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IMPACT OF OPTIC FLOW CHARACTERISTICS IN VIRTUAL REALITY ON VECTION AND VISUALLY INDUCED MOTION SICKNESS.

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Abstract

The present study investigates how the field of view (central vs. peripheral stimulation) and the spatial reference frame of the visual content (head-referenced vs. gravity-referenced) jointly influence vection strength, subjective presence, and visually induced motion sickness (VIMS) in immersive virtual reality (VR). Thirty-eight participants, pre-screened for VIMS susceptibility, experienced four experimental conditions combining these factors. During eight-minute trials, participants performed cyclical head roll tilts while being exposed to optic flow composed of expanding frames and provided continuous vection ratings. VIMS was assessed using the MISC rating during exposure, as well as the SSQ and MSAQ questionnaires before and after exposure. Results revealed a significant Reference Frame $\times$ Field of View interaction on vection: peripheral stimulation enhanced vection relative to central stimulation in the head-referenced visual framing, whereas this advantage was reversed in gravity-referenced framing, where central stimulation elicited stronger vection responses. The vection–presence relationship was strongest in the head-referenced condition but did not reach significance under gravity-referenced central stimulation. Cluster analysis identified two vection sensitivity profiles (high vs. low), which differentially modulated VIMS outcomes. In high-sensitive individuals, gravity-referenced framing substantially attenuated discomfort accumulation and post-exposure symptom severity, while peripheral stimulation accelerated symptom onset. In low-sensitive individuals, reference frame effects were absent, and only peripheral stimulation exerted a modest adverse effect on discomfort. These findings support a susceptibility-dependent model of VIMS in which the reference frame constitutes an effective mitigation lever primarily for vection-prone individuals, with direct implications for the design of adaptive and ergonomically optimized VR environments.

Keywords: Vection, VIMS, Cybersickness, Reference frame, Field of view

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Consent to participate: Prior to participation, all participants provided written informed consent, having been fully informed of the voluntary nature of their participation and their right to withdraw at any time without consequence.

Ethics approval: The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki (1964) and received approval from the relevant national ethics committee (CERSTAPS: IRB Agreement No. 00012476-2025-26-10-442).

Author contribution: A.B., H.C., J.M.P., C.B and L.B. conceived and designed the experiment, A.B. and L.B. collected the data, A.B., H.C., and L.B. performed the analysis, A.B. and L.B. wrote the paper. All authors have read and approved the manuscript.

1. Introduction

The past decade has been characterized by remarkable advancements in virtual reality (VR) technology, driven by substantial improvements in display resolution, system latency, refresh rates, and expanded fields of view (FoV) (Cipresso et al., 2018). These technological refinements have profoundly enhanced immersion and presence (Anthes et al., 2016), enabling users to experience increasingly compelling simulations of self-motion and environmental interactions. However, as visual realism increases, so does the occurrence of cybersickness - a constellation of symptoms including nausea, disorientation, dizziness, and oculomotor strain - which remains a major obstacle to the widespread adoption of VR systems (Allison and Palmisano, 2025; Weech et al., 2019).

A key challenge of immersive VR design is to elicit compelling vection, defined as the illusory perception of self-motion induced by visual stimulation in a physically stationary observer (Dizmen and So, 2023; Kuiper et al., 2019). Vection plays a central role in ecological validity of VR contents: without a convincing sensation of self-motion, most immersive experiences lack realism and engagement (Riecke et al., 2004). However, the extent to which the emergence of vection contributes to cybersickness and VR discomfort remains unclear. In this article, we will hereafter refer to Visually Induced Motion Sickness (VIMS) as VR discomfort generated by dynamic visual content and optic flow.

While several studies report positive correlations between vection strength and VIMS severity (Diels et al., 2007; Hettinger et al., 1990; Keshavarz et al., 2015; Moss and Muth, 2011; Palmisano et al., 2007), other findings demonstrate that robust vection can occur in the absence of substantial VIMS, or that VIMS may arise even when vection is weak (Kuiper et al., 2019; Palmisano et al., 2017; Webb and Griffin, 2003). Moreover, abrupt changes in vection strength - rather than sustained vection magnitude alone - have been shown to exacerbate VIMS (Bonato et al., 2008). Prolonged vection exposure can also induce symptoms ranging from mild uneasiness to severe nausea and vomiting (Kennedy et al., 2010; Laessoe et al., 2023). Together, these findings suggest that vection is neither a necessary nor a sufficient condition for VIMS. Instead, vection and VIMS appear to share partially overlapping mechanisms while remaining functionally dissociable. It may therefore be valuable to re-examine the relationship between vection and VIMS by systematically considering the primary factors that influence visually induced self-motion perception.

Here, we will focus on two broad classes of visual parameters on vection elicitation. The first concerns the spatial distribution and dynamics of visual stimulation: peripheral visual stimulation is particularly potent in self-motion perception (Berthoz et al., 1975; Brandt et al., 1973), and this effect is further amplified by stimulus velocity (Keshavarz et al., 2019; Nakamura and Shimojo, 1999), prolonged exposure (Seno et al., 2018), and accelerating optic flow patterns that generate compelling depth vection (Palmisano et al., 2008). The second concerns the structural organization of the visual scene (Bringoux et al., 2009; Park and Koo, 2025). The spatial coherence of environmental cues, such as the inclusion of 3-D geometrical features and meaningful polarized objects, has been shown to increase the inductive power of visual surroundings (Bringoux et al., 2009; Cian et al., 2001). Furthermore, the stability of reference frames - specifically the presence of world-stationary "rest frames" (Cao et al., 2018; Prothero et al., 1999) - and the degree to which the scene provides reliable anchoring information, such

as an Independent Visual Background (IVB; Allison and Palmisano, 2025), significantly shape how the brain processes visual inputs. These factors determine whether the visual system interprets retinal motion as self-motion (scene or background motion) rather than object motion (foreground motion), a distinction that is fundamental to the experience of compelling vection (Dizmen and So, 2023; Kuiper et al., 2019; Pöhlmann et al., 2022).

Crucially, these same parameters also exert significant, although different effects on VIMS. The spatial distribution of visual stimulation - and in particular the dominance of peripheral optic flow - is known to destabilize postural and perceptual reference systems, with peripheral-only stimulation producing stronger autonomic symptoms and postural instability than central stimulation (Kim and Kim, 2019). Restricting peripheral stimulation through vignetting reliably attenuates VIMS (Allison and Palmisano, 2025), while even limited peripheral motion cues remain sufficient to elicit vection (Dizmen and So, 2023). Together, these findings suggest that the peripheral visual field plays a prominent role in driving discomfort relative to its contribution to self-motion perception itself. Similarly, the structural organization of the scene influences VIMS through mechanisms distinct from those governing vection intensity: the presence of stable rest frames or IVB provides spatial anchoring cues that mitigate discomfort (Allison and Palmisano, 2025; Cao et al., 2018), visually rich three-dimensional environments exert stronger influence on perceived verticality than sparse scenes (Bringoux et al., 2009), and certain motion axes - such as illusory rotations - prove more provocative than linear expansions (Pöhlmann et al., 2022).

Taken together, these observations challenge conventional accounts of the relationship between vection and VIMS. Rather than conceptualizing VIMS as a direct byproduct of vection strength, we propose that discomfort emerges when visual motion cues generate inconsistencies between spatial reference frames that the nervous system fails to reconcile into a stable representation of self-motion (Bos and Bles, 1998). Within this perspective, visual manipulations may simultaneously enhance vection and provoke VIMS, not because one phenomenon necessarily causes the other, but because both depend on how the spatial structure of the visual environment interacts with perceptual and postural reference systems. The balance between compelling self-motion perception and discomfort may therefore depend on the extent to which visual stimulation preserves, destabilizes, or reconfigures the dynamic stability of spatial reference frames over time.

Building on this framework, the present study investigates how visual stimulation zones (central vs. peripheral) and spatial anchoring cues within the visual environment jointly influence vection and VIMS. More specifically, we test the hypotheses that (1) peripheral-dominant stimulation will enhance vection strength relative to central-dominant stimulation; (2) peripheral-dominant stimulation will increase VIMS severity by affecting spatial reference integration, likely due to the neurophysiological properties of the visual system; and (3) stable spatial anchoring cues, such as independent visual backgrounds, will attenuate VIMS by reinforcing reference frame stability, without diminishing vection.

2. Materials and Methods

2.1. Population

Sixty-six participants (31 females, 35 males; mean age: 20.0 ± 1.4 years) were recruited through an online questionnaire. Participants were asked to provide their age, gender, and to report any history of vestibular

disorders. Susceptibility to visually induced motion sickness (VIMS) was assessed using the Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ; Keshavarz et al., 2023). Inclusion criteria were based on VIMSSQ scores. Specifically, a susceptibility threshold corresponding to the 25th percentile of the normative distribution reported by Keshavarz et al. (2023) was applied, and only participants with a VIMSSQ score ≤ 9.17 were included. The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki (1964) and received approval from the relevant national ethics committee (CERSTAPS: IRB Agreement No. 00012476-2025-26-10-442). Prior to participation, all participants provided written informed consent, having been fully informed of the voluntary nature of their participation and their right to withdraw at any time without consequence.

2.2. Apparatus

Immersive visual environments, developed in Unity by the Mediterranean Virtual Reality Center (CRVM, Marseille), were displayed using a Meta Quest Pro® head-mounted display (HMD). The HMD provided a field of view of 106° horizontally and 96° vertically, with a resolution of 1800 × 1920 pixels per eye and a refresh rate of 90 Hz. Head motion and gaze position were continuously recorded using the integrated inertial and eye-tracking sensors. Vection strength was continuously assessed through joystick input, with anteroposterior deflection linearly mapped to self-reported vection intensity. All data streams were sampled at 90 Hz.

