Exp Brain Res (2017) 235:3111–3127
DOI 10.1007/s00221-017-5033-1

RESEARCH ARTICLE

The Shepard–Risset glissando: music that moves you

Rebecca A. Mursic[1] · Bernhard E. Riecke[2] · Deborah Apthorp[3,4] · Stephen Palmisano[1]

Received: 22 March 2017 / Accepted: 12 July 2017 / Published online: 25 July 2017
© Springer-Verlag GmbH Germany 2017

Abstract Sounds are thought to contribute to the perceptions of self-motion, often via higher-level, cognitive mechanisms. This study examined whether illusory self-motion (i.e. vection) could be induced by auditory metaphorical motion stimulation (without providing any spatialized or low-level sensory information consistent with self-motion). Five different types of auditory stimuli were presented in mono to our 20 blindfolded, stationary participants (via a loud speaker array): (1) an ascending Shepard–Risset glissando; (2) a descending Shepard–Risset glissando; (3) a combined Shepard–Risset glissando; (4) a combined-adjusted (loudness-controlled) Shepard–Risset glissando; and (5) a white-noise control stimulus. We found that auditory vection was consistently induced by all four Shepard–Risset glissandi compared to the white-noise control. This metaphorical auditory vection appeared similar in strength to the vection induced by the visual reference stimulus simulating vertical self-motion. Replicating past visual vection findings, we also found that individual differences in postural instability appeared to significantly predict auditory vection strength ratings. These findings are consistent with the notion that auditory contributions to self-motion perception may be predominantly due to higher-level cognitive factors.

Keywords Illusory self-motion · Vection · Auditory perception · Shepard–Risset glissando · Postural sway

Electronic supplementary material The online version of this article (doi:10.1007/s00221-017-5033-1) contains supplementary material, which is available to authorized users.

✉ Rebecca A. Mursic
rm2707@uowmail.edu.au

[1] School of Psychology, University of Wollongong, Wollongong, NSW 2522, Australia

[2] School of Interactive Arts and Technology (SIAT), Simon Fraser University, 250-13450 102nd Avenue, Surrey, BC V3T 0A3, Canada

[3] Research School of Psychology, College of Medicine, Biology and Environment, Australian National University, Canberra, ACT 2601, Australia

[4] Research School of Computer Science, College of Engineering and Computer Science, Australian National University, Canberra, ACT 2601, Australia

Introduction

Vection has traditionally been used to refer to visual illusions of self-motion elicited in stationary observers by large patterns of optic flow (Brandt et al. 1973; Hettinger et al. 2014; Palmisano et al. 2015). These visual illusions of self-motion occur in the absence of any physical motion, and despite conflicting cues from other senses that the observer is stationary (Lackner 1977; Keshavarz et al. 2014). Visually induced vection is generally assumed to be the result of low-level perceptual processes associated with self-motion. Consistent with this notion, early research identified a variety of low-level visual stimulus factors (display size, speed, density, etc.) that could significantly affect the induction of vection (see Riecke 2010 for a review). However, the experience of visual vection is now known also to depend on higher-level cognitive factors (e.g. Keshavarz et al. 2017; Lepecq et al. 1995; Palmisano and Chan 2004; Riecke et al. 2005; Riecke et al. 2006).

Cognitive contributions to visual vection

Ecological plausibility, semantics, metaphor and a variety of other cognitive manipulations have been shown to alter

the induction, strength and timing of visual vection (see reviews in Riecke 2009, 2010). Riecke et al. (2006), for example, showed that more naturalistic visual self-motion simulations produced superior vection convincingness ratings compared to scrambled or inverted versions of the same visual moving scene. Similarly, presenting a naturalistic stimulus upside-down resulted in less convincing self-motion illusions. As this vection advantage appeared difficult to explain based on the low-level visual stimulus factors—since the physical properties of all these displays were very similar—it strongly suggests a cognitive origin/basis to the effect.

Another study by Seno and Fukuda (2012) investigated the role of semantic meaning in the train illusion[1] (induced via computer-generated displays). They found that vection could be altered by changing the meaning associated with the motion display, holding low-level visual stimulus factors (i.e. speed, depth and size) relatively constant. Displays typically simulated a foreground scene consistent with the observer standing inside a train. Vection was more compelling when the display simulated motion of a second train compared to the motion of a grating pattern. In both cases this visual motion was seen through the windows of the observer's nearer train. Vection was also stronger when the motion was seen only through the observer's train windows than when it was also seen through the train's open (as opposed to closed) doors. By contrast, cognitive information which promotes object/scene motion has been shown to impair vection induction. For example, Ogawa and Seno (2014) discovered that meaningful stimuli representing objects in free-fall (i.e. leaves, petals and feathers) could inhibit vection relative to non-meaningful stimuli of similar size, colour and luminance. These results combined, provide further support for the notion that cognitive/semantic factors influence visual vection.

While somewhat controversial, recent research even suggests that vection can be induced in the absence of any explicit visual motion via purely cognitive mechanisms (Seno et al. 2012b). Participants were presented with displays consisting of two stationary curved lines which simulated a series of winding road edges while driving in darkness. Vection was significantly stronger for the road stimuli than the control conditions that did not resemble a road. Adding explicitly moving characters to the display as well as the road lines (which gave an impression of driving past a traffic sign) also appeared to enhance this cognitive-vection effect. The authors concluded that vection can be induced metaphorically via implicit, as opposed to explicit, visual motion. This suggests that it might also be possible to induce vection metaphorically via the stimulation of other non-visual self-motion senses.

Auditory vection

While the research reviewed above has shown that vection can be induced purely by visual stimulation, multiple senses are known to be involved in the perception of self-motion (these include the vestibular system of the inner ear, the proprioceptive system of muscle joint receptors, the somatosensory system of cutaneous receptors and the auditory system—Palmisano et al. 2015). Compared to vision, the role that audition plays in vection has received much less attention (see Väljamäe 2009 for a review). While it has long been known that illusions of self-motion could be induced via auditory stimulation (Dodge 1923; Lackner 1977), this auditory vection tends to be less compelling than visually induced vection (Keshavarz et al. 2014; Väljamäe 2009; Riecke et al. 2009). Auditory vection is typically induced by rotating or translating real or virtual sound fields around a stationary, blind-folded listener. For example, in the earliest recorded study, Dodge (1923) found that illusions of complete self-rotation could be produced by physically rotating sound stimuli around a stationary listener. Lackner (1977) subsequently replicated and extended these auditory vection findings. The auditory stimulation in this study was provided by external (physically rotating loud speakers) or internal sound-fields (rotary simulations delivered through headphones). Auditory vection in the dark was elicited in all conditions, but was significantly facilitated by presenting the sound-field externally. Consistent with Dodge (1923), this auditory vection was accompanied by compensatory nystagmus[2] (in the opposite direction to the perceived self-rotation).

Research has shown auditory vection can be facilitated by manipulating a variety of low-level stimulus factors. For example, increasing the velocity of the sound source movements and increasing the number of sound sources have been found to enrich circular (Keshavarz et al. 2014; Larsson et al. 2004; Väljamäe et al. 2004) and linear (Väljamäe et al. 2005) auditory vection. Using artificial sounds to induce vection, Väljamäe et al. (2005) found that looming sound sources produced more compelling auditory vection than receding sound sources, and that auditorily simulated

[1] When sitting in a stationary train, a train on an adjacent track begins to move and the observer typically misperceives their own train as moving in the opposite direction based on this visual motion stimulation (Dodge 1923).

[2] Nystagmus refers to reflexive eye movements comprised of a mixture of slow phase (smooth pursuit) and fast (saccade) movements. This is normally induced by (1) the voluntary tracking of a moving visual field or (2) compensatory vestibular action during rotation of the head. In either case, nystagmus works to stabilize the foveal image in the event of scene/self-motion (Purves et al. 2001).

self-translation was more effective than auditorily simulated self-rotation.

Cognitive contributions to auditory vection

Evidence has also begun to emerge that top-down cognitive influences can play an important role in auditory vection. In fact, according to Väljamäe and Sell (2014), the role of audition in illusory self-motion perception may be more related to cognitive aspects than to physically accurate acoustic cues. The perceived strength of auditory vection appears to depend on factors such as context and/or interpretation of the sound source. Several researchers proposed that ecological sounds are the most useful in deciphering whether it is oneself or one's environment that is in motion (Larsson et al. 2004; Riecke et al. 2005; Väljamäe et al. 2008).

Väljamäe et al. (2008) hypothesised that auditory vection could be facilitated by sounds that are normally associated with self-motion. They found that forwards/backwards auditory vection was facilitated by engine sounds compared to auditory landmark stimuli. According to Väljamäe and colleagues engine sounds were integrated by the listener as being metaphorically representative of the self in motion.

Several researchers further investigated cognitive influences on circular auditory vection by rotating acoustic fields around their stationary listeners. They found that this circular vection was superior for auditory landmark stimuli (a church bell or a fountain sound) compared to dynamic sound objects (the sound of driving a bus or footsteps) or artificial sounds (e.g. pink noise) (Larsson et al. 2004; Riecke et al. 2005; Väljamäe and Sell 2014). The authors concluded that auditory landmarks provided a stable frame of reference within the acoustic array, thereby strengthening relative self-motion perception. Taken together, the results above suggest that the way sounds are interpreted is important for the facilitation of auditory vection.

Effects of metaphorical auditory stimuli on visual vection

Recent work by Seno et al. (2012a) found that certain sounds facilitated visually induced vection even though the sounds they used were not strictly ecological for the situation. They found that upwards/downwards visual vection was enhanced by pure tone sound stimuli which increased/decreased in frequency [perceived by a listener as pitch—the degree of highness/lowness of an acoustic signal (Plack et al. 2006)], whereas forward/backwards visual vection was enhanced by pure tones which increased/decreased in intensity [closely related to amplitude; perceived as loudness (Olson 1972)].

Seno (2013) also found that the strength and timing of visually induced vection could be enhanced by listening to music that was rated as subjectively more 'active' (compared to less active music and no music control conditions). He speculated that active music increases the physiological arousal of the participants, which in turn facilitated vection. Thus, it would appear that musical/auditory stimuli can alter the perception of self-motion in various capacities.

While the metaphorical auditory stimuli used in this study were perceptually plausible for the situation, they were not strictly ecological (i.e. not what would be expected during self-motion based on physics). These sounds were also not able to induce auditory vection on their own (as they were only presented very briefly). These findings appear to show that visually induced illusions of self-motion can be significantly enhanced by artificial, metaphorical auditory stimulation.

