basis of their acceleration profiles, we would have expected that jittering radial flow should produce more sensory conflict than oscillating radial flow, which in turn would generate more sensory conflict than the pure radial flow (as the last simulated self-motion with a constant linear velocity and it was expected to produce only minimal or transient sensory conflict). However, previous research has shown that the jitter advantage for vection is remarkably robust to manipulations of jitter temporal frequency (within a range of $1 - 30$ Hz—see Palmisano et al 2000). Thus, if global perspective oscillation is found to produce a greater vection advantage than global perspective jitter in this experiment, then it would be more likely to be due to either the periodicity and/or predictability of the oscillation as opposed to temporal frequency differences between oscillation and the jitter.

2.1 Method

2.1.1 *Participants.* Eleven male and twelve female undergraduate psychology students (aged between 17 and 38 years) received course credit for their participation in this experiment. All had normal or corrected-to-normal vision and were unaware of the experimental hypotheses. The data from two female participants were not used as they discontinued the experiment after experiencing motion sickness.

2.1.2 *Design.* Three independent variables were manipulated in this experiment.
(i) *Acceleration axis.* Visual displays either simulated pure forward self-motion in depth at 2.8 m s^{-1} (non-accelerating displays) or forward self-motion in depth at 2.8 m s^{-1} combined with additional self-acceleration. When present, this additional acceleration was applied exclusively along either the observer's horizontal (x), vertical (y), or depth (z) axis, depending on the trial.
(ii) *Acceleration type.* On any one frame of an accelerating display, the size and direction of the displacement due to the simulated self-acceleration either varied randomly (global perspective jitter) or periodically (global perspective oscillation).
(iii) *Acceleration amplitude.* For accelerating displays, the displacement due to the simulated self-acceleration varied between either $-\frac{1}{3}$ to $\frac{1}{3}$ or $-\frac{1}{6}$ to $\frac{1}{6}$ of the simulated constant-velocity forward displacement. Two dependent variables were measured for each trial: (i) the vection latency—the time from the start of the display until the observers first indicated that they were experiencing vection by moving the computer mouse; and (ii) the average tracking speed of vection in depth—participants moved the computer mouse along a track (away from them, along the y axis of the mouse) to indicate their perceived speed of forward self-motion in depth. Speed estimates were

obtained for each track (based on the change in mouse position which was sampled 8 times per second). At the end of each track, participants picked up the mouse and reset it to the start position (reset periods were excluded from the data). Both vection measures were similar to those used in previous studies (eg Telford and Frost 1993; see Palmisano 2002 for more detail).

2.1.3 *Apparatus.* Displays were generated on a Macintosh G4 personal computer and projected onto a large Mylar screen by a Sanyo XGA 2200 data projector [resolution was 1024 (horizontal) $\times$ 768 (vertical); the update rate was 30 Hz]. This screen sub-tended a visual angle of 56 deg $\times$ 56 deg when viewed through a large, cylindrical tube attached to a head-and-chin rest 1.5 m distant. The tube blocked the observer's view of his/her stationary surroundings (which included the screen's frame). Observers moved an Apple Pro optical sensor mouse (10.5 cm long and 5.8 cm wide) between two rails on the table in front of them (each was 72 cm long, 1 cm wide, and 0.2 cm high) to represent their perceived speed of self-motion in depth (the track between the rails had a width of 7 cm).

2.1.4 *Visual displays.* Non-accelerating self-motion displays were patterns of radially expanding optic flow, consisting of 400 blue moving filled-in squares (1.8 cd m^{-2}) on a black background (0.03 cd m^{-2}). These square objects, which had the same simulated physical size (7 cm $\times$ 7 cm), were randomly positioned in space so as to form a 3-D cloud that extended 10 m along the depth axis. In order to simulate forward self-motion in depth at 2.8 m s^{-1}, the optical velocity and size (0.4 deg $\times$ 3.08 deg) of each object increased (in accordance with each other) throughout the display. When objects disappeared off the edge of the screen or reached the boundary of the near clipping plane, they were replaced at the opposite end of space at the same horizontal and vertical coordinates.