2.3. Experimental Conditions, Design, and Procedure

2.3.1. Visual Stimulation

Participants were exposed to an anteroposterior translational optic flow consisting of expanding white rectangular frames against a black background, simulating forward self-motion at a constant velocity of 6 m/s (So et al., 2001). Four visual conditions were defined by the factorial combination of two independent variables: Reference Frame, defined by the orientation of the expanding visual frames with respect to the participant or the external environment (head-referenced vs. gravity-referenced) and stimulated Field of View (central vs. peripheral). The central visual field was defined as the region extending ± 10 deg from the cyclopean eye, whereas the peripheral visual field comprised the area beyond ± 10 deg up to the limits of the display. This yielded the following conditions: Head-ref/Peripheral, Head-ref/Central, Gravity-ref/Peripheral, and Gravity-ref/Central (Fig. 1).

2.3.2. Experimental Design and Task

A fully within-subjects design was employed, such that each participant was exposed to all four visual conditions across two separate sessions. Throughout each VR exposure, participants were instructed to maintain their gaze straight ahead while performing continuous cyclical head tilts in the roll plane, alternating between leftward and rightward movements. Head movements were guided by two concurrent auditory signals: a metronome tone cuing a target half-cycle frequency of 0.4 Hz - a frequency known to reliably elicit VIMS (Bos and Bles, 1998; O'Hanlon and McCauley, 1974) - and a feedback tone triggered automatically whenever tilt amplitude exceeded ± 20 deg,

indicating the required reversal point. Participants were instructed to synchronize their movements with both signals to maintain the prescribed amplitude and rhythm throughout the exposure. Compliance was monitored continuously by the experimenter.

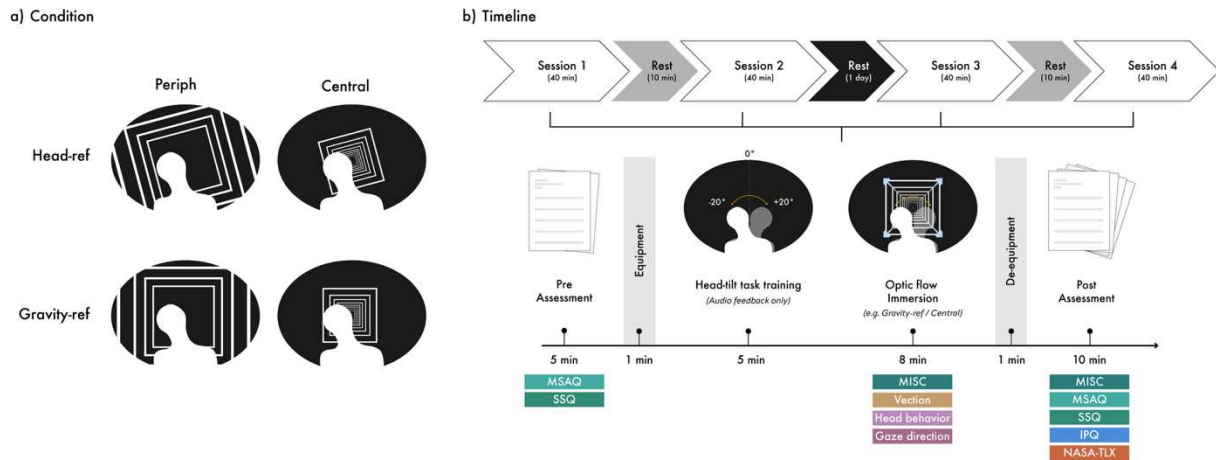


Fig. 1 Experimental design and procedure

Note. (a) Schematic representation of the experimental conditions, highlighting the different visual displays anchored to the head displacement (upper frames) or the external environment (lower frames) (b) Timeline of the experimental protocol. Participants completed all experimental conditions across two testing days. The order of conditions was counterbalanced both within and between testing days.

2.3.3. Procedure

Participants completed two experimental sessions separated by a minimum of 24 hours. Each session comprised two visual conditions, with a mandatory rest period of at least 30 minutes between conditions, or until full symptomatic recovery was achieved. Condition order was counterbalanced across participants. Upon arrival at each session, participants completed the Motion Sickness Assessment Questionnaire (Gianaros et al., 2010) and the French-validated version of the Simulator Sickness Questionnaire (Bouchard et al., 2009) to establish pre-exposure baseline measures. They were then familiarized with the Misery Scale (MISC, Bos et al., 2005), an 11-point ordinal scale ranging from 0 ("No problems") to 10 ("Vomiting"). A brief practice phase (~5 minutes) allowed participants to familiarize themselves with the head-tilt task and the joystick-based vection rating procedure.

Each VR exposure lasted up to eight minutes, during which participants performed the head-tilt task while providing continuous joystick-based vection ratings. MISC scores were collected verbally at one-minute intervals throughout exposure and during the subsequent recovery period. Exposure was terminated early either at the participant's request or if the MISC score exceeded 4. Post-exposure monitoring continued until either two consecutive MISC scores of 0 were recorded or 10 minutes had elapsed. A score of 0 was required before initiating any subsequent condition.

Following each exposure, participants completed the SSQ and MSAQ to quantify VIMS severity, the Igroup Presence Questionnaire (IPQ; Schubert et al., 2001) to assess subjective sense of presence, and the French version of the NASA Task Load Index (Cegarra and Morgado, 2009) to evaluate perceived workload.

2.4. Data Reduction and Statistical Analysis

VIMS was indexed by three complementary measures, each selected to capture a distinct dimension of the symptomatic response. The MISC was employed as a continuous, time-resolved index of overall discomfort throughout immersion, enabling dynamic tracking of symptom onset and progression. The MSAQ was chosen for its sensitivity to motion sickness specifically elicited by active head movements, rendering it particularly appropriate given the cyclical roll-plane head tilts performed by participants. The SSQ was included on account of its established relevance to simulator- and VR-induced sickness, making it especially suited to contexts in which a stationary observer is exposed to dynamic optic flow - precisely the condition under investigation here. Both the MSAQ and SSQ were administered pre- and post-exposure to quantify symptoms changes. Continuous vection ratings were derived from the joystick position time series. Presence and workload were assessed post-exposure via the IPQ and NASA-TLX, respectively. Head-tilt task performance was characterized by mean oscillation frequency and mean reversal amplitude. Gaze behavior was quantified by computing (i) gaze compliance, defined as the proportion of time gaze remained within $\pm 2^\circ$ of the mean fixation direction, and (ii) gaze position variability across exposure.

All kinematic, oculomotor, and joystick data were acquired at 90 Hz. Preprocessing and statistical analyses were performed in MATLAB and RStudio. Linear mixed models (LMMs) were used to assess the effects of Reference Frame (RF: head-referenced vs. gravity-referenced), Field of View (FoV: central vs. peripheral), and, when applicable, Time (pre vs. post) or continuous exposure duration (minute-by-minute) on all dependent variables, including VIMS scores (MISC, MSAQ, SSQ), vection, presence (IPQ), perceived workload (NASA-TLX), and behavioral measures (gaze and head tilt). Participant was included as a random intercept in all models; random slopes for Time or minute were added where appropriate to account for within-subject temporal variability. Fixed-effect estimates, 95% confidence intervals, and p-values were derived using Wald t-distribution approximations. Model fit was characterized by marginal R^2 (variance explained by fixed effects) and conditional R^2 (total variance explained including random effects). Model assumptions were evaluated by visual inspection of residual distributions and residual-versus-fitted plots. Significant main effects and interactions were followed by post-hoc pairwise comparisons with appropriate corrections.

3. Results

From the 66 individuals who responded to the online screening questionnaire, 27 were excluded prior to enrolment for the following reasons: 3 presented pre-existing vestibular disorders, 15 did not meet the minimum susceptibility threshold on VIMSSQ (score ≤ 9.17), and 9 could not be scheduled due to availability constraints. The remaining 39 participants were enrolled and completed all experimental conditions. Data from one participant were subsequently excluded due to a technical failure of the VR headset recording system during data acquisition,

resulting in a final sample of 38 participants. No participant discontinued any experimental condition prematurely; all completed the full 8-minute exposure across the four conditions. The final sample comprised 38 young adults (see descriptive statistics in Table 1). The mean VIMSSQ score was 33.8 ± 16.4 , corresponding approximately to the 65th percentile of the normative distribution (Keshavarz et al., 2023).

Table 1: Descriptive characteristics of the study sample

Characteristic	N=38
Gender	
Female	17 (44.7%)
Male	21 (55.3%)
Age	
	21.7 $\pm$ 3.5 18 - 31
VIMSSQ	
Q1	0 (0%)
Q2	11 (28.9%)
Q3	17 (44.8%)
Q4	10 (26.3%)

N (%); Mean $\pm$ SD | Min - Max

Note. Quartile boundaries are derived from the normative distribution of the general population (Keshavarz et al., 2023). Only participants scoring above the 25th percentile (Q1 upper bound: score > 9.17), were eligible for inclusion. Q1 is therefore not represented in the sample.

The results were organized as follows. We first examined potential confounding factors to establish that observed differences across conditions reflected genuine perceptual and physiological responses rather than variations in task demand or compliance. We then assessed the effects of the experimental manipulations on subjective presence, before turning to the core analyses of vection - where we characterized condition-level effects, identified individual sensitivity profiles, and examined the relationship between vection and presence. Finally, we investigated how these profiles modulated VIMS outcomes across the three assessment instruments.