Can purely metaphorical auditory stimuli induce vection?

Recent research increasingly shows that cognitive/metaphorical stimuli can influence visual, auditory and even audiovisual vection (Larsson et al. 2004; Riecke et al. 2009; Seno et al. 2012a, b; Väljamäe et al. 2008). The current study will, for the first time, examine whether vection can be induced by purely metaphorical auditory stimulation, using Shepard–Risset glissando sound stimuli. The Shepard scale is an auditory illusion of pitch discrimination. It induces an illusory perception of perpetually ascending/descending pitch that paradoxically seems to get no higher or lower (Shepard 1964; Deutsch 1992; Shimizu et al. 2007). Shepard's manipulation works because multiple tones are played simultaneously (some notes are played loudly, while others are practically inaudible). When these tones are played as a cyclically repeating ascending or descending scale, the shift in relative pitch cannot be perceived (Shimizu et al. 2007). This corresponds to a sound that is rising or falling infinitely.

In 1968, Jean-Claude Risset created a continuous variation of the discrete step-wise Shepard scale, known as the Shepard–Risset glissando (Vernooij et al. 2016). According to Vernooij et al. (2016) the Shepard–Risset glissando has been reported to induce experiences of disrupted equilibrium and the accompanying sensation that one is falling. Some additional sources report occasional unpleasant physical side-effects associated with listening to Shepard scales, including changes in heart rate and respiration, dizziness, headaches and nausea (Orini et al. 2012; Pigeon 2013).

Whilst rotating spatialized sound fields have long been known to induce auditory illusions of self-rotation (e.g. Dodge 1923), it is not explicitly known whether vection can be induced by metaphorical auditory stimulation alone (i.e. without any moving spatialized sound). Auditory metaphors for bodily motion have, however, been proposed in other research areas. For example, Eitan and Granot (2006) argue for a perceptual mapping between pitch height (high/low) and vertical height (up/down): an acoustic signal which ascends/descends in pitch tends to be perceived as the upwards/downwards motion of the observer, respectively. However, an increase in pitch is neither veridically correlated with upwards vertical motion, nor is a decrease in pitch correlated with downwards vertical motion: in physics, according to the Doppler effect,[3] an object falling vertically towards an observer on the ground would actually emit an increasing frequency (pitch) (Seno et al. 2012b; Hedger et al. 2013). Thus, the association is likely to be metaphorical (based on naïve physics/intuition) rather than ecological (consistent with actual physics).

Musical scales have even been found to influence visual-motion judgements. Hedger et al. (2013) found that prolonged exposure to ascending/descending musical scales could cross-modally influence visual-motion judgements when presented with a random dot kinematogram in a manner analogous to visual motion aftereffects. Metaphorical motion in the ascending/descending musical scales shifted sensitivity to visual-motion direction in the opposite metaphorical direction. The authors claim that their results provide evidence for a perceptually-rooted mechanism for the correspondence between pitch height and perceived vertical motion.

It is expected that ascending/descending Shepard–Risset glissandi will be consistent with the notion of 'perceptual plausibility' as discussed by Seno et al. (2012a), in that the potential motion information provided will be largely metaphorical. The gliding, continuous progression of tones comprising the Shepard–Risset glissando may be more indicative of motion than the stepwise progressions of pure tones examined previously by Seno and colleagues. The multiple layers of tones moving up/down a scale in Shepard–Risset glissando stimuli also provide richer information about the dynamics of the acoustic scene.

[3] The Doppler Effect: the shift in sound frequency produced by the changing distance between the observer and a moving sound source (Väljamäe 2009). The emitted frequency of the sound wave (unchanged at the point of passage) is perceived to become progressively higher as the sound source approaches the observer or progressively lower as the sound source moves away from the observer (Neuhoff and McBeath 1996).

The current study: can Shepard–Risset glissando stimuli induce auditory vection?

This experiment examined whether Shepard–Risset glissando stimuli could induce auditory vection in the absence of other sensory cues. To test reports of disrupted equilibrium and "falling" sensations induced by Shepard scales (Vernooij et al. 2016), any potential vection induced by our Shepard–Risset glissando stimuli will be compared to that induced by a visual vection stimuli (upwards/downwards global optical flow) as well as a white-noise control stimulus. The experimental sound stimuli include: (1) an ascending Shepard–Risset glissando (base frequency moving upwards); (2) a descending Shepard–Risset glissando (base frequency moving downwards); (3) a combined Shepard stimulus ((1) and (2) added together); (4) a combined (loudness-controlled) Shepard–Risset glissando [average decibels matched with (1)][4]; and (5) a white-noise control stimulus (see Fig. 2 for frequency by time spectrograms of these different auditory stimuli). Combined and combined-adjusted Shepard–Risset glissandi were designed as additional control stimuli; serving to distort the metaphorical direction information thought to drive the potential for vection (making direction somewhat ambiguous), whilst keeping the physical stimulus properties constant (compared to white noise which is a qualitatively and quantitatively dissimilar stimulus). We predicted that if it was possible to induce auditory vection using Shepard–Risset glissandi, then the strength of this illusion should be stronger for stimuli portraying a more stable metaphorical direction [i.e. conditions (1) and (2)]. For this reason, ascending stimuli and descending stimuli were expected to induce more compelling vection than the combined/combined-adjusted stimuli.

To test whether any metaphorical auditory vection reported by our listeners was genuine and not arising from experimenter demands, spontaneous postural instability was also measured prior to testing.[5] Palmisano et al. (2015) have proposed that postural instability could serve as an objective measure of vection. Previous research has found that postural instability during quiet stance appears

[4] Since adding ascending/descending together increases the overall loudness, we reduced the amplitude of the combined-adjusted Shepard–Risset glissando to match the average decibels of the ascending Shepard–Risset glissando as an additional control for effects of loudness/intensity.

[5] Shepard stimuli have been associated with a range of unusual bodily sensations that could be confused with vection (e.g. disrupted equilibrium, nausea etc.). Thus, we included a measure of vection direction (because other sensations are less likely to have an associated direction) and measured participants' postural instability prior to any exposure to visual or auditory stimuli in an attempt to cross-validate the results.

to predict the strength of visually induced vection (Palmisano et al. 2014; Apthorp et al. 2014). If a similar predictive relationship holds for auditory vection, then this would allow the authenticity of the results to be checked/confirmed. We might predict that those who rely more on visual cues to stabilise their posture [greater Romberg (i.e. "eyes closed"/"eyes open") ratios of postural instability] will be less susceptible to auditory vection (lower strength ratings). Employing the same methodology as Palmisano et al. (2014), participants' postural instability was measured for 60 s with their eyes open and 60 s with their eyes closed before exposure to any visual or auditory self-motion simulation.

Methods

Participants

Thirteen female and seven male participants (aged between 18 and 33 years) were recruited from the University of Wollongong and from the general population (M = 21.8, SD = 3.4). All participants had normal or corrected to normal vision and no reported visual, vestibular, neurological or gastrointestinal impairments. The University of Wollongong Human Research Ethics Committee approved the study in advance (HE16/047) and all participants provided written informed consent prior to participation. These protocols were in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Design

The independent variable manipulated in this experiment was the type of auditory stimulation presented on each trial. The five different auditory stimuli were each repeated 4 times (twice per block). The dependent variables measured in this experiment were: vection onset and duration (measured during each trial), vection strength (verbal strength rating from 0 to 10) and subjective reports of vection direction (measured directly after each trial). For each non-vection trial, the onset latency was assigned the value of the total trial duration (30 s). Participants' spontaneous postural instability was also measured before any experience of vection as a potential check for the effects of experimenter demands on responding. Since participants were instructed to report their perceived self-motion to all five auditory stimuli, it was possible that those more responsive to these demand characteristics might falsely report or inflate their vection ratings (particularly during white-noise control trials). However, if individual differences in postural instability predict the strength of auditory vection (as they appear to do for visual vection), then this should provide additional evidence that the vection results are genuine and not due to experimenter demands (this particular relationship would be difficult to fake, as the sway data was obtained before any exposure to visual/auditory vection).

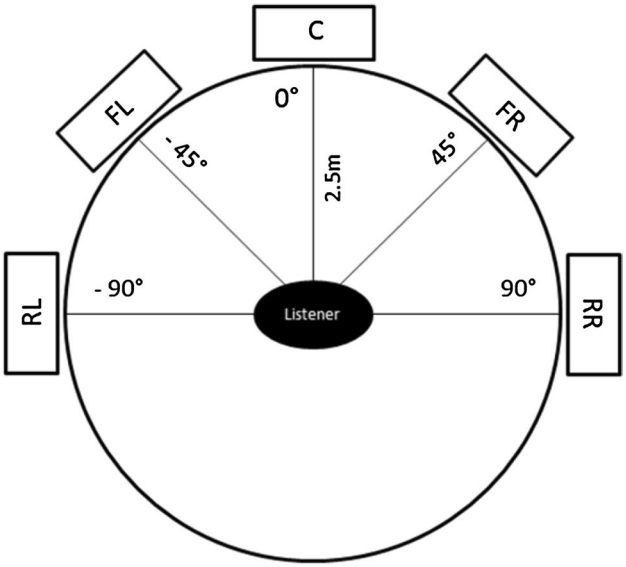


Fig. 1 Illustration of experimental surround sound speaker setup. *RL* rear left, *FL* front left, *C* Centre, *FR* front right, and *RR* rear right speakers

Apparatus

Before both the visual vection demonstrations and the main auditory vection experiment, participants stood on a Bertec balance plate (http://bertec.com/products/balance-plates.html) to measure changes in their centre of foot pressure (CoP). All visual displays were generated by a Dell Precision T3500 PC and then front-projected onto a large screen (3.9 m wide by 1.5 m high) by a NEC NP—P401WG LCD projector (1280 × 800 pixel resolution; refresh rate = 60 Hz). As participants were positioned 4.1 metres in front of the screen, these displays subtended a visual area of 54° horizontally and 21° vertically. Participants' vection latency and duration responses were recorded with a Dell M0C5U0 USB Scroll 3 Button Optical Mouse and verbal strength ratings were entered in via a Dell Y-U0003-DEL5 Slim design USB multimedia keyboard. All sound stimuli were presented to participants via Logitech Z906 5.1 speaker surround sound system. The five speakers were each located at a distance of 2.5 m from the listener, one placed directly in front of them (0°), one each at ±45° in front and to the left and right of them, and one each at ±90° to either side of the listener (see Fig. 1).