Accelerating self-motion displays were identical to non-accelerating self-motion displays, with the sole exception that they also contained an additional optic-flow component, which simulated self-acceleration along one of the participant's three orthog-onal body axes. Importantly, both types of simulated self-acceleration had no effect on the average simulated speed of self-motion in depth. The effects of both global perspective jitter and global perspective oscillation summed to zero over the duration of the trial (see figure 2).

These additional accelerating optic-flow components were generated in the following manner (see figure 2). On each frame, a single displacement value was chosen from a uniform distribution ranging from either $-\frac{1}{3}$ to $\frac{1}{3}$ or $-\frac{1}{6}$ to $\frac{1}{6}$ of the constant simulated forward displacement. For oscillating displays, displacement values increased in one direction (eg up) steadily for either 0.9 s or 1.75 s (for the small and large oscillation amplitudes, respectively) and then decreased over the same time period (at zero the displacement direction reversed—eg down). However, for jittering displays, displacement values varied randomly in size and direction from one acceleration frame to the next. In both types of accelerating display, the visible displacement of each object depended on its simulated location in depth—that is, a perspective transformation was applied to the displacement value, the result being either global perspective jitter or global perspective oscillation. Depending on the trial, the perturbing displacement was applied along either the horizontal, vertical, or depth axis.

2.1.5 *Procedure.* Participants were told that they would be shown displays of moving objects and that: "sometimes the objects may appear to be moving towards you; at other times you may feel as if you are moving towards the objects. Your task is as follows. If the objects appear to be moving, then press down on the mouse and hold it down as long as the objects continue to move. However, if you feel that you are
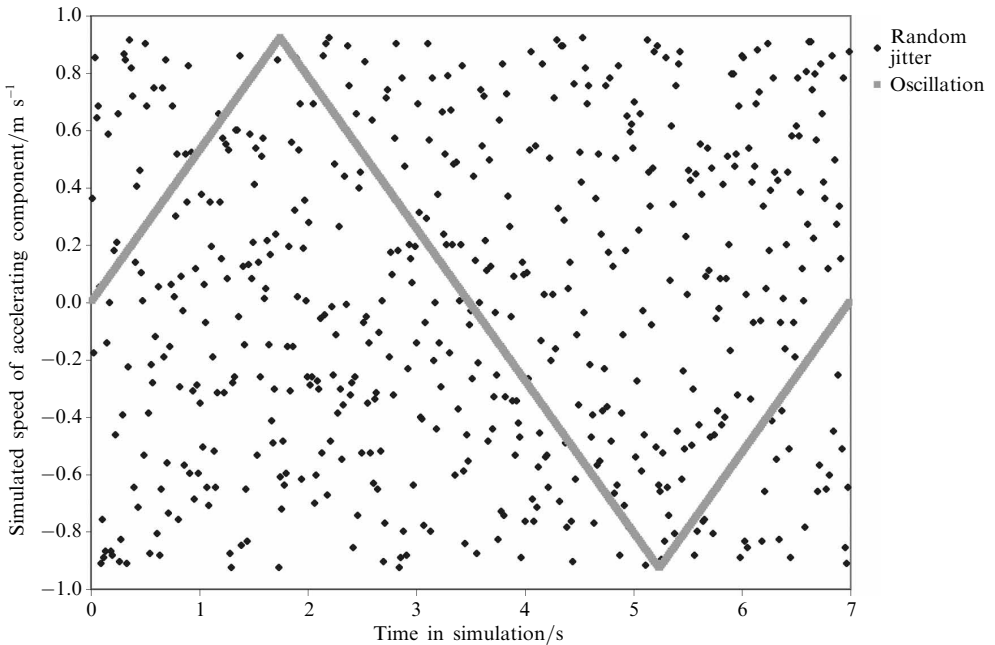
Figure 2. A comparison of the instantaneous velocities of self-motion represented by global perspective jitter and oscillation over a 7 s period. This figure depicts jitter- and oscillation-based self-accelerations for the large-amplitude conditions only ($-\frac{1}{3}$ to $\frac{1}{3}$ of the simulated forward speed of 2.8 m s^{-1}). Positive values on the vertical axis represent rightward, downward, or backward directions of self-motion—depending on the axis of the simulated self-acceleration.