3.1. Control factors

Before examining the primary outcomes of interest, we assessed whether the experimental conditions differed in ways that could confound the interpretation of subsequent results. Specifically, we verified that head-tilt task performance, perceived workload, and gaze behavior were not systematically affected by the visual manipulations. Ruling out these potential confounds ensures that observed differences in vection, presence, and VIMS can be attributed more confidently to the experimental factors themselves.

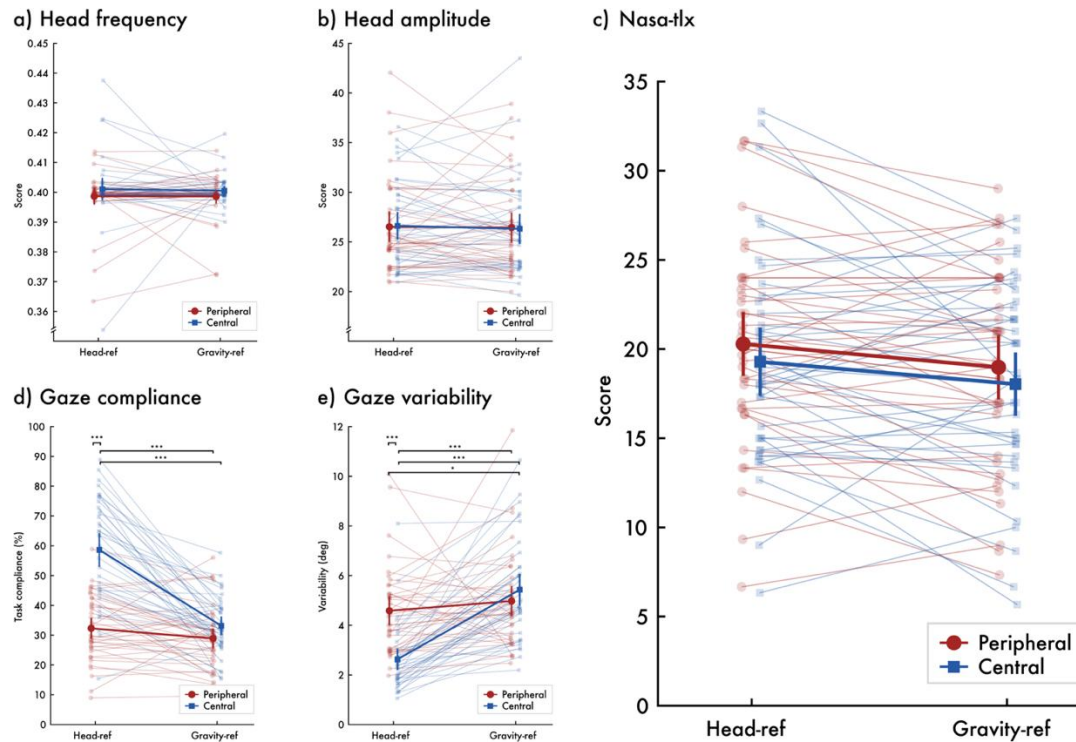


Fig. 2 Task compliance and performance metrics across experimental conditions

Note. (a) Mean head oscillation frequency (Hz), (b) mean head turnaround-point amplitude (absolute angular displacement, degree), (c) mean NASA-TLX workload scores, (d) gaze direction compliance (percentage of time gaze remained within $\pm 2^\circ$ of the target direction), and (e) gaze direction variability (mean standard deviation, degree) across the Head-ref and Gravity-ref reference frame conditions, shown separately for Peripheral (red) and Central (blue) display types. Individual participant data are displayed as connected lines linking paired observations across conditions. Markers represent condition means, and error bars indicate 95% confidence intervals around the mean. Note the discontinuous y-axis in panels (a) and (b). Significance levels are indicated as follows: * $p < .05$, *** $p < .001$.

Head-tilt task performance was consistent across conditions (Fig. 2.a & 2.b), with neither oscillation frequency nor amplitude influenced by reference frame, field of view, or their interaction (all $p \geq .131$), confirming task equivalence across the experimental design.

Perceived workload was similarly unaffected, with no significant effect of reference frame, field of view, or their interaction on total NASA-TLX scores (all $p \geq .088$), indicating that the experimental conditions did not differentially affect participants in terms of perceived effort or demand (Fig. 2.c).

Gaze behavior, by contrast, was substantially modulated by the experimental conditions (Fig. 2.d & 2.e). Compliance and variability were both primarily driven by a significant RF $\times$ FoV interaction (both $p < .001$): the Head-ref/Central condition yielded the highest compliance and lowest variability. To determine whether these fluctuations carried any predictive weight over the primary outcomes, gaze compliance and variability were

introduced as moderating variables of the $RF \times FoV$ effect on both vection and VIMS (Model 3) and compared against a baseline model excluding these terms using AIC, marginal R^2 , and likelihood ratio tests. These comparisons consistently showed that adding gaze variables failed to improve model fit for vection strength, both across the full sample ($\chi^2 = 0.097$, $p = .952$) and within each sensitivity vection group (all $p \geq .326$) (see *Section 3.3.2* for further details on the grouping procedure). The same pattern held for VIMS, where gaze moderators systematically worsened model fit (ΔAIC ranging from -5 to -40) without reaching significance in any likelihood ratio test (all $p \geq .05$). Gaze behavior therefore appears to be an epiphenomenon of the experimental manipulation rather than a driving mechanism of the perceptual and comfort outcomes examined below.

3.2. Presence

Having established that the conditions were equivalent in terms of task demand and behavioral compliance, we next examined whether the experimental manipulations produced differential levels of subjective presence. This analysis was motivated by the well-established theoretical link between self-motion perception and immersive experience: conditions that elicit stronger vection are generally expected to be experienced as more spatially immersive. Assessing presence at this stage allows us to determine whether the experimental configurations had perceptually meaningful consequences beyond vection itself and sets the stage for examining the vection-presence relationship in *Section 3.3.3*.

The model for total IPQ presence score (Fig. 3.a) showed substantial explanatory power (conditional $R^2 = 0.63$; marginal $R^2 = 0.08$). Significant main effects of RF ($\beta = -0.33$, 95% CI [-0.59, -0.06], $p = .016$) and FoV ($\beta = 0.42$, 95% CI [0.16, 0.69], $p = .002$) were observed, while the $RF \times FoV$ interaction was not significant ($p = .629$), indicating that the contributions of reference frame and field of view to presence were additive rather than contingent on one another. Head-referenced framing and peripheral stimulation were each independently associated with higher presence ratings.

These effects were overall mirrored at the subscale level (Fig. 3.b). Significant main effects of RF and FoV were observed for both General Presence (conditional $R^2 = 0.56$; marginal $R^2 = 0.13$) and Spatial Presence (conditional $R^2 = 0.58$; marginal $R^2 = 0.08$). The Involvement subscale (conditional $R^2 = 0.53$; marginal $R^2 = 0.03$) showed no significant effects, suggesting that the observed presence modulations were primarily driven by spatial and environmental dimensions of immersion rather than by attentional engagement.

Taken together, these findings confirm that reference frame and field of view exerted independent, additive effects on subjective presence. The extent to which these presence differences co-varied with vection strength will be examined in *Section 3.3.3*.

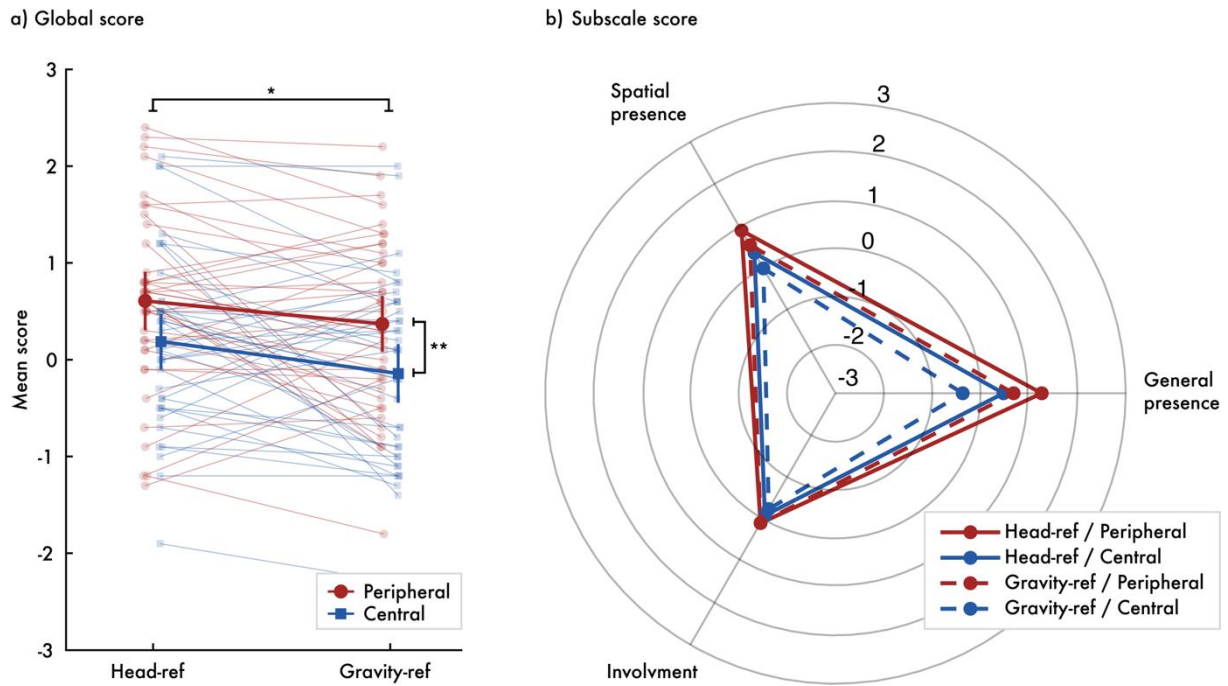


Fig. 3 IPQ presence scores across experimental conditions

Note. In this context, positive factor scores represent participants who report higher levels of the underlying presence component, while negative scores indicate lower-than-average levels of that component within the sample. (a) Mean total IPQ scores for the Head-ref and Gravity-ref conditions, shown separately for Peripheral (red) and Central (blue) display types. Individual participant scores are displayed as connected lines connecting paired observations. Error bars represent 95% confidence intervals around the mean. (b) Radar plot depicting mean scores for each of the three retained IPQ subscales - Spatial Presence, General presence, and Involvement - across the four experimental conditions: Head-ref/Peripheral (solid red), Head-ref/Central (solid blue), Gravity-ref/Peripheral (dashed red), and Gravity-ref/Central (dashed blue). The Realism subscale was excluded from the analysis as it was deemed not applicable to the virtual stimulation used in the present study. Significance levels are indicated as follows: * $p < .05$, ** $p < .01$.