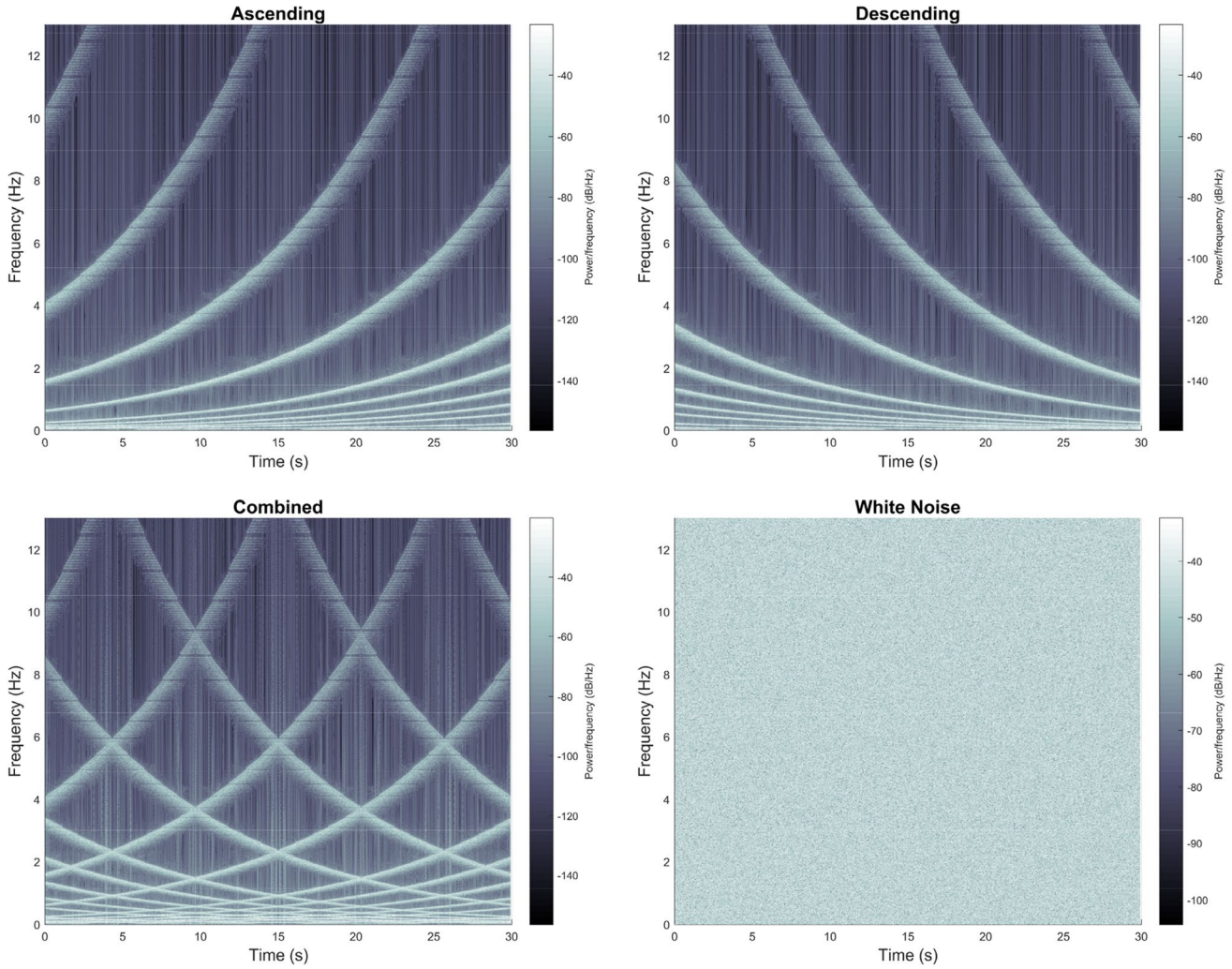


Fig. 2 Frequency by time spectrograms of the different types of auditory stimuli. Four types of Shepard–Risset glissando stimuli were compared to a white-noise control (*bottom right*): ascending (*top left*); descending (*top right*); combined (*bottom left*); and combined-adjusted *(not pictured)*

Visual and auditory stimuli

Visual self-motion displays simulated upwards/downwards self-motion at a constant velocity of 0.7 m/s (see demo movie in the supplementary materials). Note that these visual self-motion displays were only used during the vection demonstration phase; for the main experiment participants were blindfolded. Each display consisted of a 3-D cloud consisting of 3000 purple circular elements (cloud dimensions were 3.9 m wide × 1.5 m high and 8.7 m deep). The luminance of these circular elements ranged from 0.3 cd/m^2 (min) to 4.0 cd/m^2 (max). They were presented on a 0.15 cd/m^2 black background. The circular elements remained the same optical size (0.4°) throughout these self-motion displays (i.e. relative size/distance information about depth was not available).

Each of the five auditory stimuli tested were presented for 30 s (see Fig. 2). These included: (1) an ascending Shepard–Risset glissando rising at a rate of 6 octaves per minute (Range = 86.1 Hz; 111.60 dB–21,963.87 Hz; −7.69 dB, *M* = 11,025 Hz; −70.15 dB, SD = 6352.84 Hz; 34.81 dB) (sampled from https://soundcloud.com/shepard-tone); (2) a descending Shepard–Risset glissando (Range = 86.13 Hz; 111.17 dB–21,963.87 Hz; −7.69 dB, *M* = 11,025 Hz; −69.98 dB, SD = 6352.84 Hz; 34.42 dB—see supplementary materials for the demo.wav file) (created by reversing the ascending Shepard–Risset glissando segment using Audacity 2.1.2 audio editing software); (3) a combined Shepard–Risset glissando (Range = 86.13 Hz; −108.38 dB to 21,963.87 Hz; −4.75 dB, *M* = 11,025 Hz; −67.05 dB, SD = 6352.84 Hz; 34.50 dB) (constructed by adding the ascending and descending Shepard–Risset glissandos

together—see supplementary materials for the demo.wav file); (4) a loudness-controlled combined Shepard–Risset glissando (Range = 86.13 Hz; −111.38 dB–21,963.87 Hz; −7.75 dB, *M* = 11,025 Hz; −70.05 dB, SD = 6352.84 Hz; 34.50 dB) [amplitude was adjusted to match to the average decibels of (1)]; and (5) a white-noise stimulus (Range = 86.13 Hz; −70.11 dB–21,963.87 Hz; −69.80 dB, *M* = 11,025 Hz; −69.94 dB, SD = 6352.84 Hz; 0.06 dB) [generated in Audacity; average amplitude was matched to that of (1)].

Procedure

Participants initially had their height recorded and then proceeded to step onto the Bertec balance plate for weight and centre of foot pressure (CoP) measurement. Participants were instructed to stand upright and still with their feet shoulder width apart, their knees kept straight and arms to their sides. CoP was measured twice for periods of 60 s prior to the experiment; first with the participant's eyes open, fixating on stationary surroundings, and second with their eyes closed.

Participants were then asked verbally if they had ever experienced the sensation of vection in real life (i.e. via the train or traffic light illusion). All participants stated they were familiar with the sensation. Before each block of auditory experimental trials, the now seated participants were next presented with four visual trials (eight in total) simulating upwards/downwards vection without any sound. The (physically large and distant) visual displays were explicitly chosen because they induced compelling experiences of vection.[6] Participants were informed that "sometimes the objects may appear to be moving relative to you and at other times you may feel as if you are moving relative to the objects. Your task is to press the button whenever you feel that you are moving." The upwards vection display (downwards flow) acted as the standard stimulus for the participant's subsequent auditory vection strength ratings in the following experimental session. Participants were instructed that the strength of any illusory self-motion experienced during these displays should be rated "5" (with "0" representing no self-motion). Each of the visual trials lasted for 30 s. Participants were instructed to hold the left mouse button down if they experienced any illusory self-motion and keep it held down for as long as they felt that they were moving (this recorded latency and duration). After each visual trial, participants were asked to report if they had felt that they were moving during the trial and if so, what was the perceived direction of this illusory self-motion. This ensured that participants were actually reporting illusory self-motion and not merely the perceived scene/object motion in the display.

Participants were then blindfolded and presented with the two experimental blocks for a total of 20 sound-only trials. The order of presentation of the sound trials was fully randomised. Each sound trial was presented for 30 s. Experimental instructions were identical to the previous visual-only trials. Participants were also informed that this was exploratory research and that: (1) they might not experience any illusion of self-motion from the auditory stimuli; and (2) if they did it might be ambiguous in terms of its direction (e.g. possibly experienced in multiple directions during the same trial). Participants were then instructed to rate the strength of any experienced self-motion verbally by magnitude estimation, relative to the visual standard stimulus, with possible estimates ranging from "0" to "10" ("0" indicating no perceived self-motion and "10" indicating self-motion perceived to be twice as strong as the standard visual stimulus).

Results

Visual vection reference

The (physically large and distant) visual displays were explicitly chosen because they induced compelling experiences of vection in the experimenters. This was also evidenced in the experimental participants by their short vection onset latencies (<10 s) (Figs. 3, 4).

The reported time-course of the vection induced by the audio-only trials was very similar to that induced in the visual display motion trials. Figures 5 and 6 show the average vection onsets and durations for the visual display and auditory conditions. Figures 7 and 8 show the vection onset and duration of the visual reference compared to each auditory condition separately.

Visual vection direction

Participants always reported that their visual vection occurred in the opposite direction to the motion of the elements in the optic flow (consistent with this visually induced vection being genuinely experienced by the participants of this study).

[6] During pilot testing, these visual motion displays were viewed while standing (with the idea of measuring sway during the displays as well as before). However, the experimenters found that these displays generated very powerful illusions and considerable perceived and physical postural instability (so much so that they did not feel comfortable standing). Accordingly, participants instead had to be seated during the actual experiment.