moving forward then release the mouse button and move the mouse along the track on the table in front of you—like so. Move the mouse so as to represent the speed of your perceived forward self-motion and keep it moving as long as the experience of forward self-motion continues. If you feel that you are only moving horizontally or vertically—but not forward—then do nothing." After four practice trials, the experimental trials were presented in a random order: each had a duration of 60 s and an inter-trial interval of 20 s. The two testing sessions were separated by a 10 min break (the second session was a replication of the first). In each testing session, participants were exposed to 6 non-accelerating displays, 6 jittering displays (small- and large-amplitude horizontal, vertical, and depth jitter), and 6 oscillating displays (small- and large-amplitude horizontal, vertical, and depth oscillation).

2.1.6 *Data analysis.* Prior to statistical analysis, vection onsets (s) and average vection tracking speeds (cm s^{-1}) were determined for each 60 s trial. The vection onset and tracking speed data were then analysed with Bonferroni-adjusted planned contrasts, which controlled the familywise error rate at 0.05. Non-vection trials were assigned a tracking latency equal to the total trial length. While the inclusion of these non-vection trials would have inflated the latencies obtained for weaker vection stimuli, they were necessary to determine the relative effectiveness of the different visual displays for vection induction.

2.2 *Results*
Vection was reported on 758 of the 792 trials (22 participants responding twice to 18 stimuli). Of the 34 trials where vection was not induced, 12 had non-accelerating displays, 14 had displays with global perspective jitter, and 8 had displays with global

perspective oscillation.[3] Both jittering and oscillating displays were found to induce significantly shorter vection onsets ($F_{1, 60} = 26.91$, $p < 0.0002$) and significantly faster average vection tracking speeds ($F_{1, 60} = 123.26$, $p < 0.0002$) than non-accelerating displays (see figure 3). Importantly, no significant difference was found between either the vection onsets ($F_{1, 60} = 1.31$, $p > 0.05$) or the average vection tracking speeds ($F_{1, 60} = 0.56$, ns) produced by jittering and oscillating displays.
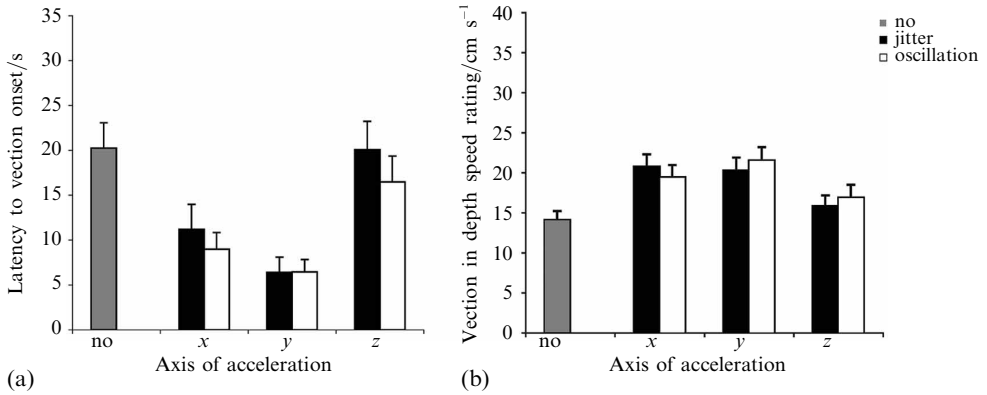

Figure 3. The effects of acceleration type (jitter and oscillation) and acceleration axis [no, horizontal (x), vertical (y), or depth (z)] on (a) the latency to vection onset and (b) the tracking speeds of vection in depth. Error bars represent standard errors of the averages.