3.3. Vection

This section examined vection across three complementary analyses. We first assessed the effects of reference frame and field of view on mean vection strength at the group level. Given the substantial inter-individual variability observed in vection responses, we then applied a clustering approach to identify distinct sensitivity profiles within the sample and examine whether condition effects replicated within each group. Finally, we investigated the relationship between vection and presence, both across the full sample and separately for each experimental condition, to determine whether this association was modulated by the visual configuration.

3.3.1. Effects of reference frame and field of view on vection

The aim of this analysis (Fig. 4) was to determine how the two experimental factors - reference frame and field of view - influenced mean vection strength, and whether their effects were independent or interactive. The model exhibited substantial explanatory power (conditional $R^2 = 0.64$; marginal $R^2 = 0.05$). First, a significant main effect of time was observed ($\beta = 0.02$, 95% CI [0.003, 0.03], $p = .016$), indicating that vection strength increased naturally over the course of the trial. Significant main effects were also observed for RF ($\beta = 0.10$, 95% CI [0.02, 0.18], $p = .010$) and FoV ($\beta = 0.13$, 95% CI [0.05, 0.21], $p = .001$). Importantly, a significant RF $\times$ FoV interaction emerged ($\beta = -0.33$, 95% CI [-0.44, -0.22], $p < .001$), indicating that the effect of field of view on vection depended on the spatial reference frame.

Pairwise comparisons revealed that the Head-ref/Peripheral condition elicited significantly stronger vection than both the Head-ref/Central (estimate = 0.125, $p = .034$) and Gravity-ref/Peripheral conditions (estimate = 0.192, $p < .001$). Similarly, the Gravity-ref/Central condition showed significantly higher vection than the Gravity-ref/Peripheral condition (estimate = 0.127, $p = .031$). No other comparisons reached significance (all $p \geq .800$).

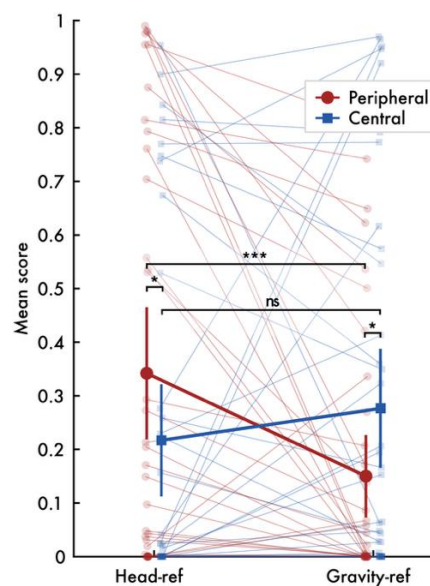


Fig. 4 Mean vection scores across experimental conditions

Note. Mean vection scores for the Head-ref and Gravity-ref conditions, shown separately for Peripheral (red) and Central (blue) display types. Individual participant scores are displayed as connected lines connecting paired observations. Error bars represent 95% confidence intervals around the mean. A crossover pattern is apparent, with Peripheral display yielding higher vection scores in the Head-ref condition relative to Central display, while this relationship reverses in the Gravity-ref condition. Significance levels are indicated as follows: ns $p > 0.05$, * $p < .05$, *** $p < .001$.

Together, these results describe a crossover pattern: in the head-referenced condition, peripheral stimulation enhanced vection relative to central stimulation, whereas this advantage was reversed in gravity-referenced condition, where central stimulation yielded stronger vection responses. Notably, this interaction remained stable

across the full exposure period, as all higher-order interactions involving time were non-significant (all $p \geq .138$). This indicates that the opposite influence of field of view depending on the reference frame did not change over time during immersion.

The substantial inter-individual variability in vection ratings observed across all conditions (SDs: Head-ref/Peripheral = 0.33, Head-ref/Central = 0.39, Gravity-ref/Peripheral = 0.35, Gravity-ref/Central = 0.24) prompted a more fine-grained examination of individual response profiles, presented in the following section.

3.3.2. Individual sensitivity profiles

Given the substantial inter-individual variability in vection responses documented above, we investigated whether participants could be partitioned into meaningful subgroups with distinct vection sensitivity levels, and whether the $RF \times FoV$ interaction observed at the group level was uniformly expressed across these subgroups or selectively driven by a specific subset of participants.

Participants were grouped using an unsupervised clustering approach applied to individual mean vection scores, standardized prior to clustering. Converging evidence from the elbow method, silhouette analysis, and the gap statistic supported a two-cluster solution. K-means clustering ($k = 2$, $nstart = 25$) yielded a vection high-sensitive ($n=12$) and a vection low-sensitive group ($n=26$), whose separation was confirmed by a linear mixed model (conditional $R^2 = 0.62$; marginal $R^2 = 0.62$; main effect of vection sensitive group: $\beta = -0.57$, 95% CI [-0.64, -0.49], $p < .001$, std. $\beta = -0.79$).

The effects of RF and FoV were then examined separately within each vection sensitive group. In the vection high-sensitive group (conditional $R^2 = 0.277$; marginal $R^2 = 0.276$) (Fig. 5.a), a significant $RF \times FoV$ interaction was observed ($\beta = -0.554$, $p = .002$), driven by a substantially higher vection in the Head-ref/Peripheral condition relative to the Gravity-ref/Peripheral condition (estimate = 0.476, $p = .001$); no other pairwise comparisons were significant (all $p \geq .077$). In the vection low-sensitive group (conditional $R^2 = 0.333$; marginal $R^2 = 0.049$) (Fig. 5.b), the $RF \times FoV$ interaction also reached significance ($\beta = -0.112$, $p = .009$), but no pairwise differences between conditions were reliable (all $p \geq .170$), indicating that the interaction reflects a subtle statistical pattern that did not translate into discriminable condition-level effects within this group.

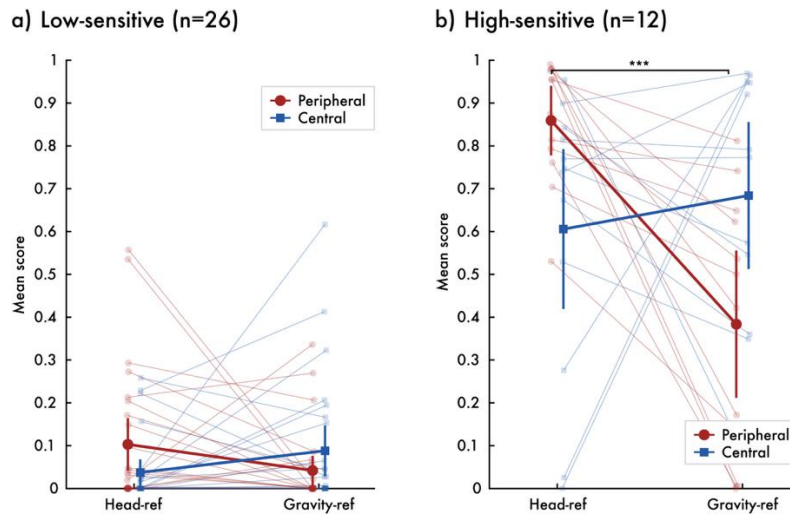


Fig. 5 Vection scores across experimental conditions as a function of vection sensitivity

Note. (a) Low-sensitivity group ($n = 26$) and (b) high-sensitivity group ($n = 12$). Mean vection scores for the Head-ref and Gravity-ref conditions, shown separately for Peripheral (red) and Central (blue) display types. Semi-transparent individual participant scores are displayed with connected lines linking paired observations across conditions. Markers represent condition means, and error bars indicate 95% confidence intervals around the mean. In both groups, a crossover pattern is observed. Significance levels are indicated as follows: *** $p < .001$.

The substantially higher marginal R^2 in the vection high-sensitive group (0.276 vs. 0.049), combined with the presence of significant post-hoc differences exclusively within this group, indicates that the $RF \times FoV$ interaction on vection was primarily driven by individuals with heightened vection susceptibility. Whether this differential sensitivity also extends to VIMS outcomes will be examined in Section 3.4.

3.3.3. Vection-presence relationship

Having established that both vection and presence were modulated by the experimental conditions, we now examine whether these two variables co-varied within participants - that is, whether individuals who reported stronger vection also experienced higher presence - and whether the strength of this association differed across experimental configurations.