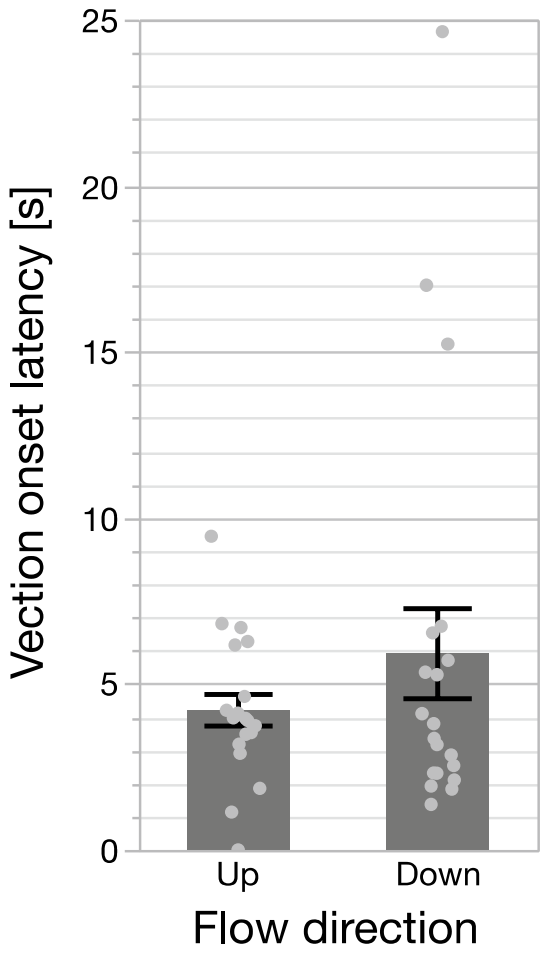


Fig. 3 Mean visual vection onset latencies for the upwards and downwards moving display motion conditions. *Error bars* represented ±1 standard error of the mean. *Grey dots* show individual participants' mean data

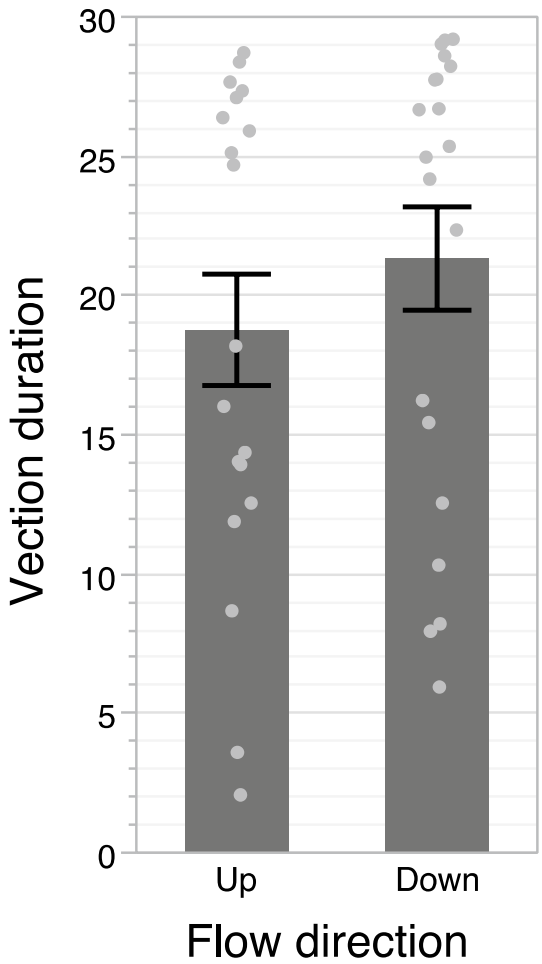


Fig. 4 Mean visual vection duration for upwards and downwards moving display motion conditions. *Error bars* represented ±1 standard error of the mean. *Grey dots* show individual participants' mean data

Main experiment: audio only trials

Participants reported experiencing auditory vection in 309 out of 400 trials (77.3%). Three separate repeated-measures ANOVAs were performed on the auditory vection strength, vection onset latency and vection duration data to determine whether sound type had a significant effect on auditory vection (Greenhouse–Geisser adjustments were used whenever the assumption of sphericity was violated). Due to a glitch with the mouse button, the onset and duration data for one participant (PS) was compromised and thus excluded from analysis.

Vection strength data

The main effect of sound type was significant for auditory vection strength, $F(4, 76) = 28.68$, $p < 0.001$ $\eta_p^2 = 0.60$ ($\varepsilon = 0.551$). Bonferroni-corrected pairwise comparisons were then conducted to further examine the origins of this effect. They revealed that vection strength ratings for the white-noise control stimulus were significantly lower than those for the ascending, descending, combined and combined-adjusted (loudness-controlled) Shepard–Risset glissando stimuli (all corrected $p < 0.05$; see Table 1). Importantly, none of the Shepard–Risset glissando stimuli differed significantly from each other in terms of auditory vection strength (all $p > 0.05$) (see Fig. 9; Table 1).

Vection timing data

The main effect of sound type was significant for auditory vection onset latency and for auditory vection duration [$F(4, 72) = 28.38$, $p < 0.001$, $\eta_p^2 = 0.60$ ($\varepsilon = 0.330$) and $F(4, 72) = 18.979$, $p < 0.001$, $\eta_p^2 = 0.513$ ($\varepsilon = 0.552$), respectively]. Bonferroni-adjusted pairwise comparisons indicated that the vection onset latency for the white-noise control stimulus was significantly longer than for ascending,

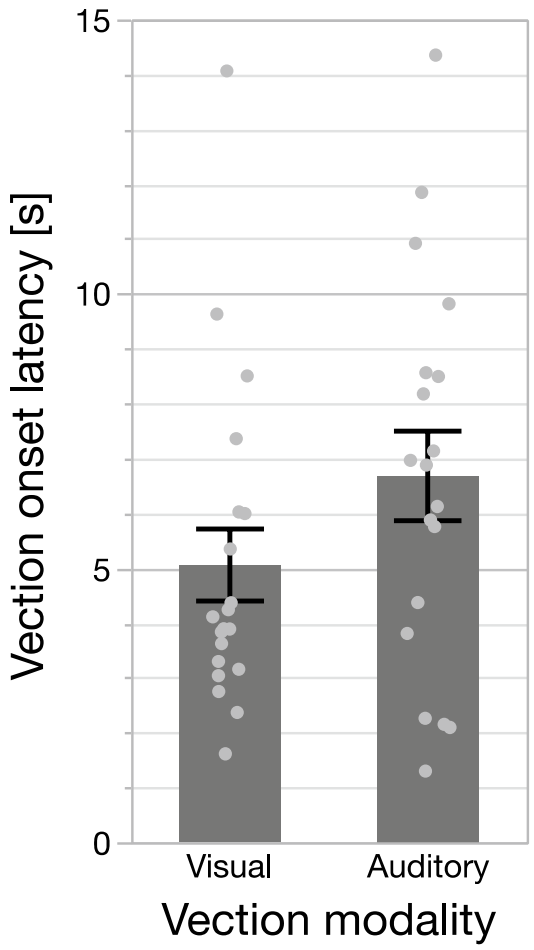


Fig. 5 Mean vection onset latencies for visual and auditory (Shepard only) vection types averaged across conditions. *Error bars* represent ±1 standard error of the mean. *Grey dots* show individual participants' mean data

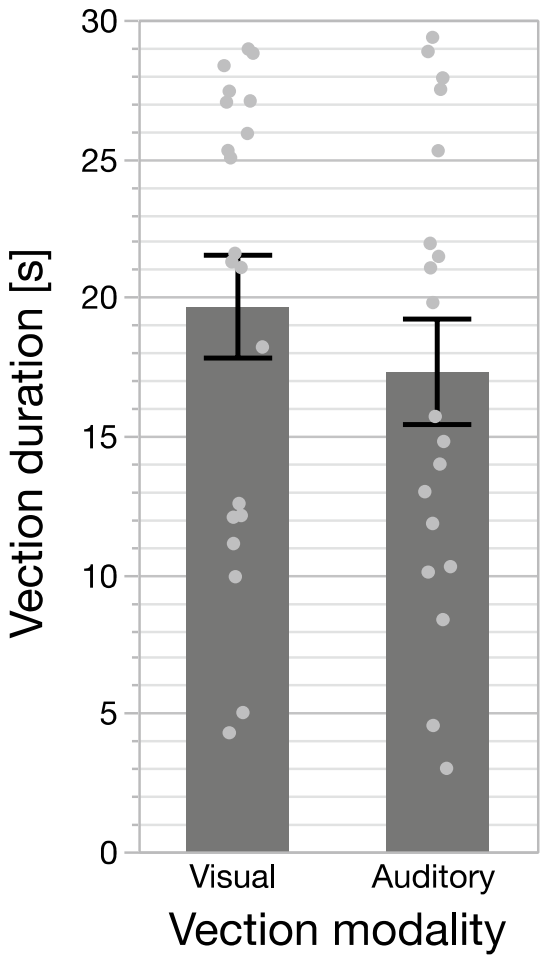


Fig. 6 Mean vection duration for visual and auditory (Shepard only) vection types averaged across conditions. *Error bars* represent ±1 standard error of the mean. *Grey dots* show individual participants' mean data

descending, combined and combined-adjusted Shepard–Risset glissando stimuli (all corrected $p < 0.05$; see Table 2). Importantly, none of the Shepard–Risset glissando stimuli differed significantly from each other in terms of auditory vection onset latency (all $p > 0.05$) (see Fig. 10).

Bonferroni-adjusted pairwise comparisons also indicated that the vection duration for the white-noise control stimulus was significantly shorter than that for the ascending, descending, combined and combined-adjusted Shepard–Risset glissando stimuli (all $p < 0.05$; see Table 3.). None of the Shepard–Risset glissando stimuli differed significantly from each other in terms of vection duration (all $p > 0.05$) (see Fig. 11).

Vection direction data

The perceived vection direction reports for each trial were next tallied into categories (up, down, forwards, backwards, left, right and other). The percentages calculated for each sound type condition are shown and described below (see Fig. 12).

For the ascending condition, upwards vection was reported in 67% of trials, and forwards vection was reported in 22% of trials. Thus, while the majority of participants experienced upwards vection during ascending trials, a substantial number of participants also perceived forwards vection, which also matches the metaphorical direction of up-forward (incline). Alternative directions were experienced in less than 10% of trials.

For the descending condition, downwards auditory vection was reported in 79% of trials and backwards vection was reported in 10% of trials. Alternative directions were experienced in less than 10% of trials.

