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Review

Beyond the Eye: Multisensory Contributions to the Sensation of Illusory Self-Motion (Vection)

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Abstract

Vection is typically defined as the embodied illusion of self-motion in the absence of real physical movement through space. Vection can occur in real-life situations (e.g., 'train illusion') and in virtual environments and simulators. The vast majority of vection research focuses on vection caused by visual stimulation. Even though visually induced vection is arguably the most compelling type of vection, the role of nonvisual sensory inputs, such as auditory, biomechanical, tactile, and vestibular cues, have recently gained more attention. Non-visual cues can play an important role in inducing vection in two ways. First, nonvisual cues can affect the occurrence and strength of vection when added to corresponding visual information. Second, nonvisual cues can also elicit vection in the absence of visual information, for instance when observers are blindfolded or tested in darkness. The present paper provides a narrative review of the literature on multimodal contributions to vection. We will discuss both the theoretical and applied relevance of multisensory processing as related to the experience of vection and provide design considerations on how to enhance vection in various contexts.

Keywords

vection, self-motion, multisensory integration, virtual reality, auditory, biomechanical, tactile, haptic, visual, vestibular, cue integration, simulation

1. Introduction

Illusory self-motion ('vection') has long fascinated humans and has been the topic of research for more than a century (Fischer and Kornmüller, 1930; Fischer and Wodak, 1924; Helmholtz, 1866; Mach, 1875; Urbantschitsch, 1897; Warren, 1895; Wood, 1895). A classic example of vection in the real world is the 'train illusion', whereby the visual motion of a train leaving the train station causes the passenger of an adjacent, stationary train to erroneously perceive their own train as moving. Vection can be perceived in all six degrees of freedom and can be subdivided into circular vection (i.e., self-rotation about any of the three body axes; yaw, pitch, roll and their combination; Allison *et al.*, 1999; Dichgans and Brandt, 1978; Held *et al.*, 1975; Wood, 1895; Young *et al.*, 1975), linear vection (i.e., translational self-motion in any of the three linear directions and their combinations; Berthoz *et al.*, 1975; Johansson, 1977; Lepecq *et al.*, 1993) and curvilinear vection (i.e., combined rotational and translational self-motion — Riecke and Feuereissen, 2012; Riecke and Jordan, 2015; Sauvan and Bonnet, 1993).

Traditionally, the vast majority of vection research has focused on illusory self-motion induced by visual stimulation (see reviews by Andersen, 1986; Dichgans and Brandt, 1978; Howard, 1982, 1986; Mergner and Becker, 1990). However, real self-motion through space always involves *multisensory* stimulation and self-motion perception is informed by sensory inputs from across the auditory, vestibular, proprioceptive, and tactile senses (Campos and Bülthoff, 2012). As such, there has been increasing interest in understanding the nonvisual contributions to vection (Hettinger *et al.*, 2014; Kooijman *et al.*, 2021; Palmisano *et al.*, 2015; Riecke and Schulte-Pelkum, 2013). The multisensory contributions to vection are particularly relevant considering the current popularity and the wide-ranging application of modern virtual reality (VR) and simulation technologies. The goal of these systems is often to represent virtual experiences with high fidelity that allow users to feel fully immersed and present within the simulated environment; which can include the realistic perception of self-movements through space.

Historically, VR systems have primarily focused on stimulating the visual system; however, advancements in technology now allow for more effective integration of additional sensory information such as spatialized auditory cues (e.g., *via* headphones), tactile cues (e.g., *via* gloves), or biomechanical cues (e.g., *via* omnidirectional treadmills). Such *multimodal* systems are thought to increase the levels of immersion, presence, and sensory–motor correspondence, which could be important for a variety of applications such as gaming, entertainment, healthcare, education, training, and telepresence/telerobotics. Consequently, a growing number of studies have begun to consider how nonvisual cues, either presented in isolation (e.g., auditory, biomechanical, or tactile

cues alone) or combined with visual or other nonvisual cues, may alter the sensation of vection. In general, while there is indeed evidence that nonvisual sensory inputs alone can induce vection and that multisensory stimulation can further enhance vection compared to unimodal stimulation, the findings in the literature are mixed. Therefore, gaining a better understanding of when and how multisensory stimulation can influence vection is not only important to advance our fundamental understanding of vection and multimodal cue integration, but can also help to better maximize or minimize vection (depending on the desired outcome) across a variety of applications.

The objectives of this narrative review are to summarize and synthesize the state-of-the-art in multisensory vection research. Notably, the goal of the present review is not to provide an overview of vection in general, as several comprehensive reviews of vection have previously been published (Hettinger et al., 2014; Palmisano et al., 2015; Riecke, 2011). Instead, we will review what is currently known about how different nonvisual sensory modalities such as auditory, tactile, proprioceptive, and vestibular cues contribute to vection, when presented in isolation or in combination with visual inputs and in combination with each other. Importantly, in this review we only focus on studies that specifically report on vection-related outcomes, such as (but not limited to) vection intensity, onset time/latency, duration, and compellingness (see Berti and Keshavarz, 2020; Kooijman et al., 2023a; Palmisano et al., 2015: Warren and Wertheim, 1990 for an overview of vection measures). Further, we do not include in this review studies that report on the perception of self-motion parameters (e.g., estimated traveled distance, heading, velocity) in the absence of explicit vection-related measures (Harris et al., 2000, 2002; Higashiyama and Koga, 2002; Jürgens and Becker, 2006, 2011). Additionally, we excluded studies that manipulated a sensory cue that did not explicitly convey the sense of vection, such as manipulating one's body position (e.g., supine or upright; Groen and Bles, 2004; Guterman and Allison, 2019; Kano, 1991; Mori et al., 2017; Nakamura and Shimojo, 1998; Oyamada et al., 2020). In the subsequent sections, we will first discuss the ability of each individual nonvisual sensory modality to induce vection before discussing modality-specific contributions to multimodal vection when added to other modalities. Overall, we identified 95 experiments presented across 85 papers, and summarized them in Supplementary Table S1).

While the literature generally agrees that vection involves an embodied perception of self-motion, there are differences with respect to whether vection is defined as mediated by visual cues alone or could be elicited by other sensory cues, and if vection is an 'illusion' in the sense that the person experiencing vection is not physically moving (or at least not moving much), or if any subjective experience of self-motion should be referred to as vection (Palmisano *et al.*, 2015). As the focus of this review is on multisensory contributions to vection, we include any sensory contributions to self-motion perception (not just visual). We also include situations with limited physical observer motions, such as walking along a treadmill while otherwise being stationary ('biomechanical vection', see section 4), VR situations where users sit on a moving-based motion simulator providing motion cueing, or VR users employing leaning to control the simulated self-motion (typically using velocity or acceleration control), as discussed in section 6. We do, however, exclude situations where the simulated or experienced self-motion is directly (e.g., linearly) related to the physical observer motion, such as when using physical walking in VR, or redirected/scaled walking.