Displays with smaller displacements due to oscillation/jitter did not produce significantly different vection onsets ($F_{1, 60} = 0.82$, ns) or average vection tracking speeds ($F_{1, 60} = 0.014$, ns) from those with larger displacements. However, there was a significant effect of the axis of the simulated self-acceleration: displays with horizontal and vertical accelerations produced significantly shorter vection onsets ($F_{1, 60} = 32.13$, $p < 0.0003$) and significantly faster average vection tracking speeds ($F_{1, 60} = 73.98$, $p < 0.0003$) than displays with depth acceleration. Displays with horizontal accelerations did not induce significantly different vection onsets ($F_{1, 60} = 3.21$, $p > 0.05$) or average vection tracking speeds ($F_{1, 60} = 2.18$, $p > 0.05$) from displays with vertical accelerations. While displays with depth accelerations were not found to produce significantly different vection onsets from non-accelerating displays ($F_{1, 60} = 0.93$, ns), they did produce significantly faster average vection tracking speeds than these controls ($F_{1, 60} = 16.80$, $p < 0.0003$).

2.3 Discussion

Despite their very different stimulus characteristics (and appearance), global perspective jitter and global perspective oscillation improved the vection in depth (induced by the constant-velocity radial-flow component) in a remarkably similar fashion.[4] While frontal-plane jitter and frontal-plane oscillation were found to reduce the latency for vection in depth, depth jitter and depth oscillation appeared to have little effect on the vection time course. An acceleration-axis effect was also observed on the perceived

[3] As in previous jitter studies, participants tended to experience vection continually from its onset until the trial ended (indicated by their tracking data). Vection dropouts were very rare for both accelerating and non-accelerating displays. On average, participants perceived object motion for 12 s longer in the non-accelerating conditions than in the horizontal/vertical accelerating conditions.
[4] Global perspective jitter simulated random broadband self-motions (up to 15 Hz), whereas global perspective oscillation simulated periodic low-frequency self-motions (0.3 Hz or 0.14 Hz). While the size and direction of the global perspective jitter varied randomly from frame to frame, oscillation effects were additive over a series of frames. As a result, the (summed) displacement due to oscillation was much greater than that due to jitter.

speed of vection in depth—although this was less pronounced than that observed for vection latency. We found that adding jitter and oscillation along each of the three axes significantly increased the perceived speed of vection in depth. However, frontal-plane jitter and frontal-plane oscillation increased participant speed ratings significantly more than equivalent depth accelerations.

One possible explanation for the above acceleration-axis effect on vection in depth was that a perceived compression of the depth axis might have reduced the perceived magnitude of simulated depth accelerations compared to simulated horizontal/vertical accelerations.[5] However, since these simulated depth accelerations were always visible (as indicated by their significant effects on vection speed) and doubling the amplitude of depth jitter/oscillation had no significant effect on vection, this explanation appears unlikely. Another possible explanation was that the sensory conflict produced by jitter and oscillation was restricted to the axis of the simulated self-acceleration. According to this notion, frontal-plane acceleration would only have restrained the induction of frontal-plane vection and depth acceleration would only have restrained vection in depth. However, since vection in depth was not impaired by depth acceleration, this explanation also appears unlikely. It was possible that this axis effect simply reflected a lower sensitivity to motion along the depth axis (compared to lateral motion—eg Regan and Beverley 1973).

The most likely explanation of the current results was that both jitter and oscillation increased the inducing potential of the radial-flow displays (rather than reducing it as visual–vestibular conflict theory would predict). Since displays containing frontal-plane jitter/oscillation-simulated global perspective motion along two axes, it was possible that they provided the visual system with stronger evidence of self-motion than depth acceleration and non-accelerating displays, which both simulated global perspective motion with respect to only one.[6] If this explanation for the acceleration axis effect is valid, then it is possible that adding constant velocity frontal-plane motion to radial-flow displays might also improve vection in depth. The logic for this proposal is as follows: if it is the number of axes indicating self-motion, rather than the presence/absence of simulated self-acceleration, that determines the type/strength of vection induced, then adding constant-velocity frontal-plane motion to radial-flow displays should improve vection in depth more than frontal-plane acceleration (as both types of display would simulate self-motion along two axes, but the former would generate minimal visual–vestibular conflict, whereas the latter would generate significant and sustained visual–vestibular conflict). This possibility was examined in experiment 2.