Pearson correlations were computed between mean vection scores and IPQ total scores, both across all observations pooled (Fig. 6.a) and separately for each condition (Fig. 6.b). Across the full dataset, a significant positive relationship was observed ($r = 0.40$, $p < .001$), confirming that stronger vection experiences were associated with higher subjective presence overall.

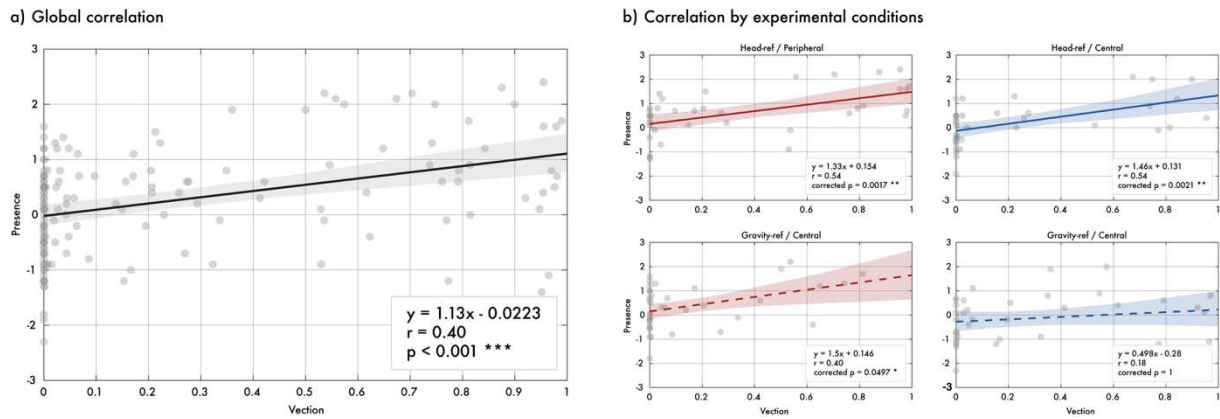


Fig. 6 Relationship between vection and presence (IPQ) scores across experimental conditions

Note. (a) Scatter plot showing the relationship between mean vection ratings and mean IPQ total scores across all observations. Each grey dot represents an individual data point. The solid black line indicates the linear regression fit, with the shaded area representing the 95% confidence interval around the regression estimate. (b) Condition-specific scatter plots illustrating the relationship between vection and presence for each experimental condition: Head-ref/Peripheral (solid red), Head-ref/Central (solid blue), Gravity-ref/Peripheral (dashed red), and Gravity-ref/Central (dashed blue). Grey dots correspond to individual observations, colored lines indicate the linear regression fits for each condition, and shaded regions represent 95% confidence intervals. Regression equations, Pearson correlation coefficients (r), and Bonferroni-corrected p -values are reported within each panel. Significance levels are indicated as follows: * $p < .05$, ** $p < .01$, *** $p < .001$.

When examined by condition, the strength of this association varied substantially. Significant positive correlations were found in both head-referenced conditions (Head-ref/Peripheral: $r = 0.54$, corrected $p = .0017$; Head-ref/Central: $r = 0.54$, corrected $p = .0021$) and, to a lesser extent, in the Gravity-ref/Peripheral condition ($r = 0.40$, corrected $p = .0497$). In contrast, the Gravity-ref/Central condition yielded only a weak, non-significant association ($r = 0.18$, corrected $p = 1.000$).

These results indicate that the vection-presence relationship is not uniform across visual configurations. It is strongest when motion is anchored to the observer's head-centered frame, and weakest - effectively absent - when motion is gravity-referenced and restricted to the central field.

3.4. VIMS

The preceding analyses established that vection responses were heterogeneous across participants and that this heterogeneity could be meaningfully captured by a two vection sensitive group distinction reflecting high and low vection sensitivity. The present section examines whether this differential structure also carries functional relevance for VIMS outcomes. Specifically, we first test whether vection-based group membership moderates the effects of RF and FoV on discomfort - a step we term vection sensitive group validation in the context of VIMS - before decomposing the effects of the experimental manipulations within each vection sensitive group separately.

Before proceeding, it is important to note that preliminary analyses of pre-exposure SSQ and MSAQ scores revealed no significant effect of RF or FoV (all $p \geq .088$), confirming that baseline symptom levels were equivalent

across conditions. Post-exposure differences can therefore be attributed to the experimental manipulations rather than to pre-existing between-condition asymmetries.

All models included RF, FoV, Vection sensitivity, and their interactions as fixed effects, with participants entered as a random intercept. For MISC ratings, immersion time was additionally included to account for within-exposure symptom dynamics.

3.4.1. Vection sensitivity as a moderator of VIMS

We first examined whether the vection-derived sensitivity group captured meaningful differences in VIMS responses at the global level - that is, before decomposing effects by the vection sensitive group. This step was intended to establish whether the categorical approximation introduced by clustering retained functional relevance when applied to discomfort outcomes, thereby justifying the group-specific analyses that follow.

MISC. The model (conditional $R^2 = 0.65$; marginal $R^2 = 0.22$) revealed a robust main effect of time ($\beta = 0.16$, 95% CI [0.13, 0.19], $p < .001$), reflecting progressive discomfort accumulation during immersion, and a significant FoV $\times$ Time interaction ($\beta = 0.06$, 95% CI [0.02, 0.11], $p < .01$), indicating steeper symptom buildup under peripheral stimulation (Fig.7). A significant main effect of vection sensitivity ($\beta = -0.55$, 95% CI [-1.07, -0.03], $p < .05$), and a significant RF $\times$ Vection sensitive group interaction ($\beta = 0.42$, 95% CI [0.20, 0.65], $p < .001$) confirmed that the protective effect of gravity-referenced framing on discomfort was not uniform across groups. All remaining interactions were non-significant (all $p \geq .068$).

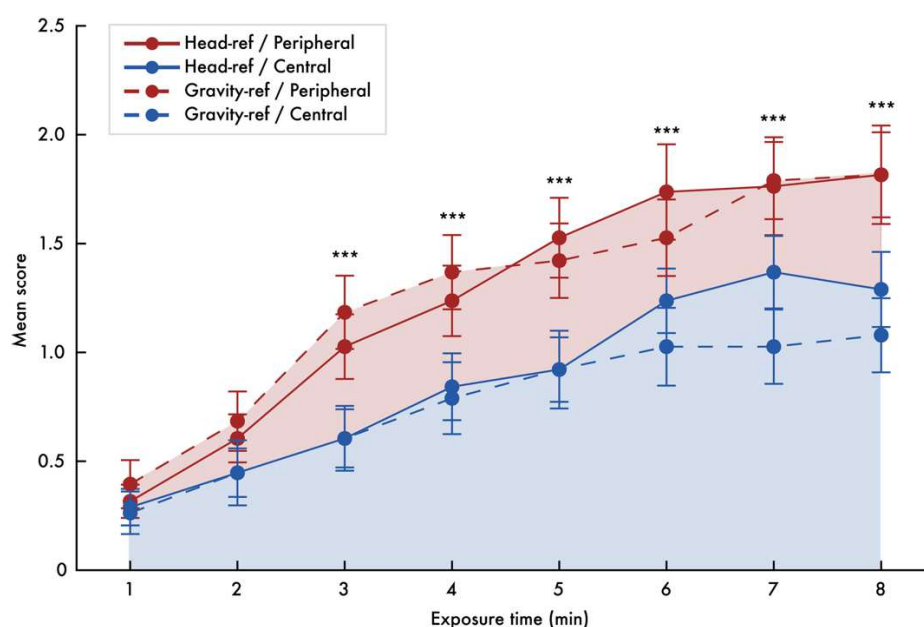


Fig. 7 MISC (Misery-Scale) discomfort scores across experimental conditions and exposure time

Note. Time course of mean MISC scores plotted minute-by-minute over the 8-minute exposure period for each of the four experimental conditions: Head-ref/Peripheral (solid red), Head-ref/Central (solid blue), Gravity-

ref/Peripheral (dashed red), and Gravity-ref/Central (dashed blue). Error bars represent 95% confidence intervals. Significance levels are indicated as follows: * $p < .05$, ** $p < .01$, *** $p < .001$.

SSQ. The model (conditional $R^2 = 0.55$; marginal $R^2 = 0.19$) yielded a significant main effect of vection sensitive group ($\beta = -4.62$, 95% CI $[-7.01, -2.22]$, $p < .001$) and a significant RF $\times$ vection sensitive group interaction ($\beta = 4.90$, 95% CI $[2.39, 7.41]$, $p < .001$), closely mirroring the MISC pattern. Although gravity-referenced framing was globally associated with lower SSQ scores ($\beta = -9.06$, 95% CI $[-13.45, -4.68]$, $p < .001$), this benefit varied substantially across vection sensitive groups. FoV and all remaining interactions were non-significant (all $p \geq .126$).

MSAQ. The model showed moderate fit (conditional $R^2 = 0.40$; marginal $R^2 = 0.14$), with no significant main effects or interactions (all $p \geq .070$). A trend-level effect of vection sensitive group membership ($\beta = -2.31$, 95% CI $[-4.80, 0.19]$, $p = .070$) was observed, consistent in direction with the MISC and SSQ findings.