2. Visual Vection

Visually-induced vection is the most widely studied type of vection and has been well documented and discussed previously (Andersen, 1986; Dichgans and Brandt, 1978; Howard, 1982, 1986; Mergner and Becker, 1990; Palmisano et al., 2011; Riecke, 2011; Schulte-Pelkum, 2007; Warren and Wertheim, 1990). Visual vection can be induced using, for example, optokinetic drums, swinging rooms, or VR displays (e.g., head-mounted displays or projectionbased systems; Brandt et al., 1973; Dichgans and Brandt, 1978; Mach, 1875). A variety of factors can affect the perception of visually-induced vection, such as the physical field-of-view (FOV), the distinction between foreground and background, and certain optic flow characteristics (e.g., speed, trajectory). For instance, increasing the FOV has long been known to enhance visual vection, both for abstract optic flow patterns like stripes and dots (Andersen and Braunstein, 1985; Brandt et al., 1973; Dichgans and Brandt, 1978; Howard and Heckmann, 1989), as well photorealistic VR stimuli (Riecke et al., 2009a). In fact, full-field stimulation can induce vection indistinguishable from physical self-motion and can no longer be easily suppressed (i.e., saturated vection; Berthoz et al., 1975; Brandt et al., 1971; Held et al., 1975; Palmisano and Gillam, 1998). Increasing the density of the optic-flow stimulus and increasing the velocity (but not necessarily the acceleration) of the moving visual pattern generally enhances vection up to a certain optimal stimulus velocity, but not further (Allison et al., 1999; Berthoz et al., 1975; Brandt et al., 1973; Dichgans and Brandt, 1978; Howard, 1986; Keshavarz et al., 2019; Schulte-Pelkum et al., 2003). Other factors contributing to increased vection include, for example, stereoscopic (relative to monocular or binocular) presentation (Allison et al., 2014; Lowther and Ware, 1996; Palmisano, 1996, 2002), fixating a stationary foreground or staring at the visual stimulus instead of relaxed viewing (Fischer and Kornmüller, 1930; Mach, 1875; Wallach, 1940; H. C. Warren, 1895), or adding simulated viewpoint or display jitter (Bubka and Bonato, 2010; Nakamura, 2010; Palmisano et al., 2000, 2003,

2011). In general, much has been learned about visual vection and several comprehensive reviews have been published recently (Berti and Keshavarz, 2020; Hettinger *et al.*, 2014; Kooijman *et al.*, 2021; Lawson and Riecke, 2014; Palmisano *et al.*, 2015; Riecke and Schulte-Pelkum, 2013, 2015). As such, the current review will primarily focus on other nonvisual sensory contributions to vection.

3. Auditory Vection

Although visually induced vection has received the most attention in the literature, it has long been known that blindfolded stationary listeners can also experience so-called auditory or audiokinetic vection from moving sound fields (Dodge, 1923; Stein, 1910, as cited in Dichgans and Brandt, 1978; Urbantschitsch, 1897). Detailed descriptions of auditory vection and associated factors have been previously reviewed (Hettinger et al., 2014; Riecke et al., 2009a; Väljamäe, 2009). Like visual vection, auditory vection can be experienced in circular and linear dimensions. Auditory vection can be induced by a variety of spatialized sound setups, such as speaker arrays positioned around the listener, or headphones producing binaural recordings or synthesized using head-related transfer function (HRTF) convolution (Dodge, 1923; Keshavarz et al., 2014a; Lackner, 1977; Marme-Karelse and Bles, 1977; Riecke et al., 2009b; Sakamoto et al., 2004; Väljamäe et al., 2005, 2008). While visual vection can be experienced by virtually all observers and can be indistinguishable from actual self-motion for full-field stimulation (Berthoz et al., 1975; Brandt et al., 1971; Held et al., 1975; Palmisano and Gillam, 1998), auditory vection is typically much weaker and less frequently observed (Väljamäe, 2009; Väljamäe and Sell, 2014). Auditory vection in blindfolded listeners can also be elicited by using auditory metaphorical motions using a Shepard-Risset glissando, a sound stimulus that is perceived to perpetual ascend (or descend) in pitch but is not spatialized (Mursic and Palmisano, 2020, 2022; Mursic et al., 2017), and can result in surprisingly compelling vection, almost at the level of visually induced vection (Mursic et al., 2017).

3.1. Combined Auditory and Visual Vection

Although auditory cues presented in isolation only create weak to moderate vection and only in 20–80% of blindfolded listeners, adding spatialized sound can significantly enhance vection when the sound moves congruently with the visual stimulus (Gagliano, 2016; Keshavarz *et al.*, 2014a; Riecke *et al.*, 2005a, b; Riecke *et al.*, 2009a). For instance, Riecke *et al.* (2009a) showed that vection intensity was increased when a rotating image of a marketplace scene was coupled with corresponding rotating sound cues, compared to a visual-only condition. However, adding stationary (nonrotating) auditory cues by

using binaurally recorded ambient sound that matched the visual scene but was not rotating did not significantly reduce vection compared to the visual-only condition (Riecke *et al.*, 2009a). Furthermore, adding nonspatialized (mono) sound did not further enhance circular vection, suggesting that the spatialization and movement of the sound sources is likely to have facilitated vection. Similar facilitating effects have also been found in trimodal paradigms (Kruijff *et al.*, 2016; Murovec *et al.*, 2021), where adding spatialized auditory cues to visual and tactile cues enhanced circular vection (i.e., increased intensity) compared to conditions where sound was not present.

While the majority of literature shows a small but significant vection enhancement when adding auditory to visual cues, a small number of studies have not observed these beneficial effects (Keshavarz and Hecht, 2012a, b; Ramkhalawansingh *et al.*, 2016). One factor that may contribute to the discrepancy across studies relates to the strength of the visual stimulus, in that very strong vection-inducing visual stimuli may leave less room for added benefits from additional sensory inputs (i.e., lead to ceiling effects). This is illustrated in Riecke *et al.* (2009a), where vection intensity was increased when auditory cues were added to the rotating visual scene, and this bimodal vection-facilitating effect was further enhanced when the field of view of the visual stimulus was reduced from $54^{\circ} \times 45^{\circ}$ to $20^{\circ} \times 15^{\circ}$, suggesting that the presence of multisensory cues was particularly effective in situations where the visual cue alone was less vection-inducing. However, this effect of greater bimodal benefits under conditions of weaker visual vection is not consistently observed (see Murovec *et al.*, 2021).

There is also some evidence that nonspatialized sounds can also enhance visually induced vection depending on the particular characteristics of the sounds (Mursic et al., 2017; Seno et al., 2012). For example, sounds increasing in intensity (as if approaching) can enhance forward vection when accompanied with radially expanding visual stimuli; however, this effect is not similarly observed for receding intensity and backward vection (Experiment 1; Seno et al., 2012). Additionally, when presented with vertical motions, ascension and descension of sound frequency (e.g., pitch) facilitate upward and downward vection, respectively (Experiment 2; Seno et al., 2012). Seno (2013) demonstrated that adding music with a fast tempo increased vection (lower vection latencies and longer durations) compared to slower tempo music and no music. The authors suggest that perceptual plausibility and cross-modal consistency might be an underlying factor explaining these observations (see also Hollya and McCollumb, 2008; Riecke et al., 2005c; Riecke et al., 2006a; Väljamäe et al., 2005). However, especially for metaphorical and other higher-level (such as top-down or cognitive) contributions to vection, other factors like experimental demand characteristics and participants expectations and speculations might also play a role (see also discussion in Palmisano et al., 2015; Riecke et *al.*, 2015a), and further studies are needed to investigate if such metaphorical vection is strong enough to also provide behavioral benefits such as helping to facilitate perspective switches (Riecke *et al.*, 2015a).