For the combined Shepard–Risset glissando condition, upwards vection was reported in 28% of trials and downwards vection was reported in 26% of trials. Based on participant reports during debriefing, the dominant

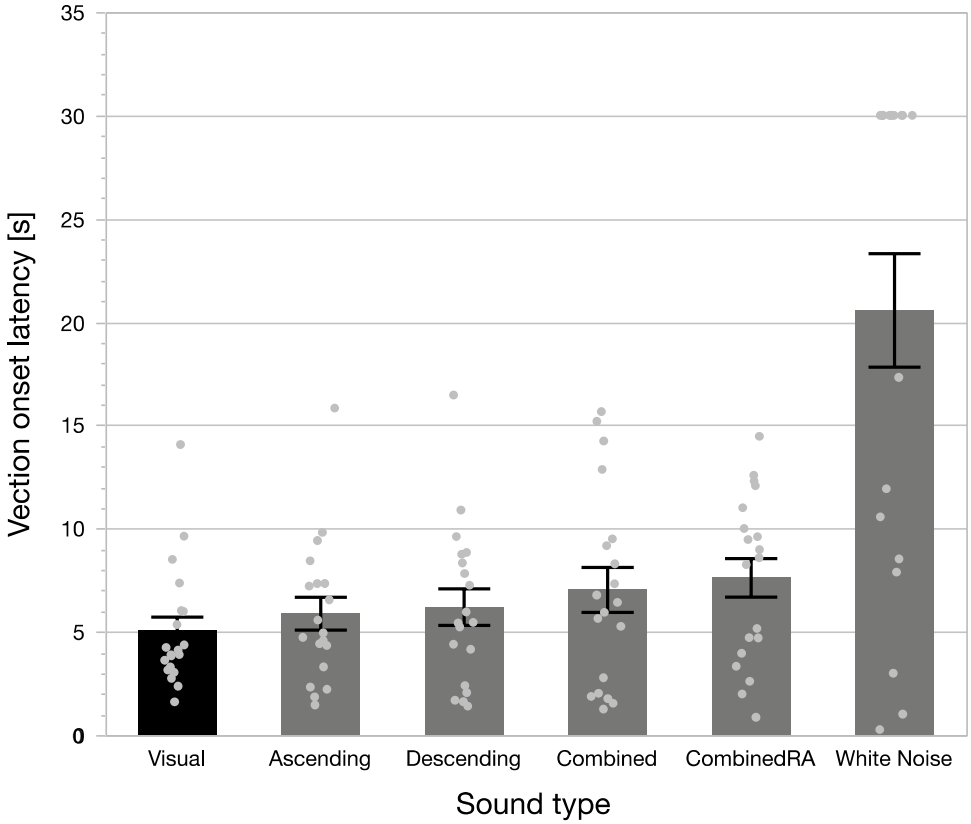


Fig. 7 Mean vection onset latencies for the visual reference stimulus compared to ascending, descending, combined, combined-adjusted Shepard–Risset glissandi and white noise conditions. *Error bars* represent ±1 standard error of the mean. *Grey dots* show individual participants' mean data

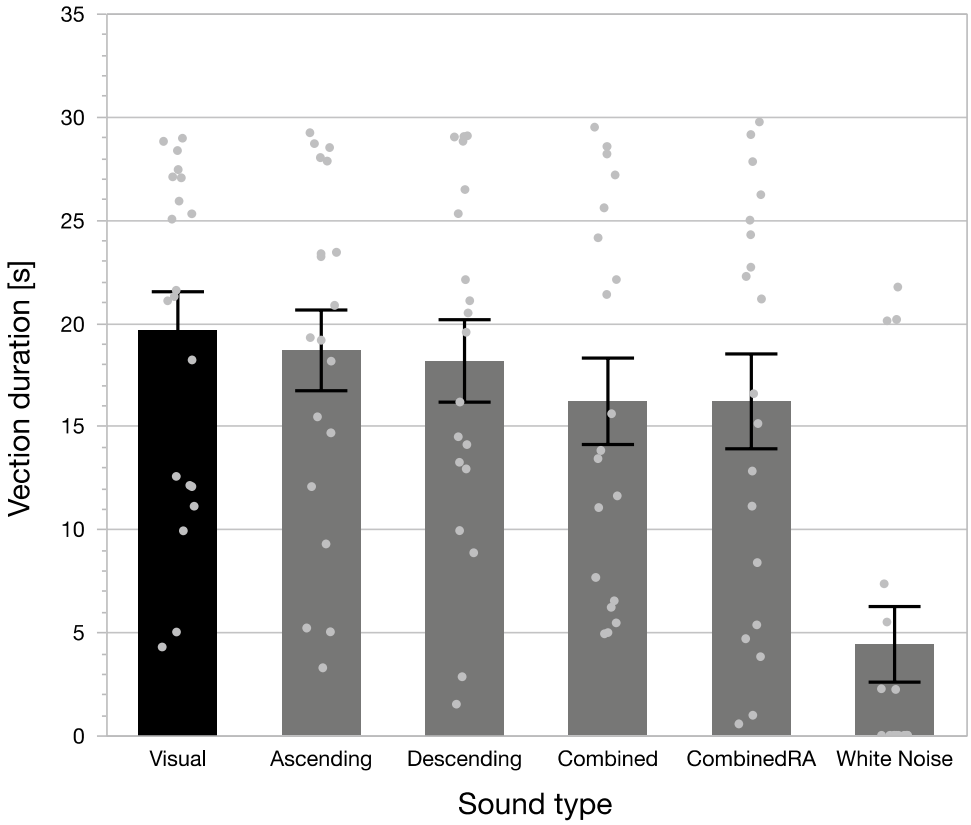


Fig. 8 Mean vection duration for the visual reference stimulus compared to ascending, descending, combined, combined-adjusted Shepard–Risset glissandi and white noise conditions. *Error bars* represent ±1 standard error of the mean. *Grey dots* show individual participants' mean data

Table 1 Bonferroni-corrected pairwise comparisons of sound type for auditory vection strength

Sound	Mean	SD	Comparisons (*t*)				
			Ascending	Descending	Combined	CombinedRA	White-noise
Ascending	5.29	2.46		1.20 (1.000)	1.74 (0.971)	2.46 (0.237)	6.91 (<0.001)*
Descending	4.99	2.16			0.82 (1.000)	1.66 (1.000)	6.45 (<0.001)*
Combined	4.72	2.51				1.63 (1.000)	6.05 (<0.001)*
CombinedRA	4.33	2.55					5.82 (<0.001)*
White-noise	1.04	1.64					

* $p < 0.05$. p values (in brackets) are derived from paired samples t tests and are Bonferroni-corrected for multiple comparisons

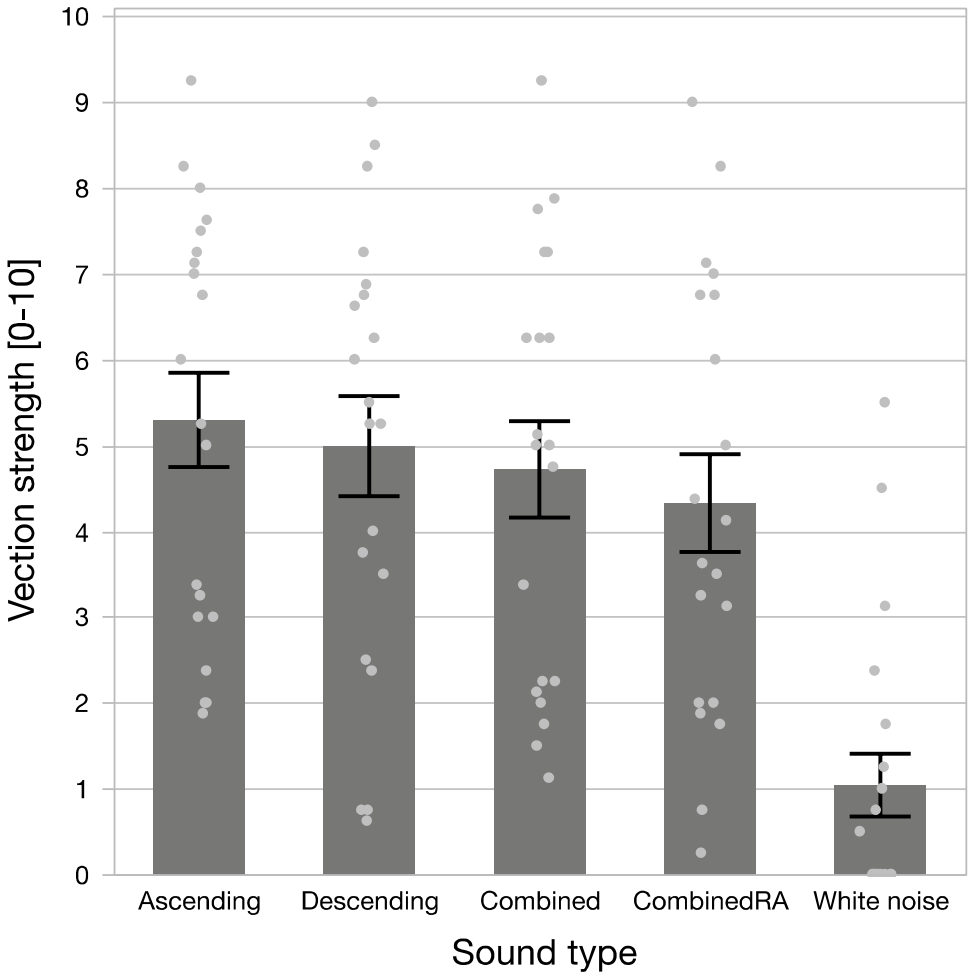


Fig. 9 Mean auditory vection strength ratings for ascending, descending combined and combined-adjusted (loudness-controlled) Shepard–Risset glissandi and white–noise sound types. *Error bars* represent ±1 standard error of the mean. *Grey dots* show individual participants' mean data

Table 2 Bonferroni-corrected pairwise comparisons of sound type for auditory vection onset

Sound	Mean	SD	Comparisons (*t*)				
			Ascending	Descending	Combined	CombinedRA	White-noise
Ascending	5.88	3.47		−0.60 (1.000)	−1.69 (1.000)	−2.00 (0.609)	−5.77 (<0.001)*
Descending	6.20	3.85			−1.07 (1.000)	−1.74 (0.991)	−5.75 (<0.001)*
Combined	7.03	4.75				−0.86 (1.000)	−5.60 (<0.001)*
CombinedRA	7.61	4.07					−4.86 (0.001)*
White-noise	20.55	11.96					

* $p < 0.05$. p values (in brackets) are derived from paired samples t tests and are Bonferroni-corrected for multiple comparisons