The convergent RF $\times$ vection sensitive group interactions across MISC and SSQ, supported by a directionally consistent trend in the MSAQ, establish vection sensitivity as a functionally meaningful moderator of VIMS outcomes. Rather than treating inter-individual variability as residual noise, these results indicate that vection-derived sensitivity profiles capture a systematic source of heterogeneity in participants' responses to the visual manipulations. The following section decomposes these effects within each vection sensitive group to identify the specific conditions under which each manipulation influences VIMS severity.

3.4.2. Vection sensitivity modulating the effects of reference frame and field of view

Having established that vection sensitive group membership moderated VIMS responses at the global level, we now examine the effects of RF and FoV separately within each group. This decomposition aims to characterize the conditions under which each visual manipulation exerts its influence on discomfort, and to determine whether the two vection sensitive groups show qualitatively distinct response profiles.

MISC. In the vection low-sensitive group ($n = 26$; conditional $R^2 = 0.57$; marginal $R^2 = 0.17$) (Fig.8.a), only the main effect of time was significant ($\beta = 0.13$, 95% CI $[0.09, 0.17]$, $p < .001$); neither RF nor FoV, nor any of their interactions with time, reached significance (all $p \geq .170$). In the vection high-sensitive group ($n = 12$; conditional $R^2 = 0.74$; marginal $R^2 = 0.23$) (Fig.8.b), discomfort accumulated robustly over time ($\beta = 0.23$, 95% CI $[0.17, 0.29]$, $p < .001$), with a significantly steeper increase under peripheral FoV (FoV $\times$ Time: $\beta = 0.11$, 95% CI $[0.03, 0.20]$, $p < .01$) and a relative attenuation under gravity-referenced framing (RF $\times$ Time: $\beta = -0.09$, 95% CI $[-0.18, -0.007]$, $p < .05$). All remaining interactions were non-significant (all $p \geq .272$).

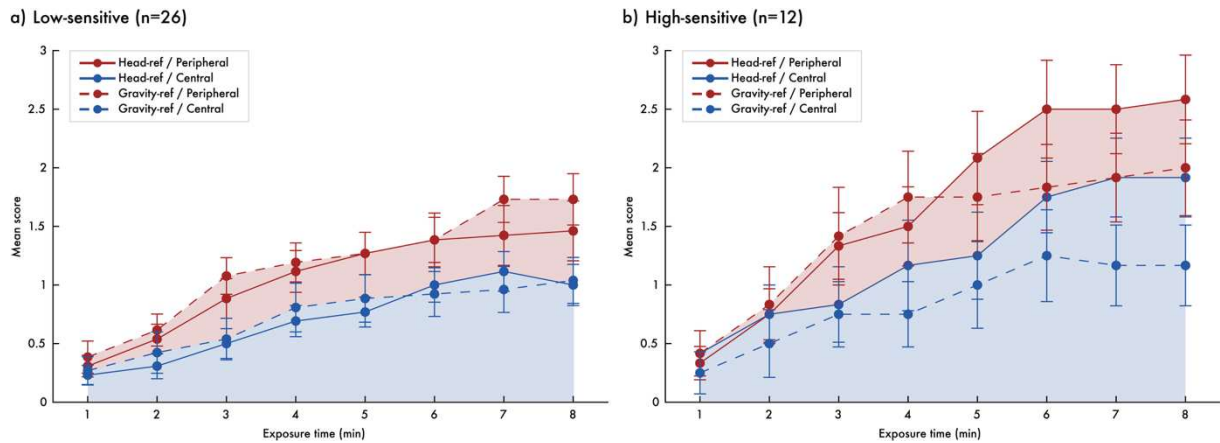


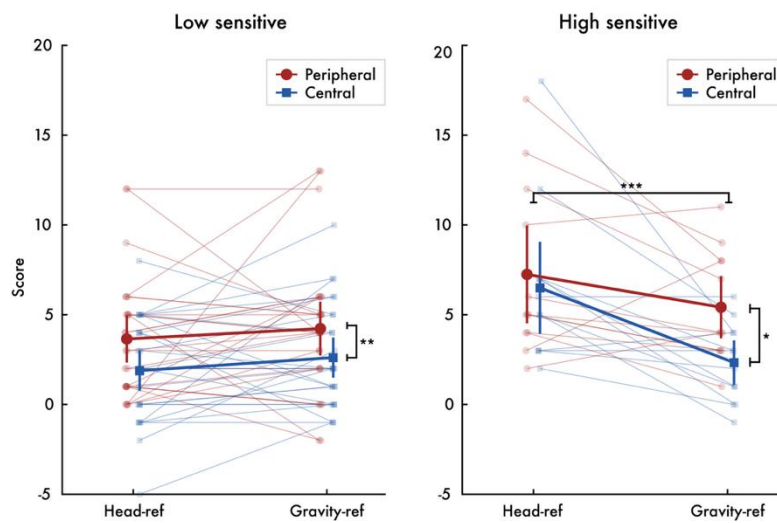
Fig. 8 MISC scores across experimental conditions as a function of exposure time and vection sensitivity

Note. (a) Low-sensitivity group ($n = 26$) and (b) high-sensitivity group ($n = 12$). Time course of mean MISC (Misery-Scale) scores plotted minute-by-minute over the 8-minute exposure period for each of the four experimental conditions: Head-ref/Peripheral (solid red), Head-ref/Central (solid blue), Gravity-ref/Peripheral (dashed red), and Gravity-ref/Central (dashed blue). Error bars represent 95% confidence intervals.

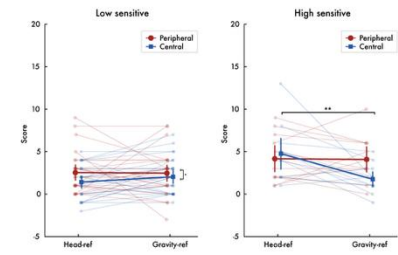
SSQ. In the vection high-sensitive group ($n = 12$; conditional $R^2 = 0.54$; marginal $R^2 = 0.20$), gravity-referenced framing was associated with substantially lower post-exposure SSQ scores ($\beta = -4.17$, 95% CI $[-6.54, -1.79]$, $p < .001$), while neither FoV ($p = .527$) nor the RF $\times$ FoV interaction ($p = .170$) reached significance (Fig.9.a). Subscale analyses (Fig.9.b) revealed that this overall benefit of gravity-referenced framing was carried by two partially distinct mechanisms. For the Nausea subscale (conditional $R^2 = 0.56$; marginal $R^2 = 0.25$), independent main effects of RF ($\beta = -1.17$, 95% CI $[-2.18, -0.16]$, $p < .05$) and FoV ($\beta = 1.33$, 95% CI $[0.32, 2.34]$, $p < .05$) were observed, with no significant interaction ($p = .415$): gravity-referenced framing reduced nausea symptoms, while peripheral stimulation independently increased them. For the Oculomotor subscale (conditional $R^2 = 0.45$; marginal $R^2 = 0.16$), a significant main effect of RF ($\beta = -3.00$, 95% CI $[-4.78, -1.22]$, $p < .01$) was qualified by a significant RF $\times$ FoV interaction ($\beta = 2.92$, 95% CI $[0.40, 5.44]$, $p < .05$). Post-hoc comparisons revealed that the oculomotor benefit of gravity-referenced framing was driven specifically by the central field of view condition: the Head-ref/central condition yielded significantly higher oculomotor scores than the Gravity-ref/central condition (estimate = 3.00, $p < .05$), whereas no significant differences were observed between the Head-ref/peripheral and Gravity-ref/peripheral conditions (estimate = 0.67, $p = 1.000$), nor between the two gravity-referenced conditions (Gravity-ref/central vs. Gravity-ref/peripheral: estimate = -2.33, $p = .075$). This pattern suggests that the oculomotor relief conferred by gravity-referenced framing was selectively present when stimulation was confined to the central visual field and was effectively abolished under peripheral stimulation.

In the vection low-sensitive group ($n = 26$; conditional $R^2 = 0.50$; marginal $R^2 = 0.07$), no effect of RF was found on overall SSQ scores ($p = .280$), but a significant main effect of FoV emerged ($\beta = 1.77$, 95% CI $[0.44, 3.10]$, $p < .01$), indicating higher post-exposure scores under peripheral stimulation. Subscale analyses confirmed that this FoV effect was primarily driven by the Oculomotor dimension ($\beta = 1.12$, 95% CI $[0.16, 2.07]$, $p < .05$; conditional $R^2 = 0.46$; marginal $R^2 = 0.04$), with no significant effect on the Nausea subscale (all $p \geq .064$). Neither the RF $\times$ FoV interaction nor any other term reached significance in either subscale model within this group (all $p \geq .204$).

a) Global score



b) Oculomotor score



c) Nausea score

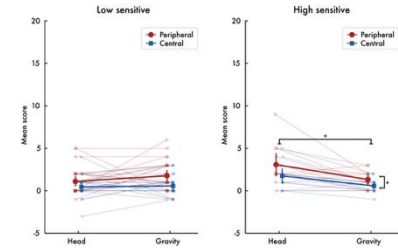


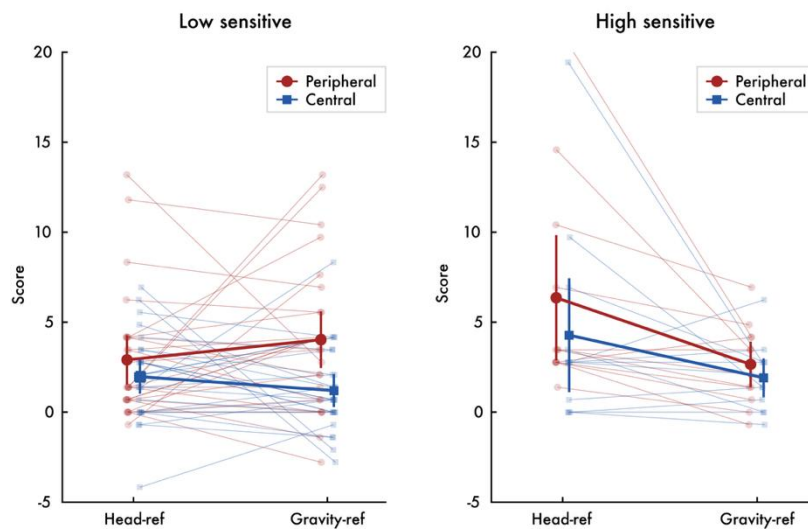
Fig. 9 SSQ scores across experimental conditions as a function of vection sensitivity

Note. (a) Global SSQ scores, (b) Oculomotor subscale scores, and (c) Nausea subscale scores for the low-sensitivity group ($n=26$) and high-sensitivity group ($n=12$). Mean scores for the Head-ref and Gravity-ref conditions are shown separately for Peripheral (red) and Central (blue) display types. Semi-transparent individual participant scores are displayed with connected lines linking paired observations across conditions. Markers represent condition means, and error bars indicate 95% confidence intervals around the mean. In both sensitivity groups, a crossover pattern is observed across experimental conditions. Significance levels are indicated as follows: * $p < .05$, ** $p < .01$, *** $p < .001$.