4. Biomechanical Vection

Biomechanical vection refers to the illusion of moving through space that is caused by sensory cues generated through, for example, walking on a circular treadmill while being otherwise stationary. These cues may include a combination of proprioceptive, tactile, and vestibular cues. These cues typically occur due to the active movement of the legs; however, other body movements such as arm movements have also been shown to influence vection. A variety of names have been used to refer to vection induced by circular or curvilinear walking motions, including *'biomechanical'* vection (Bruggeman *et al.*, 2009; Riecke *et al.*, 2011), 'apparent stepping around' (Bles, 1981; Bles and Kapteyn, 1977), *'podokinesthetic'* vection (Becker *et al.*, 2002), and *'podokinesthetic'* vection (Jürgens and Becker, 2011). For the sake of consistency, we will use the term biomechanical vection in this review.

VR-integrated walking interfaces are becoming increasingly available, affordable, and sophisticated (Di Luca *et al.*, 2021; Nilsson *et al.*, 2018; Steinicke *et al.*, 2013) and can include, for example, linear treadmills, circular treadmills, omnidirectional treadmills, and low-friction surfaces (Campos and Bülthoff, 2012; Cherni *et al.*, 2020; Frissen *et al.*, 2013; Riecke *et al.*, 2018). Circular treadmill walking often involves stepping along a rotating floor plate, similar to a carousel, in order to remain stationary in place. Omnidirectional treadmills allow for walking in all directions (e.g., Cherni *et al.*, 2020; Frissen *et al.*, 2013; Riecke *et al.*, 2018).

Circular treadmills have been shown to induce vection fairly reliably, and lead to circular vection when people are positioned above the rotation center, and curvilinear vection when people walk off-center (Becker *et al.*, 2002; Bles, 1981; Bles and Kapteyn, 1977; Garing, 1999; J. Lackner and DiZio, 1984; Riecke *et al.*, 2015b). However, walking even on highly sophisticated linear or omnidirectional treadmills does not seem to be sufficient for reliably inducing vection (Durgin *et al.*, 2005; Riecke and Schulte-Pelkum, 2013). This discrepancy is surprising given that that the biomechanics of linear treadmills are equipped with force feedback harnesses (Hollerbach, 2002; Steinicke *et al.*, 2013), whereas walking on circular treadmills is arguably less common. Nevertheless, biomechanical circular vection can be induced in most blindfolded observers, with reported rates of occurrence including 80% (Garing, 1999), 90% (Bruggeman *et al.*, 2009) and almost 100% (Bles, 1981; Riecke *et al.*, 2015a). Biomechanical circular vection tends to be

much more compelling than auditory vection, yielding vection intensity ratings comparable to visually induced circular vection (Riecke *et al.*, 2015b).

Sensations of illusory self-motion can also be achieved by passive arm movements. When participants are seated stationary inside a completely dark optokinetic drum that slowly rotates around the earth-vertical axis, participants can experience strong illusory self-rotation (arthrokinetic circular vection) by reaching out to touch the moving walls of the drum with their hand, and letting their arm be passively rotated around their shoulder joint (Brandt *et al.*, 1977). Such arthrokinetic vection was reported as quite compelling with a very short onset latency (1–3 s), and could not be distinguished from actual self-motion. This was corroborated by an arthrokinetic nystagmus and considerable after-effects for both nystagmus and circular vection. Further, producing hand-over-hand walking-like sideways motions to stay in contact with a sideways-moving desk-like platform elicited linear sideways vection in 37% of trials (Bles *et al.*, 1995).

4.1. Combined Biomechanical and Visual Vection

Although biomechanical cues provided by circular treadmill walking have been shown to induce compelling sensations of circular vection when presented alone (Bles, 1981; Garing, 1999; Lackner and DiZio, 1984; Riecke et al., 2015b), surprisingly little research to date has investigated the contribution of these cues when jointly presented with corresponding visual cues. In one of the first studies investigating the effect of visual combined with biomechanical cues on vection, Lackner and DiZio (1988) had participants walk off-center on a rotatable circular platform centered inside a large, independently rotatable optokinetic drum. When the platform and the drum rotated synchronously and in the same direction while participants were stepping to stay in place, most participants reported a compelling sensation of vection, resulting in feelings of saturated vection (e.g., that they were forward-walking off-center on a stationary circular platform inside a stationary drum (Bles and Kapteyn, 1977; DiZio and Lackner, 2002). Freiberg et al. (2013) and Riecke et al. (2015b) compared vection ratings when rotating visual cues and biomechanical cues from stepping along a circular treadmill were presented either individually or simultaneously. In both studies, vection onset times were fastest and vection intensity and vection compellingness were highest in the bimodal conditions compared to either one of the unimodal conditions.

Interestingly, unlike circular vection, the act of walking on a *linear* treadmill by itself is insufficient to reliably induce vection (Riecke and Schulte-Pelkum, 2013), and forward linear vection can even be *reduced* if visual cues are combined with biomechanical cues from walking on a linear treadmill (Ash *et al.*, 2013; Kitazaki *et al.*, 2010; Onimaru *et al.*, 2010; Palmisano *et al.*, 2014; see also discussion in Riecke and Schulte-Pelkum, 2013), even if visual

and walking speeds are the same (but see Seno et al., 2011a). For instance, compared to standing still, vection is reduced when expanding optic flow (simulating forward self-motion) is combined with forward linear treadmill walking at the same speed (Ash et al., 2013; Kitazaki et al., 2010; Onimaru et al., 2010; Palmisano et al., 2014). Similarly, backward vection is reduced when visually contracting optic flow simulating backward motion is combined with backward treadmill walking (Onimaru et al., 2010). The underlying reasons for reductions in visual vection for linear treadmill walking are not yet fully understood and several possible explanations have been discussed (Ash et al., 2013; Riecke and Schulte-Pelkum, 2013). For example, this effect could be related to the 'freezing illusion' as described by Wertheim and Reymond (2007), where an optic-flow pattern suddenly appears to freeze when vestibular stimulation is added. Another explanation is offered by the 'Pavard and Berthoz' effect (Pavard and Berthoz, 1977), in that the walking cues may reduce the perceived relative visual speed (see also Durgin et al., 2005b), and thus, result in decreased vection. It remains an open question, though, how these potential explanations might contribute to inhibiting only biomechanical linear, but not circular vection.

The addition of arm movements, on the other hand, has been shown to increase linear vection when accompanied with visual stimulation. For instance, linear vection in depth was enhanced when standing observers were exposed to visual cues while mimicking breaststroke swimming using arm and upper-body movements, and vection enhancement was stronger for congruent optic flow (expanding optic flow simulating forward self-motion) than incongruent (backward) optic flow (Seno *et al.*, 2013).