3 Experiment 2: Effect of constant-velocity frontal-plane motion on vection in depth

In experiment 2 we examined the vection in depth induced by displays simulating constant-velocity oblique self-motion. These patterns of optic flow had two components: (i) a radial component which represented constant forward self-motion (at 2.8 m s^{-1}); and (ii) a lamellar component which represented constant upward or leftward self-motion (at either 0.47 m s^{-1} or 0.93 m s^{-1}). The vection in depth induced by these displays was

[5] Simulated and rated speeds of self-motion in depth differed approximately by a scale factor of 10. This discrepancy might indicate a perceived compression of the depth axis (as perceived forward speed depends on perceived environmental distance) and/or that the presence of a texture ground plane might have been required for accurate flow speed scaling (Durgin et al 2005). Alternatively, this discrepancy between simulated and perceived speed might indicate that participants scaled their vection-speed-rating response (as the simulated speed of self-motion in depth was rather fast). Irrespective of the cause of this discrepancy, the simulated speeds and perceived speed-rating data provided in this paper are both best viewed in relative (as opposed to absolute) terms.
[6] In debriefing, we checked that frontal-plane jitter/oscillation had in fact produced compelling experiences of frontal-plane self-motion. All of our participants spontaneously reported experiencing significant horizontal and vertical vection during both types of accelerating display.

compared to: (i) control (radial-flow only) displays simulating only forward self-motion at 2.8 m s^{-1}; and (ii) jittering displays simulating forward self-motion at 2.8 m s^{-1} combined with horizontal/vertical random self-accelerations (ranging between either $+0.47$ m s^{-1} and -0.47 m s^{-1} or $+0.93$ m s^{-1} and -0.93 m s^{-1}). If perspective motion with respect to two axes provides a more convincing self-motion stimulus than perspective motion relative to only one axis (irrespective of its velocity profile), then we would expect to find a vection-in-depth advantage for oblique self-motion displays (compared to the control displays simulating only constant-velocity forward-self-motion). However, if the presence/ absence of simulated self-acceleration is the important factor in determining the pattern of results in experiment 1, we would only expect to find a vection-in-depth advantage for the jittering displays.

3.1 Method
The apparatus and procedure were identical to those of experiment 1.

3.1.1 Participants.
Five male and sixteen female undergraduate psychology students (aged between 18 and 32 years) received course credit for their participation in this experiment. All had normal or corrected-to-normal vision and were unaware of the exper- imental hypotheses. The data from one participant were not used as she discontinued the experiment after experiencing motion sickness.

3.1.2 Design.
We compared the vection induced by three types of displays: (i) oblique self-motion displays simulated constant-velocity forward self-motion combined with constant-velocity leftwards or upwards self-motion; (ii) jittering self-motion displays simulated constant-velocity forward self-motion in depth combined with random accelerating horizontal or vertical self-motions; and (iii) control displays simulated constant-velocity forward self-motion in depth. The simulated forward speed of self- motion was 2.8 m s^{-1} in all three display conditions. For oblique self-motion displays, the constant speed of the leftwards or upwards motion was either $\frac{1}{3}$ or $\frac{1}{6}$ of the forward speed of 2.8 m s^{-1}. For jittering displays, jitter magnitude ranged randomly from either $-\frac{1}{3}$ to $\frac{1}{3}$ or $-\frac{1}{6}$ to $\frac{1}{6}$ of this forward speed. Each of these conditions was presented twice to the participants in a random order.

3.2 Results
Vection was reported on 238 of the 240 trials (20 participants responding twice to 12 stimuli). Of the 2 trials where vection was not induced, both had non-accelerating displays. Importantly, oblique self-motion displays did not produce significantly differ- ent vection onsets ($F_{1,38} = 0.16$, ns) or average vection tracking speeds ($F_{1,38} = 1.37$, $p > 0.05$) than control displays indicating only self-motion in depth (see figure 4). As in experiment 1, adding horizontal or vertical global perspective jitter to displays was found to produce significantly shorter vection onsets ($F_{1,38} = 7.71$, $p < 0.009$) and significantly faster average vection tracking speeds ($F_{1,38} = 8.79$, $p < 0.005$) compared to both types of non-jittering displays. Both of the jitter-amplitude conditions examined ($-\frac{1}{3}$ to $\frac{1}{3}$ and $-\frac{1}{6}$ to $\frac{1}{6}$) were found to have similar effects on vection onsets and average vection tracking speeds (with $F < 1$ in both cases).