These subscale-level findings refine the interpretation of the overall SSQ pattern. In vection high-sensitive individuals, gravity-referenced framing reduced both nausea and oculomotor discomfort, but the oculomotor benefit was conditional on central field stimulation - an interaction absent for the nausea dimension, where RF and FoV exerted independent additive effects. In vection low-sensitive individuals, the adverse effect of peripheral stimulation on global SSQ scores was attributable specifically to increased oculomotor load, with no corresponding effect on nausea. Taken together, these results suggest that the two subscales are differentially affected by the experimental manipulations: nausea appears more responsive to the spatial coherence of the reference frame, while oculomotor symptoms reflect the combined influence of visual stimulation zone and reference frame stability in a susceptibility-dependent manner.

MSAQ. In neither Vection sensitive group did RF, FoV, or their interaction reach significance (all $p \geq .100$) (Fig.10). In the vection high-sensitive group, the direction of the RF effect ($\beta = -2.37$) remained consistent with the MISC and SSQ patterns, suggesting a trend toward reduced post-exposure symptoms under gravity-referenced framing, albeit below conventional thresholds. This pattern of weaker MSAQ sensitivity was consistent across both groups and aligns with the global-level findings reported above.

a) Global score



b) Subscales

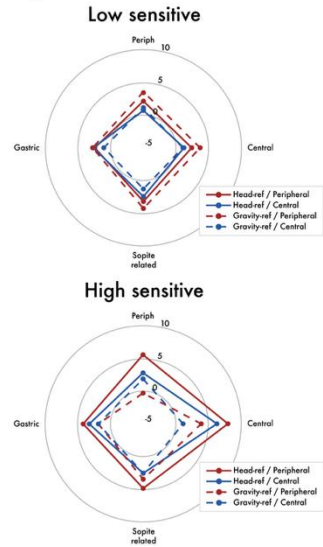


Fig. 10 MSAQ scores across experimental conditions as a function of vection sensitivity

Note. (a) Global MSAQ total scores for the low-sensitivity group ($n=26$, left) and high-sensitivity group ($n=12$, right). Mean scores for the Head-ref and Gravity-ref conditions are shown separately for Peripheral (red) and Central (blue) display types. Semi-transparent individual participant scores are displayed with connected lines linking paired observations across conditions. Markers represent condition means, and error bars indicate 95% confidence intervals around the mean. (b) Radar plots depicting mean scores for each of the four MSAQ subscales - Central, Peripheral, Gastric, and Sopite-related - across the four experimental conditions: Head-ref/Peripheral (solid red), Head-ref/Central (solid blue), Gravity-ref/Peripheral (dashed red), and Gravity-ref/Central (dashed blue), shown separately for the low-sensitivity group (up) and the high-sensitivity group (down).

Across MISC and SSQ outcomes, a consistent and conceptually coherent pattern emerges from the vection sensitive group specific analyses. Vection high-sensitive individuals were affected by both the temporal dynamics of discomfort and the reference frame manipulation: gravity-referenced framing attenuated VIMS accumulation and reduced post-exposure severity in this group, while peripheral stimulation accelerated symptom onset. Vection low-sensitive individuals, by contrast, showed a more restricted profile, with only a modest but reliable adverse effect of peripheral FoV on post-exposure SSQ scores, and no meaningful modulation by reference frame. Taken together, these findings validate the functional relevance of the vection-derived clustering and support a susceptibility-dependent model of VIMS, in which reference frame constitutes an effective mitigation lever primarily for individuals prone to strong vection-induced discomfort.

4. Discussion

The present study investigated how field of view and spatial reference frame influence visually induced self-motion perception and visually induced motion sickness during immersive virtual reality exposure. Specifically, we examined the effects of central versus peripheral visual stimulation and head- versus gravity-referenced environments on vection, presence, VIMS, and behavioral responses. Several converging findings emerged from the analyses.

First, the experimental manipulations successfully modulated vection and presence without substantially affecting task performance or perceived workload, confirming that the observed perceptual differences reflect genuine responses to the visual manipulations rather than confounds related to task demand. Second, vection responses exhibited marked inter-individual variability, giving rise to two distinct sensitivity profiles that differentially modulated the effects of the experimental factors. Third, vection and presence were positively associated across conditions, with the strength of this relationship depending on the spatial configuration of the visual scene. Finally, VIMS outcomes were consistently modulated by vection sensitivity, with reference frame effects on discomfort emerging selectively in vection high-sensitive individuals, while peripheral stimulation exerted an independent adverse effect in vection low-sensitive individuals. Together, these findings support a susceptibility-dependent model of visually induced motion sickness in which the perceptual and comfort consequences of visual motion parameters cannot be fully understood without accounting for individual differences in vection sensitivity.

4.1. Vection-presence relationship: virtual scene characteristics matter

Across the full sample, vection intensity was positively associated with subjective presence, replicating the frequently reported link between compelling self-motion perception and the sense of "being there" in a virtual environment (Allison and Palmisano, 2025; Dizmen and So, 2023; Lin et al., 2002; Park and Koo, 2025). However, condition-specific analyses revealed that this relationship was not uniform across experimental configurations. The vection-presence correlation was strongest and most robust in both head-referenced conditions, attenuated but significant in the Gravity-ref/Peripheral condition, and absent in the Gravity-ref/Central condition.

This modulation suggests that the coupling between self-motion perception and presence is not an invariant property of vection per se but depends on the broader sensory (visual) context in which self-motion is experienced. In head-referenced environments, where the optic flow is spatially anchored to the observer's head, vection and the feeling of environmental immersion may co-vary more tightly because both are driven by the same egocentric motion signal. In gravity-referenced environments -particularly under central stimulation, which produced the weakest vection-presence link- the stabilizing effect of allocentric orientation cues may partially decouple the perceptual experience of self-motion from the cognitive sense of environmental presence. Some authors have proposed that presence emerges primarily from cognitive engagement and sensorimotor contingency, rather than from self-motion cues alone (Wei et al., 2018; Yip and Saunders, 2023); the present results suggest that these two pathways may be differentially recruited depending on how the visual scene is spatially organized in the virtual world.

4.2. Vection Responses: Interaction Effects and Individual Differences

Overall, both reference frame and field of view exerted significant main effects on vection strength, with head-referenced and peripheral conditions respectively associated with stronger self-motion perception. Critically, however, these effects were qualified by a significant $RF \times FoV$ interaction, reflecting a crossover pattern: peripheral stimulation enhanced vection relative to central stimulation in the head-referenced condition, whereas this relationship was reversed under gravity-referenced framing, where central stimulation elicited stronger vection responses.

This dissociation suggests that the perceptual weighting of motion cues is not determined solely by the field of view but depends on how those cues interact with the broader spatial reference frame structuring the visual scene (Allison and Palmisano, 2025; Bringoux et al., 2009; Chung and Barnett-Cowan, 2023). In head-referenced environments, peripheral optic flow constitutes the dominant available cue for estimating self-motion, consistent with classical findings emphasizing the privileged role of the peripheral visual field - linked to the magnocellular "where" pathway - in large-field motion processing (Brandt et al., 1973; Dichgans and Brandt, 1978; Kim and Kim, 2019). In gravity-referenced environments, however, the global scene provides stronger allocentric orientation cues, potentially stabilizing the spatial representation of the environment and increasing the relative informativeness of foveal motion signals for self-motion estimation. This account aligns with "Rest Frame" theories, which propose that stable environmental features provide a consistent reference enabling the central nervous system to disambiguate self-motion from world-motion (Allison and Palmisano, 2025; Cao et al., 2018; Prothero et al., 1999). Under such conditions, central motion signals may become more tightly coupled to the stable background and thus more effective in driving vection, whereas peripheral signals lose part of their dominant role.

The $RF \times FoV$ interaction was unchanged over the course of the exposure period, as evidenced by the non-significance of all high-order interactions involving time. This temporal stability suggests that the differential weighting of visual stimulation zones across reference frames reflects a relatively stable perceptual mechanism rather than a dynamic recalibration process unfolding during immersion.