4.2. Combined Biomechanical and Auditory Vection

Biomechanically-induced circular vection can also be influenced by the addition of auditory stimuli. For instance, Riecke *et al.* (2011) demonstrated that the concurrent presentation of rotating binaural spatialized auditory cues during blindfolded stepping along a rotating circular treadmill that participants were seated above significantly increased vection compared to conditions where auditory and biomechanical cues were each presented in isolation. In a related study, Riecke *et al.* (2010) showed that while spatialized sound enhanced vection when the sound was rotating synchronously with the rotating circular treadmill blindfolded listeners were stepping along (while seated), vection was impaired when the spatialized sound was stationary.

5. Tactile Vection

Tactile cues to self-motion can include stimuli such as sliding touch, airflow directed toward the skin, and vibrotactile cues. The use of tactile cues to induce

or enhance vection is becoming increasingly popular, but yielding mixed results across studies (for a review, see Costes and Lécuyer, 2023; Kooijman et al., 2021). One method of providing vection-inducing tactile stimulation is 'sliding touch', where participants use their hands or feet to touch moving surfaces in the surrounding area (Brandt et al., 1977). For example, circular vection was induced in blindfolded participants when they touched the rotating floor of a circular treadmill with their restrained feet such that they felt the floor sliding underneath their feet (Lackner and DiZio, 1984). This sensation was further strengthened when their hands also touched a circular rail that slid beneath their outstretched hands. Similarly, Dichgans and Brandt reported that touching the inside of a moving optokinetic drum in complete darkness can also induce circular vection, although vection intensity was rather weak (Dichgans and Brandt, 1978). More recently, Murovec et al. (2021) used a motorized circular ring that rotated underneath the fingertips of participants and found that although tactile cues alone elicited vection in a few participants, the overall effect was very weak and did not statistically differ from a control condition with no tactile stimulation.

Another common method of providing tactile stimulation to the skin is *via* airflow simulating wind. There is mixed evidence as to whether airflow alone can induce vection. For instance, Murata *et al.* (2014) were able to successfully induce forward linear vection in a subset of blindfolded participants when constant airflow was directed at their back, but Seno *et al.* (2011b) did not find similar results. Although the literature on vection generated by tactile cues alone is rather limited, combining tactile and other sensory cues have received more attention.

5.1. Combined Tactile/Haptic and Visual Vection

Murovec *et al.* (2021, 2022) showed that adding tactile cues (participants' hands touching a rotating circular ring) to synchronously rotating visual and auditory stimuli significantly enhanced the intensity and duration of vection compared to visual and auditory stimuli alone. However, Van Doorn *et al.* (2012) showed that vection was not enhanced when adding tactile stimulation to visual inputs by sliding the tip of a metal rod up and down the participant's back at a speed equal to the up/down motions of an optokinetic stimulus.

In a study by Ouarti *et al.* (2014), participants held a handlebar attached to a 6DOF force feedback device (Haption Virtuose; tactile and proprioceptive inputs) that pushed the handlebar in the direction and with a force aligned (or contra-aligned) with either the current acceleration or velocity vector of a visual motion scene depicted on a projection screen. Participants were instructed to resist the push/pull of the haptic device to keep it in the same position. Irrespective of whether a push or pull paradigm was used, this force feedback enhanced vection, especially when forces were proportional to

the visually displayed accelerations. This could have useful implications for low-cost vection enhancement for various vehicle simulators (e.g., helicopter simulator cyclic stick).

With regards to airflow, Seno *et al.* (2011a) found that providing wind increased the sensation of vection when presented alongside congruent, expanding optic flow (see also Feng *et al.*, 2016). However, vection was not enhanced when wind was presented with contracting optic-flow stimuli corresponding with backward self-motion, indicating the importance of multimodal directional consistency. Yahata *et al.* (2021) demonstrated increased vection when the visual stimulus of a corridor that was on fire was paired with hot-temperature wind, but not with room-temperature wind. Similarly, greater vection magnitude scores were observed when room-temperature wind was introduced in a nonfiery corridor compared to no wind.

While vibrotactile stimulation alone does not seem to be sufficient to reliably induce vection (Tinga et al., 2018), vibration cues have been shown to enhance vection when presented in addition to other sensory stimuli. For example, adding vibrations to the seat and floor plate of a motion platform or wheelchair device during visually induced vection reduced vection onset latencies and increased convincingness ratings of vection (Riecke et al., 2005b; Schulte-Pelkum, 2007). However, when vibrations did not match the velocity profile of the visual simulation, decreased vection was reported. Adding vibrations to the participants' shoes can also enhance the sensation of vection compared to visual stimulation alone (Hayashizaki et al., 2015; Ikei et al., 2014; Kitazaki et al., 2016; Kruijff et al., 2016; Matsuda et al., 2021; Nilsson et al., 2012). The type of vibration can also modulate the onset and strength of vection: for example, increased vection was experienced by participants who viewed an optic-flow stimulus while experiencing vibratory stimulation to their feet in the pattern of saw tooth (Nordahl et al., 2012) and sinusoidal waveforms (Farkhatdinov et al., 2013), relative to white/pink noise waveforms. Other studies observed mixed results, in that adding footstep vibrations to an optic-flow stimulus did not increase the perceived sensation of movement (Feng et al., 2016), or increased sensations only in a subset of participants (Tamada et al., 2017). Kruijff et al. (2016) found that adding foot roll-off vibrations and footstep sounds to a visual scene significantly increased participants' sensation of vection. Another study (Lind et al., 2016) found that adding vibrations to visual, auditory, and leaning-based vestibular/proprioceptive cues yielded increased ratings of realism and compellingness; however, vection intensity was not affected.

Riecke *et al.* (2005b) suggested that adding vibrations might enhance vection via at least two potential mechanisms: (1) adding vibrations introduces noise to the vestibular system rendering vestibular estimates less reliable, in

turn decreasing the visuo-vestibular cue conflict (visually moving but physically stationary) and facilitating visual vection and; (2) adding vibrations may add to the realism of the visually simulated motion as most real-world motions are accompanied by some kind of vibration. Consistent with the latter argument, the three participants in the Riecke *et al.* (2005b) study who reported that the vibrations did not match the visual velocity profile also experienced reduced vection when vibration cues were added to the visuals, and they explained that the conflict made the self-motion illusion less realistic and convincing.

5.2. Combined Tactile, Visual, and Auditory Vection

Auditory vection in blindfolded participants can also be enhanced by providing concurrent vibration cues, both for circular vection (Riecke et al., 2005c, 2009b) and forward linear vection (Väljamäe et al., 2006). Further, Soave et al. (2020) found significant increases in linear forward vection intensity in a visual-auditory-haptic condition relative to audio-visual and visual-only conditions. Overall, because generalized vibrations and tactile cues can typically be provided with relatively little cost and technical complexity, they may be a cost-effective way to enhance self-motion perception for a variety of applications. Importantly, recent research has shown that congruency between vibrational cues and audio-visual vection stimuli is critical to achieve a multimodal enhancing effect. Kooijman et al. (2023b) demonstrated that audio-visual vection induced through a flight simulator was less intense and less convincing when vibrations were applied to the participants neck. Here, the authors speculated that the addition of vibrations was detrimental to vection because the delayed presentation caused them to be interpreted as a conflicting stimulus to the auditory and visual cues.