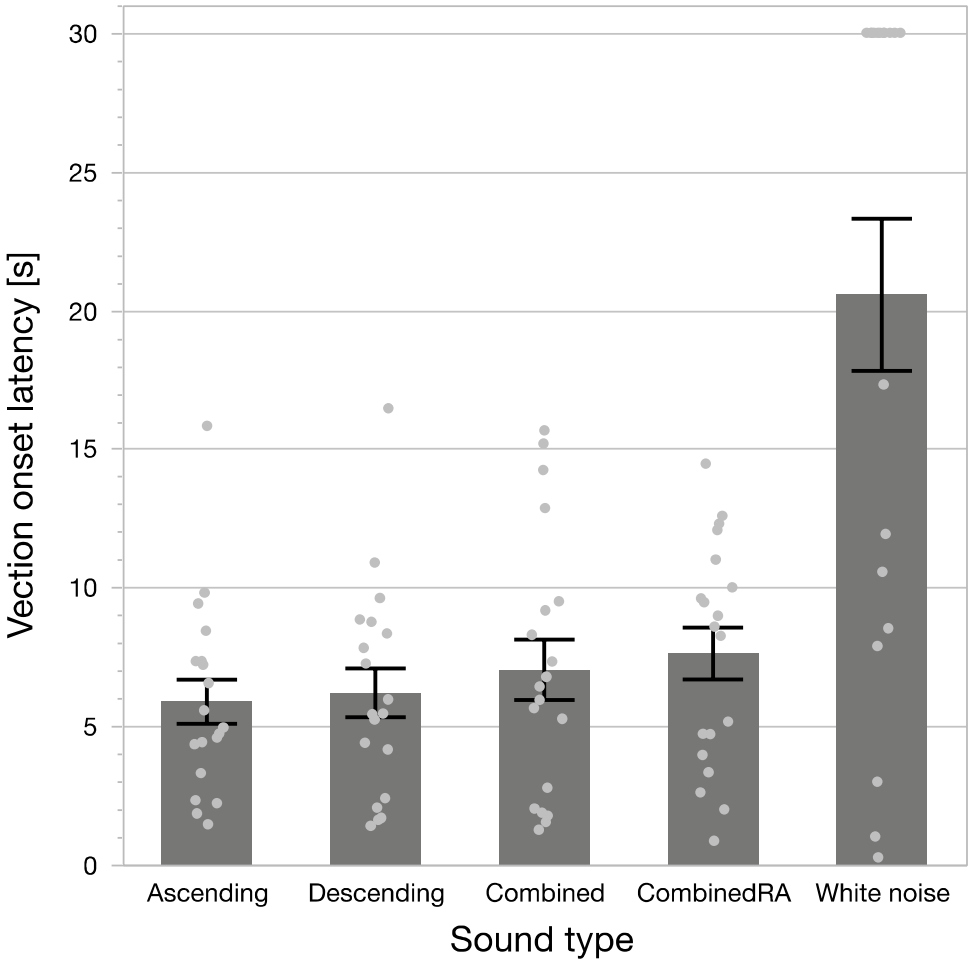


Fig. 10 Mean auditory vection onset latencies for ascending, descending, combined and combined-adjusted (loudness-controlled) Shepard–Risset glissandi and white-noise sound types. *Error bars* represent ±1 standard error of the mean. *Grey dots* show individual participants' mean data

Table 3 Bonferroni-corrected pairwise comparisons of sound type for auditory vection duration

Sound	Mean	SD	Comparisons (*t*)				
			Ascending	Descending	Combined	CombinedRA	White-noise
Ascending	18.66	8.54		0.39 (1.000)	1.98 (0.626)	1.59 (1.000)	5.45 (<0.001)*
Descending	18.15	8.73			1.18 (1.000)	1.21 (1.000)	6.22 (<0.001)*
Combined	16.19	9.13				0.01 (1.000)	4.42 (0.003)*
CombinedRA	16.18	10.03					−5.00 (0.001)*
White-noise	4.17	10.03					

* $p < 0.05$. p values (in brackets) are derived from paired samples t tests and are Bonferroni-corrected for multiple comparisons

perceived direction typically flipped between upwards and downwards (presumably based on which scale in this stimulus was more audible or attended to at a given time). However, alternative directions were reported to a greater extent (>10%) than in ascending and descending conditions, indicating the ambiguity/instability of the combined Shepard stimulus. Forwards vection was reported in 14% of trials, backwards vection was reported in 11% of trials. Alternative directions were experienced in less than 10% of trials.

For the combined-adjusted (loudness-controlled) condition, upwards vection was reported in 28% of trials and downwards vection was reported in 35% of trials. Forwards vection was reported in 4% of trials, backwards auditory vection was reported in 6% of trials, right vection was reported in 4% of trials, left vection was

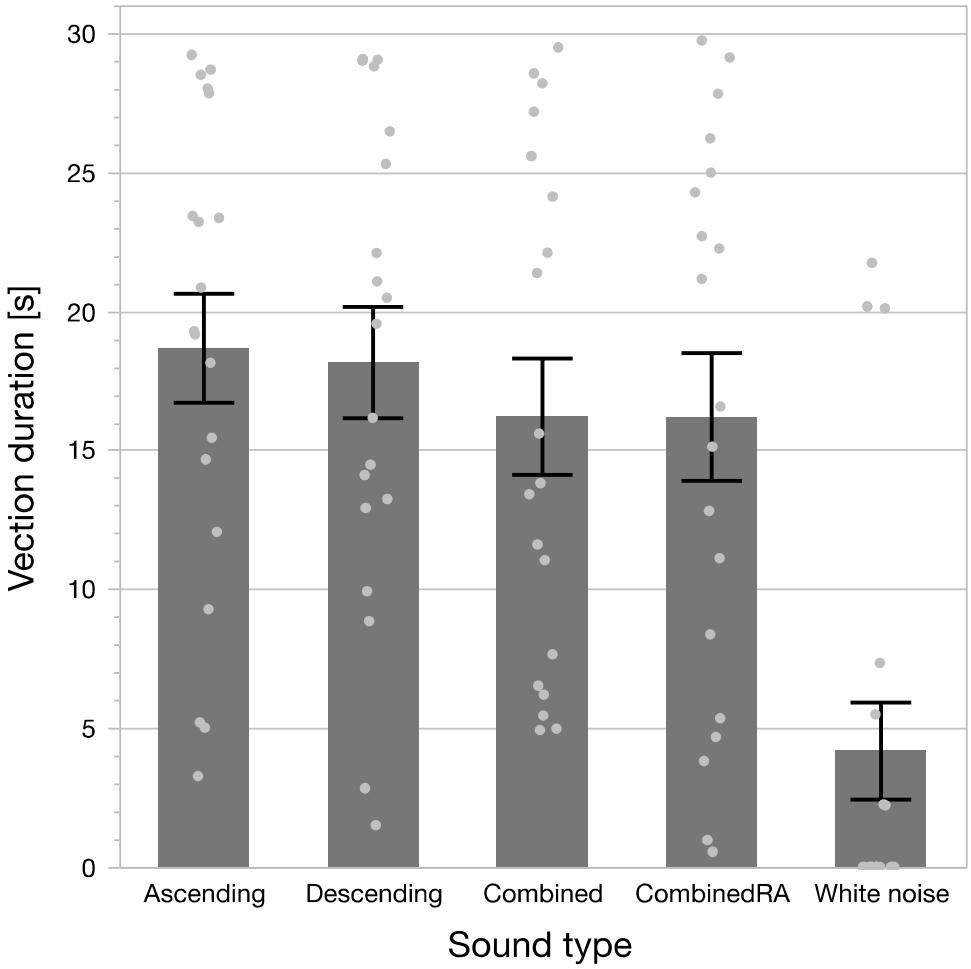


Fig. 11 Mean auditory vection duration for ascending, descending, combined and combined-adjusted (loudness-controlled) Shepard–Risset glissandi and white-noise control sound types. *Error bars* represent ±1 standard error of the mean. *Grey dots* show individual participants' mean data

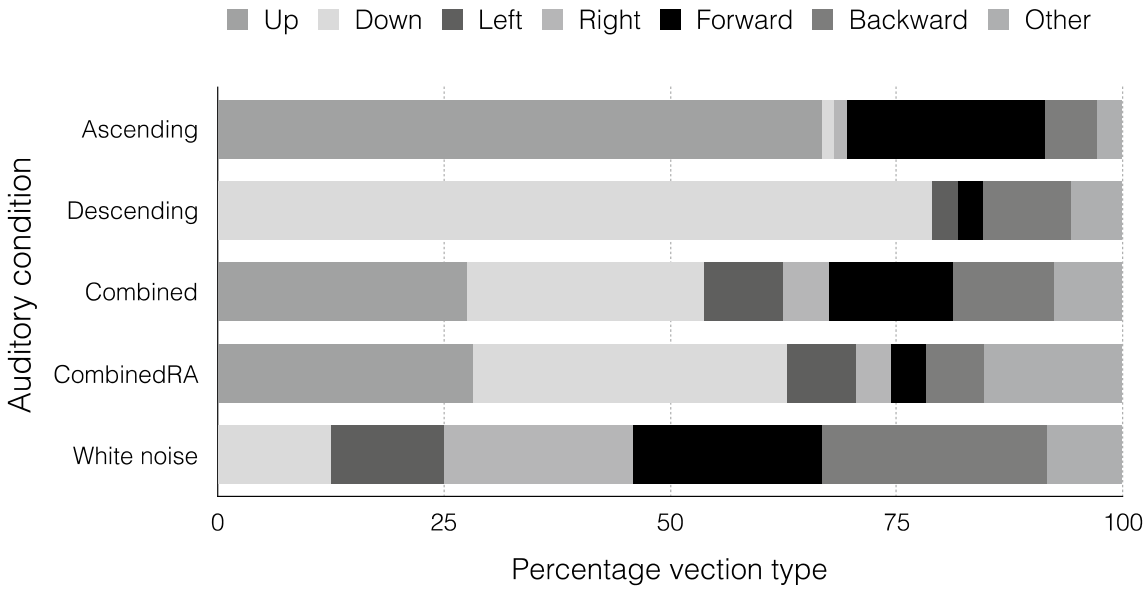


Fig. 12 Percentages of perceived vection directions for all five sound type conditions

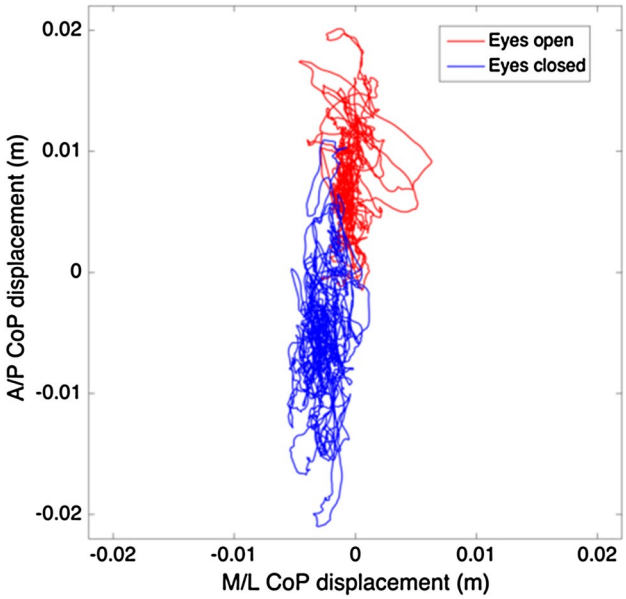


Fig. 13 Example quiet-stance anterior/posterior (A/P) and medial/lateral (M/L) sway-path for a single representative participant (EMC). This figure shows sway with eyes open over a 60 s period

reported in 8% of trials and other vection directions (circular, spiral or ambiguous motion) were reported in 15% of trials.