3.3 Discussion
As in previous experiments, adding frontal-plane global perspective jitter to radial flow was found to reduce the onset latencies and increase tracking speeds of vection in depth relative to all non-jittering displays (ie constant-velocity forward self-motion only and constant-velocity oblique self-motion). However, adding constant-velocity upward or leftward motion to radial flow (to simulate oblique self-motion) was found to have no significant effect on either the latency or the speed of vection in depth (compared to displays simulating forward self-motion alone). Thus, it appears that adding
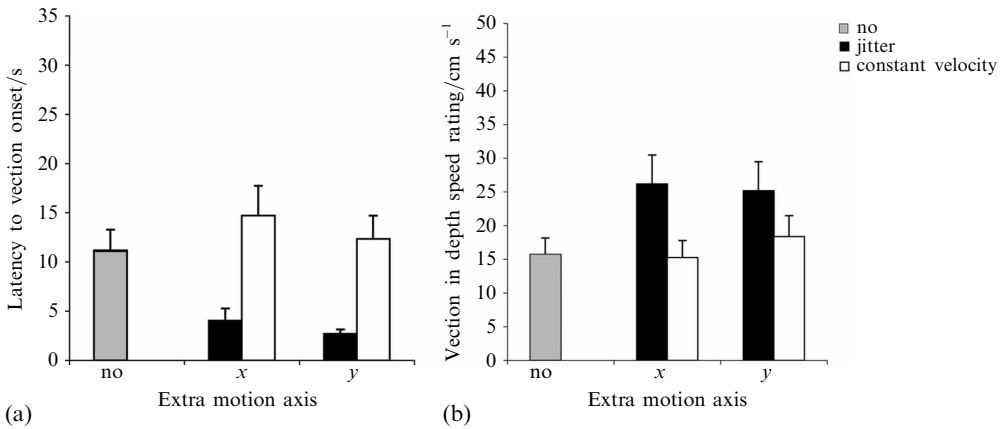
Figure 4. The effects of extra motion type (jittering and constant velocity) and extra motion axis [no, horizontal (x), vertical (y), or depth (z)] on (a) the latency to vection onset and (b) the tracking speeds of vection in depth. Error bars represent standard errors of the averages.

frontal-plane motion to radial flow only improves vection in depth when the overall simulated self-motion has an accelerating profile (ie it simulates changes in terms of the speed and/or the direction of self-motion). Thus, the crucial factor appears to be that jittering and oscillating radial-flow displays simulated self-motion with a changing trajectory, whereas the oblique self-motion displays used in this experiment did not.

4 Conclusions

Previously, it has been suggested that the visual – vestibular conflict produced during a purely visual simulation of a roller-coaster ride should result in weak/ambiguous vection (eg Wann and Rushton 1994). Contrary to this proposal, we found that adding simulated horizontal and vertical self-accelerations to displays representing constant-velocity self-motion in depth actually facilitated the induction of vection in depth. Latencies for the onset of vection-in-depth were not only reduced when inducing displays simulated unusual jittering self-motions in depth (random changes in the speed and the direction of self-motion), but also when they simulated more realistic self-motions (similar to driving through a series of chicanes or over a series of hills and valleys). These findings suggest that the vection time course often depends more on the nature of the optic flow (its salience and inducing potential), than on its predicted sensory conflict (whether the visual stimulus should or should not be accompanied by confirming inputs from the other senses).