6. Vestibular Vection

Although the term vestibular vection is hardly used in the literature, it describes illusory self-motion induced by direct vestibular stimulation and physical motion cueing elicited by various interfaces such as moving-base motion simulators or leaning-based VR locomotion interfaces. With regards to *direct vestibular stimulation*, caloric (Young, 1984) and galvanic (e.g., Berthold and Dzendolet, 1973; Dzendolet, 1963) vestibular stimulation are common techniques to stimulate the vestibular organs without moving the participant. In the context of vection, galvanic vestibular stimulation (GVS) through electrical stimulation delivered directly to the vestibular nerve fibers has been predominantly applied.

With regards to *motion cueing*, advanced virtual reality simulators (driving/flying) can offer physical motion *via* diverse setups such as hexapod motion platforms (Stewart platforms), linear sled platforms, robot arms (cyber motion simulator), or cable robot simulators to increase the user's sensation of self-motion (Campos and Bülthoff, 2012; Harris *et al.*, 2002). These moving-base simulators are able to provide vestibular stimulation by way of passively moving users in the direction of the simulated self-motion and subsequently applying motion washout filters to slowly and ideally imperceivably move them back to their original position while visually portraying continued forward self-motion (see Lawson and Riecke, 2014 for an overview). As such, these devices can both introduce real self-motion as well as create, for example, sustained illusory self-motion (i.e., vection) using momentary motion-cuing techniques.

6.1. Combined Vestibular and Visual Vection

6.1.1. Direct Vestibular Stimulation

Several studies on electrical stimulation of the vestibular system (GVS) have shown that it is possible to produce compelling vection (primarily rotation along the roll axis) using GVS (Cress *et al.*, 1996). For example, Cress *et al.* (1997) contrasted the effects of visually induced roll vection, electrical stimulation of the vestibular nerve alone (producing illusions of roll motion), and combined visual and electrical vestibular stimulation and found that the latter bimodal condition produced sensations of self-motion that were rated as significantly more realistic by participants than either of the two unimodal conditions alone.

In studies where optokinetic stimulation is coupled with GVS, a facilitatory effect is often found (Lepecq et al., 2006). Specifically, Maeda et al. (2005) demonstrated that adding anti-phase GVS (e.g., visual stimulation and GVS in opposite directions) can enhance upward linear vection, relative to GVS in phase with the visual stimulus, GVS-only, or visual-only conditions. Weech and Troje (2017) also showed that applying direct vestibular stimulation (GVS and bone conducted vibration) to the mastoids while observing a wide-field visual rotation about the roll axis significantly reduced vection onset latency. It has been suggested that adding direct vestibular stimulation can reduce the sensory mismatch between the visual and vestibular systems, and thus propagate the sensation of vection more quickly. Important to consider is that GVS has side-effects including creating unpleasant or even painful sensations. Alcohol consumption can also affect the vestibular system and greater alcohol consumption has been associated with increased vection (Seno and Nakamura, 2013). In sum, direct vestibular stimulation (apart from physically moving users) does not seem suitable for most applications and benefits are typically outweighed by undesirable side-effects.

6.1.2. Passive Motion Cueing

Vestibular stimulation through passively moving a seated participant while viewing a visual motion stimulus has been shown to effectively enhance vection (Melcher and Henn, 1981; Schulte-Pelkum, 2007). For example, Wong and Frost (1981) presented seated participants with rotating optokinetic stimulation while vestibular cues were delivered through brief physical rotations (clockwise and counter clockwise) to the participants' chair. Vection onset latencies were significantly shortened when vestibular motion in the opposite direction of the visual motion were added compared to conditions with visual stimulation alone. Similarly, Berger et al. (2010) showed that linear self-motion simulation was reported as most 'believable' when visual accelerations were combined with concurrent backward physical pitches of a hexapod motion simulator compared to visual accelerations alone. Combining sinusoidal vertical physical and visual motion that was out of phase from each other showed that vection was dominated by the visually-indicated selfmotion, and was more compelling for larger physical movements, even though the physical movements were incongruent (Wright, 2009).

However, large physical motions might not always be needed to significantly enhance vection. For example, using a motion platform to provide small inertial accelerations (kicks) of only 1-3 cm that coincide with the onset of visually simulated forward motions can be enough to almost double vection intensity and convincingness ratings, and reduce by more than half vection onset latencies (Riecke et al., 2006b; Schulte-Pelkum, 2007). Similarly, vection has been enhanced by small kicks provided to a manual wheelchair participants were seated in (Schulte-Pelkum, 2007), or tilting a gaming chair in the direction of simulated self-motion in VR (Feuereissen, 2013; Riecke and Feuereissen, 2012). Furthermore, Groen and Bles (2004) found that vection occurrences increased from 60% (in the visual-only condition) to 100% when fore-aft body tilting was synchronously applied in a way that was coincident with the fore-aft visual motion. Koge et al. (2015) used an elevator as a motion platform which moved up, down, or not at all, paired with a visual stimulus which always displayed upward motion. When elevator motion and visual motion were consistent (i.e., both representing upward motion), vection intensity was highest relative to inconsistent directional motion and visualonly conditions. Thus, consistency between visual and vestibular cues (e.g., alignment in both timing and direction) is likely an important factor for successfully enhancing vection (see also Berger et al., 2010; Wong and Frost, 1981).

6.1.3. Active Motion Cueing

Vection in virtual environments can also be increased through user-powered motion cueing interfaces (e.g., leaning-based interfaces) that provide additional body-centered self-motion cues (vestibular and proprioceptive) compared to, for instance, hand-held controllers. For example, augmenting a manual wheelchair with force feedback by adding elastic bands, such that users could provide themselves with minimal motion cueing, significantly enhanced vection (reduced onset latency and heightened intensity and convincingness ratings) compared to joystick or mouse-based locomotion control (Riecke, 2006). Kruijff et al. (2015) had participants engage in static leaning (remaining in a forward- or backward-tilted position) or remaining upright for the duration of a virtual environment navigation task using a joystick (Experiment 1). Participants also engaged in dynamic leaning (leaning forward as they tilted their joystick forward to start forward self-motion through the VR; Experiment 2). Although static leaning did not significantly influence vection (even though it increased perceived distance traveled), dynamic leaning intensified forward linear vection and also improved user's involvement, engagement, and enjoyment relative to joystick control.

Similar robust vection facilitation was found when users actively controlled self-motion in VR by leaning, as tracked by measuring torso inclination (Riecke *et al.*, 2016), or as tracked by measuring center-of-pressure changes for users standing on a Wii balance board force plate (Kruijff *et al.*, 2016). Particularly strong vection facilitation has been observed when the head-mounted display's built-in position tracking was used to control virtual self-motions (compared to standard hand-held controllers), both for ground-based locomotion in VR when seated (Hashemian *et al.*, 2021; Riecke *et al.*, 2021) or standing (Hashemian *et al.*, 2023; 'NaviBoard', Riecke *et al.*, 2021), as well as for 3D locomotion (flying) (Adhikari *et al.*, 2021; Hashemian *et al.*, 2020).