Relationships between auditory vection and postural instability

Prior to exposure to any visual or auditory experimental stimuli, participants stood on a balance plate with both eyes open (looking at the stationary room in which they were standing) and eyes closed for 60 s each. The CoP displacement data (in metres) were first smoothed using a low-pass order-5 Butterworth filter with a cut-off frequency of 10 Hz (to remove unwanted high-frequency artefacts). The smoothed anterior/posterior (A/P) and medial/lateral (M/P) CoP data for each eyes-open and eye-closed recording were then converted into sway path length estimates. Path length was calculated as the total distance travelled in meteres by the centre of pressure (CoP) over each 60 s period. Figure 13 provides examples of the eyes open and eyes closed sway paths for one participant (EMC).

To examine the possibility that individual differences in postural stability might predict auditory vection strength, onset and duration measures, linear regression analyses were performed. The Romberg quotient (i.e. eyes-closed/eyes-open ratio) for path length served as the predictor for these analyses and the averaged vection strength ratings for the four Shepard–Risset glissando stimuli served as the dependent variable. The linear regression revealed that the Romberg ratio of sway path

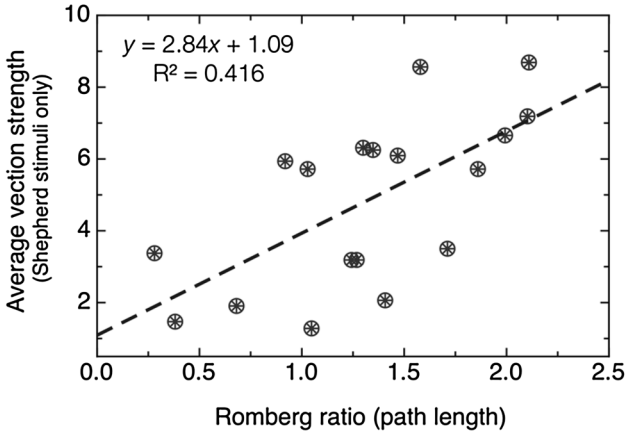


Fig. 14 The relationship between individual differences in eyes-closed/eyes-open sway path length and the average vection strength induced by the four different Shepard stimuli

length significantly predicted auditory vection strength ratings ($R^2 = 0.41$, $t_{17} = 3.38$, $p = 0.004$)—see Fig. 14.[7] That is, participants who swayed more with eyes closed compared to open also tended to experience stronger vection on average.

A Spearman's Rank Order correlation was also run to check whether this relationship might have been due to the influence of outliers. In this analysis, the relationship between postural instability and auditory vection strength remained statistically significant [$r_s(16) = 0.667$, $p = 0.002$].

Discussion

Our results support the proposal that auditory vection can be induced via purely metaphorical self-motion stimuli (Shepard–Risset glissando stimuli). A number of factors indicate that the auditory vection experienced in this experiment was genuine. Auditory vection was reported by all 20 participants and was induced in 77.25% of trials. In addition, all four types of Shepard–Risset glissando stimuli were found to induce auditory vection at strengths that were comparable to the visual vection reference stimulus (even though the visual vection stimuli were simulating actual self-motion and the Shepard–Risset glissando auditory vection stimuli were only metaphorical, lacking inherent spatial or

[7] Romberg ratios of sway path length did not significantly predict auditory vection onset ($R^2 = 0.003$, $t_{16} = 0.219$, $p = 0.830$) or auditory vection duration ($R^2 = 0.118$, $t_{16} = 1.414$, $p = 0.178$). However, these null findings were not unexpected, as past studies have only been able to predict vection strength ratings using postural instability.

self-motion information). It should be noted that whilst the visual vection reference stimulus was perceived to be compelling by the experimenters, it can only be assumed that our naive participants all experienced strong vection—and that, by comparison, their experiences of auditory vection were also strong—because absolute vection strength was not measured in this study. Future studies should explicitly rate the absolute strength of these vection experiences to assure a fairer comparison between modalities.

Nine of our participants also reported experiencing auditory vection during some of the white-noise trials (the remaining 11 participants only reported auditory vection during Shepard–Risset glissando stimuli trials). This was unexpected as the white-noise trials were originally included as auditory non-vection controls. While these nine participants might have been more responsive to demand characteristics during the experiment, it is also possible that the auditory vection they experienced during white noise was genuine (e.g. one participant EC spontaneously reported feeling "Like I'm being pushed down by something" in response to white-noise during debriefing). Importantly, the four Shepard–Risset glissando stimuli always induced significantly more compelling auditory vection (in terms of vection strength, latency and duration) than the white-noise control, providing partial support that the auditory vection elicited by Shepard–Risset glissandi was genuine.[8]

Further evidence that the vection induced by the four Shepard–Risset glissando stimuli was genuine was provided by the postural instability data. Consistent with the findings of previous studies on visual vection (e.g. Apthorp et al. 2014; Palmisano et al. 2014), we found that individual differences in spontaneous postural instability also predicted the (averaged) strength of the auditory vection induced by our Shepard stimuli. The observed pattern of data, however, was contrary to what we predicted. That is, participants who swayed more with eyes closed compared to eyes open also tended to experience stronger auditory vection.

It is possible that the Shepard–Risset glissandi elicited visual percepts/imagery which in turn induced vection. For example, Mast et al. (2001) found evidence that vection was enhanced by conditions which also involved the mental imagery of visual motion. Further consistent with this possibility, Shimizu et al. (2007) have also attributed the characteristic patterns of brain activity in the occipital lobe evoked by Shepard scales to visual imagery.

[8] We ran a subsequent analysis with these nine participants removed. The same pattern of significant results was found when those who reported auditory vection to white noise (potentially high demand) were excluded.

However, the perception and control of self-motion receives contributions from multiple modalities. Likewise, postural control relies on complex multisensory integration (e.g. Apthorp et al. 2014; Butler et al. 2010; Stoffregen et al. 2000). Thus, just as vision is not the only sense that contributes to the maintenance of posture, vection is also determined by other processes than vision alone. Therefore, it is also possible that eyes open and closed differences in postural instability are predictive of individual susceptibility to vection across modalities. Conclusions in this regard cannot be made from the current data. Further systematic examination will be required. Nevertheless, this predictive relationship appears to provide additional confirmatory evidence that the auditory vection induced by metaphorical Shepard–Risset glissando stimuli was authentic.

It is worth mentioning that the future of vection research lies in relying less definitively on subjective reports and in developing more objective indices (see Palmisano et al. 2015). This will be particularly important for further improving the investigation of auditory vection (which as shown in this study is increasingly being shown to be heavily influenced by cognitive factors). Recent research has begun to utilise electroencephalography (EEG) as an objective marker of visual vection (Keshavarz and Berti 2014; Keshavarz et al. 2015; Palmisano et al. 2016). Thus, future studies should also examine the phenomenon of auditory vection using EEG.

We had also predicted that auditory vection would be stronger for stimuli portraying a consistent metaphorical direction (e.g. only ascending glissando, as opposed to overlaid ascending/descending glissandos). However, we failed to find a difference between our consistent directional (ascending/descending) stimuli versus and our less stable or bi-stable (combined/combined-adjusted) Shepard stimuli. On the one hand, this null finding might simply have resulted because multiple vection directions were commonly perceived for all four of these auditory stimuli (i.e. the ascending/descending stimuli were perceived to be more stable than the combined stimuli). Alternatively, participants might have predominantly only attended to one of the two glissando directions at any given time, similar to optical bi-stable illusions like the rotating Necker cube (where viewers can perceive one consistent motion direction for a certain period of time before the percept might switch to the opposite direction).

It was expected that there would be metaphorical association between ascending/descending pitch and upwards/downwards motion of the listener. Indeed, ascending Shepard–Risset glissandi elicited predominantly upwards vection and descending Shepard–Risset glissandi elicited predominantly downwards vection. As mentioned previously, this association is not what would be expected based on physics, but rather naïve intuition. Subjective

reports of forwards/backwards (in depth) vection directions were also frequent. The latter may be explained by the Doppler Effect: a listener moving in depth towards a sound source would perceive an increase in pitch and a subsequent decrease in pitch as they move away. Thus, the way in which the Shepard–Risset glissandi were interpreted could have influenced the perceived direction of self-motion. That is, listeners can either (1) integrate their perception of self-motion with the direction of the sound or (2) perceive themselves as moving relative to a stationary sound source. Interestingly, the former interpretation is contrary to what is observed in visual vection studies; i.e. elements moving visually upwards/downwards tend to elicit vection in the opposite direction.

A surprising finding was that in the context of previous research the metaphorical auditory vection experienced in the current study appeared to be stronger than the typical low-level sensory auditory vection induced by moving sound fields. Metaphorical auditory vection was comparable to that induced by the ecological visual vection reference stimulus and was reported by all of our participants, whereas auditory vection in past research tended to be transient and present in less than 60% of participants (Riecke et al. 2009). This suggests that metaphorical auditory vection might be stronger in nature than that induced by low-level, physically accurate sound stimuli. Indeed, Riecke et al. (2005) and Väljamäe and Sell (2014) have highlighted the importance of top-down cognitive processes over low-level sensory cues in auditory vection. As auditory pitch discrimination is much clearer and accurate compared to sound localization, this might also have contributed to the surprisingly strong vection-inducing potential of Shepard–Risset glissandos as compared to moving spatialized sound fields. However, further research will be needed to directly compare these different types of auditorily induced vection.