Beyond average condition effects, vection responses exhibited substantial inter-individual variability, motivating a data-driven clustering approach. Converging evidence from statistical clustering supported the existence of two vection sensitive groups, namely a vection high-sensitive and a vection low-sensitive sub-sample. Crucially, the $RF \times FoV$ interaction on vection was significant in both vection sensitive groups, but its functional expression differed markedly. In vection high-sensitive individuals, significant post-hoc differences - most prominently a substantially higher vection in the Head-ref/Peripheral condition relative to the Gravity-ref/Peripheral condition - confirmed that the interaction translated into robust condition-level distinctions. In vection low-sensitive individuals, by contrast, the interaction reached significance but yielded no reliable pairwise differences, indicating a subtle pattern that did not manifest as discriminable condition effects within this group. The substantially higher marginal R^2 in the vection high-sensitive group further underscores that the fixed-effect structure of the $RF \times FoV$ interaction is primarily carried by individuals with heightened vection susceptibility.

These findings are consistent with previous work showing that susceptibility to visually induced self-motion varies widely across individuals (Allison and Palmisano, 2025; Pöhlmann et al., 2022), and that differences in perceptual style - specifically the tendency to rely on visual versus bodily cues for spatial orientation - may underlie these profiles (Barrett and Thornton, 1968; Chung and Barnett-Cowan, 2023). Individuals with higher field dependence may be more strongly driven by the global visual background and its spatial organization, rendering them more sensitive to manipulations that alter the reference frame or the relative salience of peripheral versus central motion signals (Bringoux et al., 2009; Kuiper et al., 2019).

4.3. Emergence of Visually Induced Motion Sickness: vection sensitivity modulation

Vection sensitivity membership proved to be a functionally meaningful moderator of VIMS outcomes across multiple instruments. At the global level, significant $RF \times$ Vection sensitive interactions were observed for both MISC and SSQ, indicating that the protective effect of gravity-referenced visual framing on discomfort was not homogeneous across the sample. Specific analyses on vection sensitive groups confirmed an asymmetric modulation: in vection high-sensitive individuals, the gravity-referenced condition was associated with substantially lower MISC accumulation rates and markedly reduced post-exposure SSQ scores, whereas no such benefit was observed in vection low-sensitive individuals. Conversely, peripheral field of view exerted an independent adverse effect on post-exposure SSQ scores in the vection low-sensitive group - an effect that was absent or overshadowed in vection high-sensitive participants, where reference frame dominated the VIMS response.

The MSAQ did not robustly replicate these patterns in either vection sensitive group, although the direction of the RF effect in vection high-sensitive individuals was consistent with the MISC and SSQ findings. This differential sensitivity across instruments is addressed in the following section.

These findings have direct implications for the interpretation of the vection-VIMS relationship. Although vection correlated significantly with both MISC and SSQ scores across the full sample, this association was not uniform: its strength varied substantially as a function of individual sensitivity. In the vection high-sensitive group, the coupling between self-motion perception and discomfort was functionally tight - gravity-referenced framing attenuated both the temporal accumulation of VIMS and post-exposure severity, while peripheral stimulation accelerated symptom onset. In the low-sensitive group, by contrast, the link between vection and VIMS was considerably weaker, with only a modest and restricted effect of peripheral FoV on oculomotor discomfort and no meaningful modulation by reference frame. These findings are consistent with a growing literature challenging the assumption that vection is a necessary or sufficient condition for VIMS (Kuiper et al., 2019; Pöhlmann et al., 2022; Webb and Griffin, 2003). Rather than being directly causal, vection and VIMS likely share partially overlapping mechanisms related to multisensory integration and spatial reference frame stability (Allison and Palmisano, 2025; Chung and Barnett-Cowan, 2023). The present data extend this view by showing that the degree of coupling between vection and VIMS is modulated by individual susceptibility: vection high-sensitive individuals appear to experience a tighter functional link between self-motion perception and discomfort, rendering them more responsive to reference frame manipulations as a mitigation strategy.

4.4. Complementarity and differential sensitivity of VIMS assessment tools

An important methodological contribution of the present study concerns the comparative sensitivity of the three VIMS instruments employed. Strong convergent validity was observed between the MSAQ and SSQ, consistent with previous meta-analytic evidence of high agreement among multi-item retrospective questionnaires (Allison and Palmisano, 2025; Park and Koo, 2025). The moderate correlations between the MISC and the post-exposure questionnaires, however, confirm that continuous in-immersion ratings and retrospective global assessments capture partially distinct dimensions of the sickness experience (Kuiper et al., 2019). While questionnaires aggregate symptoms into a single cumulative score, the MISC captures the temporal dynamics of discomfort onset and progression - a feature that proved particularly informative in the present study, where significant $\text{FoV} \times \text{Time}$ and $\text{RF} \times \text{Time}$ interactions within the vection high-sensitive group revealed differential accumulation trajectories across conditions that would have been invisible to a purely post-hoc assessment approach (Cao et al., 2018; Fernandes and Feiner, 2016).

Beyond this general convergence, the three instruments also differed in their sensitivity to the specific experimental manipulations. The SSQ was primarily responsive to the field of view factor, with peripheral stimulation associated with higher scores - a pattern consistent with the SSQ's historical development for simulator contexts where visual display characteristics, including field of view and optic flow intensity, are primary drivers of disorientation and oculomotor disturbance (Allison and Palmisano, 2025; Bouchard et al., 2009). The MSAQ, by contrast, showed a trend toward sensitivity to the reference frame manipulation, with lower scores in the gravity-referenced condition in vection high-sensitive individuals. Given that the MSAQ was originally developed to assess motion sickness across a broad range of multidimensional motion environments, including real-world transport contexts (Gianaros et al., 2010), it may be more attuned to factors affecting perceived spatial orientation and the alignment of egocentric and gravitational references (Bringoux et al., 2009; Chung and Barnett-Cowan, 2023). However, the MSAQ's overall weaker responsiveness to the experimental factors suggests that its sensitivity may be better suited to paradigms involving physical motion or vestibular stimulation than to purely visually induced conditions such as those examined here.

Taken together, these results confirm that the three instruments provide complementary rather than redundant information: the SSQ is particularly responsive to visual display characteristics, the MSAQ may capture aspects of spatial disorientation more broadly, and the MISC offers the critical advantage of temporal resolution. The concurrent use of all three instruments thus enables a more complete characterization of VIMS than any single tool would allow.

4.5. Toward a vection susceptibility-dependent model of VIMS in VR

Considered jointly, the present findings support a model in which the perceptual and comfort consequences of visual motion parameters in VR are not uniform across observers but are shaped by individual susceptibility to vection. In vection high-sensitive individuals, the visual manipulation exerts coordinated effects on both self-motion perception and discomfort, with reference frame emerging as a primary determinant of VIMS severity. In vection low-sensitive individuals, the effects of reference frame are attenuated or absent, while peripheral stimulation acts as an independent sensory factor with modest but reliable adverse consequences. This dissociation

suggests that the mechanisms linking visual motion parameters to VIMS operate through at least two partially distinct pathways: one tied to the strength and coherence of the vection signal and its interaction with spatial reference systems, and another related to more peripheral sensory processing of optic flow, independent of compelling self-motion perception.

From a practical standpoint, these results suggest that reference frame manipulations - specifically the use of gravity-anchored visual environments in VR - may constitute an effective mitigation strategy for VIMS, but primarily for individuals who are prone to strong vection sensations. For vection low-sensitive users, managing the spatial extent of peripheral stimulation may be a more relevant design lever. Future work employing prospective screening of vection sensitivity, alongside computational models of multisensory integration, may help refine these profiles and translate them into personalized VR adaptation strategies.

5. Limitations and Conclusion

The present study has some limitations that nevertheless warrant consideration. First, individual differences in perceptual style - and more specifically, field dependence-independence - were not assessed prior to the experimental sessions. Field dependence, which characterizes the extent to which individuals rely on visual rather than vestibular or proprioceptive cues for spatial orientation (Isableu et al., 2010), is likely to modulate vection sensitivity and may therefore account for part of the inter-individual variability observed in the present data. Future research should systematically measure this perceptual style, as it may help identify meaningful subgroup differences in both immersion and VIMS susceptibility. Second, the virtual environment displayed in this study was deliberately kept visually sparse, relying on low-level optic flow stimuli with minimal semantic content and limited environmental complexity. Although this approach affords experimental control and ensures replicability, it may constrain the ecological validity of the findings and limit their generalizability to more visually rich and contextually complex VR scenarios encountered in real-world applications. Third, the present study employed a passive viewing paradigm in which participants remained stationary throughout the experimental session. While this design allowed for precise control of visual input, it does not capture the full complexity of real-world conditions in which self-motion perception arises from the concurrent stimulation of visual, vestibular, and proprioceptive channels. Extending the present paradigm to contexts where observers are subjected to actual physical motion - such as dynamic driving simulators or naturalistic in-vehicle settings - would constitute a critical next step toward establishing the ecological validity of these findings and evaluating their translational relevance for applied domains in which managing the interplay between vection, presence, and discomfort carries direct practical consequences.

Despite these considerations, the present study demonstrates that the effects of visual parameters such as peripheral stimulation and spatial reference frames may differ according to individual vection sensitivity profiles. Accounting for these differences may represent an important step toward the development of adaptive VR systems capable of optimizing immersion while minimizing VIMS. Overall, these findings contribute to a better understanding of the perceptual mechanisms underlying immersive self-motion and provide valuable insights for the design of virtual environments that balance strong presence with acceptable levels of user comfort. Such findings could be indeed of particular promise for ecologically grounded applications in which visual self-motion cues interact with real physical motion, such as in driving simulation or in-vehicle displays.

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