6.2. Head Oscillation and Whole-Body Movements and Orientations

Adding visual oscillations or viewpoint jitter to a vection-inducing visual stimulus has been shown to reliably enhance vection compared to a smooth optic-flow display, even though it increases visual–vestibular conflicts that one might assume should reduce vection (Nakamura, 2013; Palmisano and Riecke, 2018; Palmisano *et al.*, 2000, 2011). Interestingly, this vection-facilitating effect of display oscillations can occur (and is often similarly strong) both when the visual display oscillations are produced by active head motions (e.g., of observers facing a screen, or wearing an HMD), gaze shifting, or just passively viewed while keeping one's head stationary (Ash and Palmisano, 2012; Ash *et al.*, 2011; Luu *et al.*, 2021; Palmisano and Kim, 2009). Forward linear vection in HMD-based VR can also be affected by how user's *head rotations* are compensated for (or not). For instance, Palmisano *et al.* (2017) found that

vection intensity was increased when user's oscillatory left–right head motions were compensated for in the contralateral direction (as is standard in HMDbased VR with head tracking), compared to the ipsilateral direction, or not compensated at all when an aperture was simulated to reduce the field of view. However, when no aperture was used and the full HMD's field of view was used, the effect of visual compensation type failed to reach significance. Other similar studies have shown no effect on vection (Kim and Palmisano, 2008; Luu *et al.*, 2021) or reduced vection (Kim *et al.*, 2015) when head rotations (in any direction) were performed while viewing optokinetic stimuli.

The literature is also somewhat mixed regarding the extent to which *whole-body movements influence vection*. When participants in Lowther and Ware (1996) were asked to move in a "left–right, forward–back motion, one step in each direction" (p. 234) while watching a circular (yaw) vection or linear (lateral) vection stimulus on a projection screen, vection onset latency was longer compared to a no-movement condition. However, when head tracking was switched on such that the projected view was coupled to participants' head position, vection onset latencies decreased to the level of the no-movement condition. Including head tracking while executing whole-body movements has been discussed as not only important for visually stabilizing the simulated scene, but also critical for establishing a primary reference frame where visual motions of the scene are more easily interpreted as vection (self-motion) instead of object motion (Riecke, 2011; von der Heyde and Riecke, 2002).

Finally, changes to inputs about physical *body orientation* (e.g., upright *vs* supine) while viewing dynamic visual stimuli may also affect vection ratings. For example, several studies have demonstrated faster vection onset times, greater linear vection intensity, and more prolonged roll vection when participants were sitting upright (aligned with gravity) compared to when they were lying supine (Guterman and Allison, 2019; Guterman *et al.*, 2012; Kano *et al.*, 1991; Oyamada *et al.*, 2020; Tovee, 1999; Wang *et al.*, 2021). Taken together, the literature suggests that vection tends to be facilitated when the direction of linear vection is parallel to the gravitational axis (Seno, 2014). Circular vection seems to be facilitated when the rotation axis is aligned with the gravitational axis, such that there is not added visual–gravitational cue conflict when experiencing circular vection.

7. Other Sensory Contributions to Vection

Other sensory manipulations likely to affect vestibular and somatosensory inputs include environmental factors such as *buoyancy* (Fauville *et al.*, 2021) and *atmospheric pressure*, which could thereby also influence vection. For example, Nishimura *et al.* (2014) decreased the atmospheric pressure within a climate chamber to simulate the experience of high altitudes (e.g., hypobaric

hypoxia) while participants viewed a moving visual stimulus. It was found that reduced pressure (simulating higher altitudes) inhibited vection, reflected by lower vection magnitude, shorter duration, and increased latency. While *smell* has received very little consideration in the vection literature, one study by Aruga *et al.* (2019) demonstrated that linear vection strength was significantly positively correlated with scent strength (lavender and banana).

8. General Discussion

The goal of the present review was to provide an overview of the existing literature on multisensory contributions to vection. Overall, we identified 95 experiments across a total of 85 papers, and summarized them in an interactive online table (see also Supplementary Material). Note that we only included experiments that explicitly compared vection between multisensory and unisensory stimulation and thus allow for assessing the impact of adding a sensory modality on vection. This table includes information on vection type (linear, circular, curvilinear), direction (front-back, lateral, up–down, yaw, pitch, roll), vection measure (intensity, duration, onset latency, convincingness), and multisensory contribution of the added cue (vection enhancement, vection enhancement in some conditions, no effect, vection reduction). The table is interactive in that readers can search and sort for specific cue combinations or modalities/parameters of interest (see Note 1).

8.1. Multisensory Contributions to Vection

Based on our review, the most commonly studied modalities in multisensory vection research apart from visual inputs include tactile (n = 40), followed by vestibular (n = 26), auditory (n = 19), and biomechanical (n = 7). Figures 1a and b provide graphical overviews of the outcomes of these experiments and potential vection enhancements when manipulating different sensory modalities in a multimodal vection context. Summaries are organized by sensory modality (Fig. 1a) and the stimulus direction (linear, curvilinear, or circular; Fig. 1b).

Overall, the literature suggests that adding sensory cues generally increases vection (\sim 73% showed vection enhancement in some or all conditions). However, whether adding sensory inputs enhances or reduces vection (and to what degree) likely depends on several factors that vary widely across studies, including (but not exclusive to) movement axis/direction, vection measures, spatial/temporal/semantic congruency across modalities, and individual participant characteristics/demographics. In Table 1 we offer considerations specific to how each modality might be used to enhance vection, and later elaborate on the applied relevance of multimodal vection research.



Figure 1. Stacked bar plot of experiments that showed a vection enhancement, vection enhancement in some conditions, no effect, or a vection reduction, depending on (a) the manipulated sensory modality in a multimodal vection approach and (b) the stimulus motion direction (linear, curvilinear, or circular). Note: Some papers may be represented more than once on the graph if (i) they conducted multiple experiments, (ii) they investigated multiple sensory cues or (iii) they investigated more than one type of vection.

Multisensory stimulation may alter the sensation of vection in at least two possible ways (see Riecke and Schulte-Pelkum, 2015 for an in-depth discussion) including bottom-up and top-down effects. First, bottom-up, sensory driven contributions directly affect vection. Generally speaking, multisensory vection enhancements seem to be more likely and stronger when each sensory cue is spatially and temporally congruent and redundant with the other co-present vection-inducing sensory inputs (Keshavarz et al., 2014a; Murovec et al., 2021; Riecke et al., 2011). Principles of multisensory integration likely contribute to these effects including, for example, bimodal vection enhancements leading to increased perceptual estimate precision and relative cue-weighting related to individual sensory reliabilities (more reliable sensory inputs being weighted higher). Optimal integration primarily occurs when multiple sensory inputs are spatially and temporally aligned, and those that fall outside of this 'window of integration' or 'coherence zone' may no longer lead to multisensory benefits (and in some cases, lead to adverse effects on perception and performance). In fact, vection can be inhibited if sensory inputs are

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Table 1.