Seno et al. (2012a) found that pure tones increasing/decreasing in pitch or intensity could enhance visually induced vection when presented simultaneously. Whilst their sound stimuli were not sufficient to induce vection on their own, they found that upwards/downwards visual vection was enhanced by pure tone sound stimuli which increased/decreased in frequency. The current study examined metaphorical auditory stimuli in isolation; however, considering these Shepard–Risset glissandi were able to induce (primarily vertical) auditory vection, it would be interesting to see whether adding them to visual displays simulating vertical self-motion would enhance visually induced vection in a manner analogous to Seno et al. (2012a, b), or whether the audio and visual presentations would interact differently.

In summary, the current study demonstrated that it is possible to induce metaphorical auditory vection by Shepard–Risset glissando stimuli in blind-folded, stationary participants. In line with previous commentaries in the auditory vection literature, the current evidence suggests that auditory contributions to self-motion perception might be based more heavily on higher-level cognitive factors. However, future research is needed to directly compare low-level versus higher-level types of auditory vection.

Acknowledgements This research was conducted with the support of the Australian Government Research Training Program Scholarship awarded to RAM. It was also supported by a University of Wollongong, Faculty of Social Sciences, Near Miss Grant awarded to SP.

References

Apthorp D, Nagle F, Palmisano S (2014) Chaos in balance: non-linear measures of postural control predict individual variation in visual illusions of motion. PLoS One 9(12):e113897. doi:10.1371/journal.pone.0113897

Brandt T, Dichgans J, Koenig E (1973) Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. Exp Brain Res 16:476–491. doi:10.1007/BF00234474

Butler JS, Smith ST, Campos JL, Bülthoff HH (2010) Bayesian integration of visual and vestibular signals for heading. J Vis 10(11):1–13. doi:10.1167/10.11.23

Deutsch D (1992) Some new pitch paradoxes and their implications. Philos Trans R Soc Lond B Biol Sci 336:391–397. doi:10.1098/rstb.1992.0073

Dodge R (1923) Thresholds of rotation. J Exp Psychol 6:107–137. doi:10.1037/h0076105

Eitan Z, Granot RY (2006) How music moves: musical parameters and listeners' images of motion. Music Percept 23:221–247. doi:10.1525/mp.2006.23.3.221

Hedger S, Nusbaum H, Lescop O, Wallisch P, Hoeckner B (2013) Music can elicit a visual motion aftereffect. Atten Percept Psychophys 75:1039–1047. doi:10.3758/s13414-013-0443-z

Hettinger LJ, Schmidt T, Jones DL, Keshavarz B (2014) Illusory self-motion in virtual environments. In: Hale KS, Stanney KM (eds) Handbook of virtual environments: design, implementation, and applications, 2nd edn. CRC Press, New York, pp 435–466

Keshavarz B, Berti S (2014) Integration of sensory information precedes the sensation of vection: a combined behavioral and event-related brain potential (ERP) study. Behav Brain Res 259:131–136. doi:10.1016/j.bbr.2013.10.045

Keshavarz B, Hettinger LJ, Vena D, Campos JL (2014) Combined effects of auditory and visual cues on the perception of vection. Exp Brain Res 232:827–836. doi:10.1007/s00221-013-3793-9

Keshavarz B, Campos JL, Berti S (2015) Vection lies in the brain of the beholder: EEG parameters as an objective measurement of vection. Front Psychol 6:1581. doi:10.3389/fpsyg.2015.01581

Keshavarz B, Speck M, Haycock B, Berti S (2017) Effect of different display types on vection and its interaction with motion direction and field dependence. iPerception 8(3):1–18. doi:10.1177/2041669517707768

Lackner JR (1977) Induction of illusory self-rotation and nystagmus by a rotating sound-field. Aviat Space Environ Med 48:129–131

Larsson P, Västfjäll D, Kleiner M (2004) Perception of self-motion and presence in auditory virtual environments. Proceedings of the seventh annual workshop of presence, Valencia, Spain 2004, pp 252–258. http://www.kyb.mpg.de/publication.html?publ=2953

Lepecq JC, Giannopulu I, Baudonniere PM (1995) Cognitive effects on visually induced body motion in children. Perception 24(4):435–449. doi:10.1068/p240435

Mast FW, Berthoz A, Kosslyn SM (2016) Mental imagery of visual motion modifies the perception of roll-vection stimulation. Perception 30(8):945–957

Neuhoff JG, McBeath MK (1996) The Doppler illusion: the influence of dynamic intensity change on perceived pitch. J Exp Pyschol Hum Percept Perform 22(4):970–985. doi:10.1037/0096-1523.22.4.970

Ogawa M, Seno T (2014) Vection is modulated by the semantic meaning of stimuli and experimental instructions. Perception 43(7):605–615

Olson HF (1972) The measurement of loudness. Audio 25(2):18–22

Orini M, Laguna P, Mainardi LT, Bailón R (2012) Influence of music emotional valence on cardio-respiratory coupling. In: The twelfth international workshop on biosignal interpretation, Como, Italy

Palmisano S, Chan AYC (2004) Jitter and size effects on vection are immune to experimental instructions and demands. Perception 33:987–1000. doi:10.1068/p5242

Palmisano S, Apthorp D, Seno T, Stapley PJ (2014) Spontaneous postural sway predicts the strengths of smooth vection. Exp Brain Res 232(4):185–1191. doi:10.1007/s00221-014-3835-y

Palmisano S, Allison R, Schira M, Barry RJ (2015) Future challenges for vection research: definitions, functional significance, measures and neural bases. Front Psychol 6:1–15. doi:10.3389/fpsyg.2015.00193/full

Palmisano S, Barry RJ, De Blasio FM, Fogarty JS (2016) Identifying objective EEG based markers of linear vection in depth. Front Psychol 7:1205. doi:10.3389/fpsyg.2016.01205

Pigeon S (2013) Shepard madness: Binaural Shepard tone generator. My noise. https://mynoise.net/NoiseMachines/shepardAudioIllusionToneGenerator.php. Accessed 20 July 17

Plack CJ, Oxenham AJ, Fay RR (2006) Pitch: neural coding and perception. Springer, New York

Purves D, Augustine GJ, Fitzpatrick D et al (2001) Neuroscience, 2nd edn. Sinauer Associates, Sunderland

Riecke BE (2009) Cognitive and higher-level contributions to illusory self-motion perception ("vection"): does the possibility of actual motion affect vection. Jpn J Psychon Sci 28(1):135–139. doi:10.14947/psychono.KJ00005878681

Riecke BE (2010) Compelling self-motion through virtual environments without actual self-motion—using self-motion illusions ("vection") to improve user experience in VR. In: Kim J (ed) Virtual reality. InTech, Rijeka, Croatia, pp 149–176. doi:10.5772/13150

Riecke BE, Västfjäll D, Larsson P, Schulte-Pelkum J (2005) Top-down and multi-modal influences on self-motion perception in virtual reality. In: 11th International conference on Human-Computer Interaction (HCI International 2005). Erlbaum, Mahwah, NJ, USA, pp 1–10

Riecke BE, Schulte-Pelkum J, Avraamides MN, Von Der Heyde M (2006) Cognitive factors can influence self-motion perception (vection) in virtual reality. ACM Trans Appl Percept 3:194–216. doi:10.1145/1498700.1498701

Riecke BE, Väljamäe A, Schulte-Pelkum J (2009) Moving sounds enhance the visually induced self-motion illusion (circular vection) in virtual reality. ACM Trans Appl Percept 6:1–26. doi:10.1145/1498700.1498701

Seno T, Fukuda H (2012) Stimulus meaning alter illusory self-motion (vection)—experimental examination of the train illusion. See Perceiving 25:631–645. doi:10.1163/18784763-00002394

Seno T, Hasuo E, Ito H, Nakajima Y (2012a) Perceptually plausible sounds facilitate visually induced self-motion perception (vection). Perception 41:577–593. doi:10.1068/p7184

Seno T, Ito H, Sunaga S (2012b) Vection can be induced in the absence of explicit motion stimuli. Exp Brain Res 219:235–244. doi:10.1007/s00221-012-3083-y

Seno T (2013) Music modulates the strength of vection. Psychology 4(7):566–568

Shepard RN (1964) Circularity in judgments of relative pitch. J Acoust Soc Am 36:2346–2353

Shimizu Y, Umeda M, Mano H, Aoki I, Higushi T, Tanaka C (2007) Neuronal response to Shepard's tones. An auditory fMRI study using multifractal analysis. Brain Res 1186:113–123. doi:10.1016/j.brainres.2007.09.097

Stoffregen TA, Pagulayan RJ, Bardy BG, Hettinger LJ (2000) Modulating postural control to facilitate visual performance. Hum Mov Sci 19:203–220. doi:10.1016/S0167-9457(00)00009-9

Väljamäe A (2009) Auditorily-induced illusory self-motion: a review. Brain Res Rev 61:240–255. doi:10.1016/j.brainresrev.2009.07.001

Väljamäe A, Sell S (2014) The influence of imagery vividness on cognitive and perceptual cues in circular auditorily-induced vection. Front Psychol 5:1–8. doi:10.3389/fpsyg.2014.01362

Väljamäe A, Larsson P, Västfjäll D, Kleiner M (2004) Auditory presence, individualized head-related transfer functions, and illusory ego-motion in virtual environments. In: Proceedings of the seventh annual workshop of presence, Valencia, Spain, pp 141–147

Väljamäe A, Larsson P, Västfjäll D, Kleiner M (2005) Traveling without moving: auditory scene cues for translational self-motion. In: Proceedings of the eleventh International conference on auditory display, Limerick, Ireland, pp 1–8

Väljamäe A, Larsson P, Västfjäll D, Kleiner M (2008) Sound representing self-motion in virtual environments enhances linear vection. Presence Teleoper Virtual Environ 17:43–56. doi:10.1162/pres.17.1.43

Vernooij E, Orcalli A, Fabbro F, Crescentini C (2016) Listening to the Shepard–Risset glissando: the relationship between emotional response, disruption of equilibrium, and personality. Front Psychol 7(300):1–10. doi:10.3389/fpsyg.2016.00300