Another important finding of experiment 1 was that while jitter and oscillation had no effect on the average *simulated* speed of self-motion in depth, jitter and oscillation were both consistently found to increase the average *perceived* speed of self-motion in depth. While only simulated horizontal and vertical self-accelerations appeared to facilitate the onset of vection in depth, simulated self-accelerations along all three orthogonal body axes were found to increase the perceived speed of vection in depth. However, as with the onset data, the effect of acceleration axis on vection speed remained. That is, we found that frontal-plane jitter and frontal-plane oscillation both increased the perceived speed of vection in depth more than the equivalent depth accelerations.

In experiment 2, we examined one potential explanation of the acceleration-axis effects on vection in depth found in the first experiment. We proposed that displays which simulated self-motion relative to two body axes might provide stronger visual evidence of self-motion than displays which simulated self-motion along only one. Contrary to this proposal, we found that adding constant-velocity frontal-plane motion

to radial displays (simulating constant-velocity forward self-motion) had no significant effect on either the onset latencies or the perceived speeds of vection in depth. The failure of constant-velocity frontal-plane motion to improve forward vection indicated that the presence of simulated self-acceleration was the crucial factor underlying both the jitter and oscillation advantages for vection in depth.

The observed acceleration advantage for vection is intriguing, since ecologically it makes sense to devote more resources to visual information indicating self-motions with changing speeds and directions (eg in order to monitor for potential future collisions) than to non-visual information indicating that the observer is stationary. On the basis of the findings of experiment 2, we revised the 'multiple-axis' explanation of the jitter and oscillation advantages for vection in depth as follows. According to this revised account, adding simulated horizontal/vertical self-accelerations to radial flow continuously changed the speed and direction of the (resultant) simulated self-motion, which in turn made the optic flow more salient to the observer, compared to conditions in which the simulated 3-D trajectory remained constant (ie radial displays with no acceleration). Furthermore, adding simulated depth accelerations to radial-flow displays produced more modest improvements because, while these changed the speed of the vection, they did not alter the direction of the self-motion.

Recent findings by Durgin et al (2005) suggest one possible limitation to the notion of a 'general' acceleration advantage for vection. In this earlier study, stationary participants had to rate the perceived speed of optic flow which simulated either: (i) constant-velocity self-motion in depth only; or (ii) constant-velocity self-motion in depth combined with horizontal and vertical self-accelerations (the latter accelerations represented the typical 'bob and sway' head movements made during walking). Contrary to the present study, speed judgments made during 'bob and sway' self-motion displays were not found to differ reliably from those made during control displays which simulated only self-motion in depth. There are, however, several reasons why the presence of simulated self-acceleration did not lead to significant differences in perception in this earlier study. First, unlike our monocularly viewed dot displays, their displays were viewed stereoscopically and provided a textured ground plane, which should have facilitated the scaling of optic-flow speed (Durgin et al 2005). This explanation of Durgin et al's null findings is intriguing, as it suggests that the acceleration advantages, such as those found in the present paper, will be cancelled if adequate environmental distance information is provided. However, there is a far more likely explanation for Durgin et al's null finding: the optic-flow durations used in their study (2.3–3.5 s) were too short for either vection to have been induced or for perceived egospeed differences between accelerating and non-accelerating display conditions to emerge.

In conclusion, the findings of the current study provide a further challenge to sensory-conflict accounts of vection. Importantly, they demonstrate that the previously reported jitter advantage for vection in depth is not a special case of self-motion perception. While constant-velocity patterns of radial flow are thought to generate minimal/transient visual–vestibular conflict, they are clearly not always the optimal inducing stimuli for vection in depth. We have shown that despite generating significant/sustained visual–vestibular conflict, optic-flow patterns that continually alter the simulated speed and/or direction of self-motion consistently produce more compelling subjective experiences of self-motion in depth. Since vection, as indicated by both onset latency and speed, was increased by two very different types of simulated self-acceleration (random broadband jitter, and periodic low-frequency oscillation), and these improvements were robust to substantial changes in amplitude, there is support for the notion of a general acceleration advantage for vection. These findings suggest that when other stimulus factors (such as area of motion stimulation, simulated speed,

and depth) are equated, displays simulating accelerating self-motions (eg a virtual roller-coaster ride) will tend to produce faster, longer-lasting experiences of illusory self-motion than those simulating constant-velocity passive transportation along a straight, even road.

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