Summary of design considerations for enhancing vection through specific modalities. For all modalities, congruency with other sensory cues indicating self-motion and the overall locomotion paradigm is important

Modality	Design considerations for enhancing vection
Auditory	Use spatialized sound rendering, ideally with multiple sound sources associated with stationary landmarks. Audio cues semantically associated with self-motion can also contribute, but tend to have weaker effects, although auditory metaphorical vection can be surprisingly powerful.
Biomechanical	Circular patterns of stepping can both induce and enhance vection, whereas linear stepping (through walking on a linear treadmill) or walking in place (without treadmill) often does not affect vection or can even impair vection. Hand-over-hand walking motions might also contribute to linear vaction
Tactile/haptic	Vibrations have been the most researched tactile cue and show the most consistent facilitation among all tactile cues, even though they are not by themselves able to induce vection. The degree of vection facilitation varies and can be small. Other tactile/haptic stimuli that can facilitate vection include wind sliding touch, and force-feedback devices
Vestibular: passive motion cueing	Inertial motion aligned with the simulated self-motion direction is most effective at increasing vection, and can be combined with full motion cueing and washout filters where feasible/appropriate. Even small inertial motions (kicks/jerks) can be effective. Cross-modal temporal and directional synchrony is essential, whereas the amplitude of vestibular stimulation seems less critical.
Vestibular: user-powered motion cueing (e.g., leaning)	Using dynamic leaning to control simulated self-motion can enhance vection, while static leaning does not. Head-centered leaning (e.g., HeadJoystick or NaviBoard) has been most effective compared to tracking chair/backrest movements or center of pressure changes.

incongruent assuming they fall outside of this binding window (e.g., Seno *et al.*, 2011a).

On the other hand, there is also evidence that *higher-level*, *cognitive factors* (top-down contributions) can also enhance or modulate vection, for example by changing believability, attentional focus, or cognitive demands (D'Amour *et al.*, 2021; Kitazaki and Sato, 2003; Palmisano and Chan, 2004; Seno *et al.*, 2011c; Trutoiu *et al.*, 2008). It is possible that multisensory inputs also affect the cognitive processes that influence vection. For example, multisensory cues have been shown to help establish a *cognitive-perceptual framework of 'movability*', where participants are primed to believe that actual self-motion is possible (Andersen and Braunstein, 1985; Lepecq *et al.*, 1995; Riecke, 2011; Riecke *et al.*, 2005c, 2009b; Schulte-Pelkum, 2007; Wright *et al.*, 2006) as discussed in detail in Riecke (2009, 2011) and Riecke and Schulte-Pelkum (2013, 2015). Vection can also be facilitated by providing more naturalistic

stimuli and improving ecological validity (Riecke, 2011; Riecke et al., 2005c; Schulte-Pelkum, 2007), which can be further enhanced by consistent multisensory stimulation (Lind et al., 2016; Nilsson et al., 2012; Nordahl et al., 2012). Facilitating effects of presenting congruent and redundant multimodal cues on vection might also be mediated by enhanced immersion, presence, convincingness and/or realism (Riecke and Schulte-Pelkum, 2015). For example, the more the laboratory conditions represent a real-life scenario, replicating the specifics of what the real world looks/sounds/feels like when experiencing physical self-motion, vection is enhanced. There is also increasing evidence that the learned semantic associations with a stimulus (e.g., its meaning) can determine whether and how much that stimulus contributes to vection, both for unisensory vection (Riecke et al., 2005c, 2006a; Väljamäe et al., 2008) and multisensory vection (Lind et al., 2016; Nilsson et al., 2012; Nordahl et al., 2012). For example, foot sole vibration was more effective in inducing vection when the visually presented virtual scene depicted the inside of a train compartment or elevator (semantically associated with vibrations of the feet in the real world), compared to scenes that did not include semantically associated visuals, such as a bathroom or a dark screen (Nilsson et al., 2012).

8.2. Applied Relevance of Multimodal Vection Research

There are many reasons why enhancing our understanding of multisensory vection as a phenomenon is important, including contributions to fundamental knowledge about how the brain perceives self-motion as well as for the development and deployment of more compelling simulations and VR-based technologies. While the vast majority of vection research has historically focused on visually induced vection, in real life actual self-motion is almost always a multisensory phenomenon. Therefore, it seems logical and advantageous to implement and combine inputs from multiple sensory systems when creating the sensation of vection. As such, multisensory vection may more accurately resemble the multisensory processes underlying actual self-motion.

There are many circumstances in the context of research (e.g., using fMRI, space-constrained lab studies) and applications (e.g., gaming, training) where the ability to physically move through expansive space is desired but limited. In those situations, vection could potentially act as a proxy for physical self-motion, allowing investigators to address questions related to self-motion that are otherwise not accessible. As such, it is important to gain a better understanding of how to create a compelling and embodied sensation of vection, including how to leverage multisensory contributions to vection under constraints of space, cost, or technical complexity, while also considering safety. Examples include virtual or mixed-reality gaming, entertainment (e.g., iMax theaters, theme parks), teleoperations, architectural walk-throughs, and virtual travel. Specifically in the context of simulation and VR technologies,

vection has been shown to be positively correlated with the sensations of 'presence' (the feeling of 'being there' in a virtual environment; Heeter, 1992) and 'involvement', both aspects that are typically desirable in these applications (Freeman *et al.*, 2000; IJsselsteijn *et al.*, 2001; Palmisano, 1996; Prothero *et al.*, 1995; Riecke and Schulte-Pelkum, 2015; Riecke *et al.*, 2004, 2006a). Lastly, there is also evidence that vection is not just a mere epiphenomenon when using VR, but can have functional benefits by facilitating perspective switches and improving spatial orientation in VR users (Palmisano *et al.*, 2015; Riecke *et al.*, 2012, 2015a). Thus, better understanding how multisensory cues contribute to vection will help to design and develop more compelling, realistic, and immersive VR experiences, which we will discuss below. Table 1 summarizes some of the main design considerations on how to enhance vection in self-motion applications such as VR and other immersive media, which will be discussed in more detail in the next section.

8.3. Design Consideration on How to Enhance Vection

Based on the present literature review, it is clear that adding congruent and semantically associated spatialized auditory and tactile cues has the potential to significantly enhance the user's experience, for example in VR, and the sensation of vection in particular. These additional sensory cues can often be provided by cost-effective means requiring relatively simple and affordable hardware (e.g., headphones and vibrotactors). Thus, it might be worth considering adding spatialized sound and vibrations to a variety of applications that include simulated observer movements, such as VR, immersive gaming, telepresence, and telerobotics, whenever an increased sense of self-motion in these applications is desired. While adding tactile flow (vibrations sweeping along a vibrotactor matrix) to the seat while viewing optic-flow stimuli has been shown to increase perceived forward velocity, more research is needed to determine if it can also increase vection (Amemiya et al., 2013a, b, 2016). There is also research suggesting that using force feedback devices might also be a promising approach to further enhance vection (Ouarti et al., 2014), although further research is needed.

Although *biomechanical cues* from stepping along circular treadmills can both induce compelling vection by themselves and enhance vection in multimodal contexts, they require more cumbersome hardware that is not commonly available, limiting the widespread utility. Furthermore, it does not seem possible to reliably induce or enhance linear vection using linear or omnidirectional treadmills as discussed earlier, and walking-in-place methods (without a linear treadmill) do not seem sufficient to enhance vection (Kruijff *et al.*, 2016).

While it is possible to induce and enhance vection using *direct vestibular stimulation* (e.g., through galvanic or caloric stimulation), these methods do

not seem very promising for most applications as they introduce undesirable side-effects, and the illusory self-motion sensations they can elicit are limited (Lawson and Riecke, 2014). Passive motion cueing can be provided using a variety of motion platforms, and even relatively small physical motions (using more affordable setups such as motorized chairs) can enhance vection, making them promising for some applications. User-powered active motion cueing approaches such as active leaning-based or human-joystick-based locomotion interfaces come at little if any additional cost and yet have shown to be effective in enhancing vection. They provide a more embodied and hands-free locomotion interface compared to the mainstream hand-held controllers, while at the same time being safer and less complex than motorized motion platforms. However, these interfaces need to be carefully designed to be effective: Earlier seated leaning-based interfaces (Swivel Chair and NaviChair) that tracked chair motions to control VR locomotion (Hashemian and Riecke, 2017; Kitson et al., 2017) did not find any significant vection facilitation when compared to handheld controllers. The Gyroxus gaming chair could enhance vection, but only if participants are moved passively rather than engaging in active control of the chair (Feuereissen, 2013; Riecke and Feuereissen, 2012). More recent leaning-based interfaces such as HeadJoystick or NaviBoard, however, provided consistent vection enhancement both for ground-based VR locomotion when seated (Hashemian et al., 2021; Riecke et al., 2021) or standing, as well as for 3D locomotion (flying) (Adhikari et al., 2021; Hashemian et al., 2020).

Finally, multisensory cues can be utilized to contribute to cognitive factors related to perceived 'movability' (Riecke and Schulte-Pelkum, 2015), for example, by seating participants on a potentially movable chair, platform, or vehicle and demonstrating (some) of its physical movement capabilities. This strategy of 'priming the ability to move' is common practice in many theme parks and arcades. This strategy may also be particularly helpful when it is difficult to induce vection purely through sensory stimulation, for example, for auditory vection which is typically weak (Lackner, 1977; Larsson et al., 2004; Väljamäe, 2007) or when the visual field of view is small (Andersen and Braunstein, 1985). This approach has been shown to enhance visual linear vection in depth in children (Lepecq et al., 1995), visual elevator (up-down) oscillatory vection in adults (Wright et al., 2006), visual roll vection in weightlessness (Young and Shelhamer, 1990; Young et al., 1983), auditory circular yaw vection (Riecke, 2011; Riecke et al., 2009b), and visual circular yaw vection in some studies (D'Amour et al., 2021) but not others (Riecke, 2011; Schulte-Pelkum, 2007; Schulte-Pelkum et al., 2004). However, more research is needed to better understand and disambiguate these different sensory and cognitive factors and how they interact.

8.4. Vection and Motion Sickness

Vection has been historically associated with the occurrence of visually induced motion sickness (VIMS), a sensation similar to traditional motion sickness that is primarily driven by stimulation of the visual system (Cha et al., 2021: Keshavarz et al., 2014a). A sensory conflict between the visual, vestibular, and proprioceptive senses is often considered one of the main causes of VIMS (Oman, 1990; Reason and Brand, 1975), along with challenges to postural control (Stoffregen and Riccio, 1991) and eye movements (Ebenholtz et al., 1994). According to the sensory conflict theory, the information provided by these systems is not in accordance with each other; for instance, the visual system may indicate self-motion, whereas the vestibular and proprioceptive systems indicate stasis (see Keshavarz et al., 2015, for a discussion). The relationship between vection and VIMS is complicated and far from being fully understood (see Keshavarz et al., 2015 for an overview). It has been argued that vection is not sufficient to cause VIMS (Keshavarz et al., 2015; Lawson, 2014), but that VIMS is a by-product when the brain processes conflicting sensory self-motion information that might be ambiguous. Following this line of reasoning, it seems plausible that maximizing vection by stimulation of multiple senses may help to reduce the level of ambiguity, which may reduce or prevent the occurrence of VIMS under some conditions. The (un)predictability of self-motion might also play an important role, in that motion sickness tends to be higher when we do not experience control over our self-motion (e.g., when being a passenger vs a driver) or self-motion is otherwise unexpected or unpredictable (Dong et al., 2011; Rolnick and Lubow, 1991; Teixeira et al., 2022). To date, only very few studies have investigated how multisensory cues may affect VIMS and the results are mixed. For instance, adding auditory cues did not reduce VIMS when added to a visual stimulus (Keshavarz et al., 2014b), but providing multisensory cues reduced the duration of VIMSrelated aftereffects in a driving simulation study (Keshavarz et al., 2018). Thus, the hypothesis that increasing vection *via* multisensory stimulation to reduce VIMS needs to be further empirically tested in future studies.

9. Summary and Future Directions

Our everyday experiences of our world are inherently multisensory, including our perception of self-motion through space. With the increasing usage of VR and mixed-reality technologies, effectively utilizing multisensory stimulation may help provide more natural and compelling sensations of being in and moving through space, which could in turn affect perception and performance. This review illustrates how combining multiple, congruent sensory inputs has a strong potential to increase vection. Interestingly, this multisensory vection enhancement is observed not only when the added/manipulated sensory cues are able to induce vection individually (e.g., biomechanical and some auditory cues), but also when they are by themselves not able to induce vection when presented alone (e.g., vibrations and some tactile and auditory cues). In general, multimodal vection facilitation is strongest when added sensory cues are congruent with the other vection-inducing stimuli with respect to both temporal aspects (e.g., synchronized multimodal stimulus onset) and spatial aspects (e.g., movement direction and to a lesser degree movement amplitude and speed), as well as with learned semantic associations (e.g., the learned associations match the self-motion scenario and metaphors, and the multisensory context is familiar).

It is important to note that the studies reviewed vary significantly across many factors, thereby limiting the ability to cross-compare the effects of different sensory manipulations. The extent to which multisensory stimulation contributes to vection likely varies due to factors such as the characteristics of the stimulus (e.g., frequency, intensity, realism, field size, reliability), the nature of the technology (hardware/software), the extent to which multiple sensory inputs are spatially/temporally/semantically congruent and redundant, the nature of the task, the outcome measures of interest, and inter-individual differences (e.g., age, biological sex, experience). As such, there is a need to better report, measure, and evaluate these factors within multisensory vection studies to establish a comprehensive understanding of their individual and combined effects. We also recommend that studies begin to integrate complementary measures of vection and to report the presence or absence of adverse side-effects alongside vection-related outcomes (Berti and Keshavarz, 2020; Kooijman, Berti, et al., 2023a; Palmisano et al., 2015; Warren and Wertheim, 1990).

Note

1. We envision the online version of this table to be a living and regularly updated representation of the current state of the multimodal vection literature, and will provide opportunities for authors to submit their accepted/published work through an online form if it is not already included in the database.

Supplementary Material

Supplementary material is available online at: https://doi.org/10.6084/m9.figshare.24289216

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