

**PRE-EXPOSURE HEAD MOTION AS AN INDICATOR
OF VISUALLY INDUCED MOTION SICKNESS
SUSCEPTIBILITY**

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Master's Thesis

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ABSTRACT

Visually induced motion sickness (VIMS) is a potential limitation to user comfort in gaming or training systems under an immersive virtual reality (VR) environment, yet objective indicators of individual susceptibility remain insufficiently established. The Postural Instability Theory proposes that a higher motion sickness (MS) incidence will occur when an individual is unable to maintain postural stability before an MS-inducing exposure. Postural instability has been associated with MS, predominantly focusing on whole-body postural responses under standing conditions, but responses under seated conditions and the role of individual head–neck control characteristics remain unclear. In addition, the individual MS severity was barely associated with postural instability during an MS-inducing exposure.

This study investigated whether pre- and in-exposure postural sway and head–trunk stabilization characteristics are associated with VIMS severity during VR exposure. Twenty-five participants completed standing and seated head-sway measurements under eyes-open and eyes-closed conditions, followed by a head–trunk stabilization test with yaw perturbation on a rotational seat and two VIMS-inducing VR exposures. VIMS severity was continuously recorded using the Misery Scale (MISC), supplemented by Simulator Sickness Questionnaire (SSQ) scores, while vection incidence was continuously reported during exposure. Head motion was characterized using time- and frequency-domain features, and head–trunk stabilization was quantified using frequency-dependent gain, phase, and coherence measures.

Pre-exposure head sway showed stronger associations with VIMS-related outcomes than head motion measured during exposure. In particular, the difference between eyes-open and eyes-closed sway in the seated condition (sit, EO-EC) exhibited the strongest overall associations, with the peak medial–lateral angular velocity showing a significant negative correlation with SSQ-nausea subscores in one of the VR exposures after correction for multiple comparisons ($\rho = -0.721$, $p_{bonf} = 0.01$, $m_{bonf} = 288$). Furthermore, the median sway frequencies calculated under the same condition (sit, EO-EC) were found to be highly positively correlated with all SSQ sub- and total scores (Nausea: $\rho = 0.605$; Oculomotor: $\rho = 0.531$; Disorientation: $\rho = 0.628$; Total Score: $\rho = 0.626$). These findings support the relevance of postural control mechanisms to individual MS severity proposed by the Postural Instability Theory in a seated VIMS context. They extend previous work by demonstrating that pre-exposure seated sway, rather than only exposure-induced postural motion, may contain information about individual VIMS susceptibility. Selected stabilization features in the head–trunk stabilization test showed associations with inverse end time, but no consistent relationships with MISC or vection incidence were observed. Overall, the findings indicate that pre-exposure seated head sway, particularly its visual dependency, may serve as a useful objective marker of individual VIMS susceptibility, while task-dependent head–neck dynamics should be considered when interpreting cervical motion responses in immersive VR environments.

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1

INTRODUCTION

THE development of automated vehicles (AVs) is progressing rapidly and is expected to fundamentally transform future transportation systems. By shifting vehicle control from human drivers to automated systems, AVs promise numerous benefits, including improved road safety, reduced traffic congestion, enhanced accessibility, and more productive use of travel time (Martínez-Díaz and Soriguera, 2018). The safety potential of AVs is particularly significant given that road traffic crashes cause approximately 1.19 million deaths worldwide each year and result in millions of non-fatal injuries, according to World Health Organization, 2023.

However, despite these well-known benefits, AVs also introduce new challenges related to passenger comfort and usability. As occupants transition from active drivers to passive passengers, their ability to perceive and anticipate vehicle motion is reduced, potentially increasing susceptibility to motion-related discomfort. While drivers rarely experience motion sickness (MS), approximately 46% of passengers report MS symptoms (Schmidt et al., 2020), particularly when performing eyes-off-road activities such as reading or interacting with mobile devices (Irmak et al., 2021).

Motion sickness, therefore, represents a significant barrier to the widespread adoption of AVs. Despite the development of numerous MS mitigation strategies, their effectiveness remains highly variable across individuals due to substantial differences in MS susceptibility. As a result, identifying objective indicators that can detect or predict the onset of MS has become an important research challenge.

One influential framework for understanding MS development is the Postural Instability Theory proposed by Stoffregen and Smart, 1998. Postural sway refers to the small, continuous oscillations of the body's center of pressure (CoP) that occur during quiet upright stance, typically quantified via CoP displacement on a force platform or via trunk or head motion recorded with motion capture or inertial sensors. These fluctuations are thought to reflect the ongoing corrective activity of the postural control system as it counteracts gravitational and inertial perturbations to maintain balance. This theory suggests that prolonged instability in postural control precedes and contributes to MS development. Specifically, measures of postural sway recorded before or during expo-

sure to motion stimuli were found to be significantly associated with whether individual participants subsequently identified themselves as motion sick. Since its introduction, numerous studies have provided further evidence supporting the relationship between postural sway and MS severity, suggesting that postural sway may serve as a promising objective indicator for predicting or detecting individual MS.

However, MS is not limited to real-world transportation: visually induced motion sickness (VIMS) is also a significant usability challenge in immersive virtual reality (VR) systems, including applications for gaming and training. VIMS commonly occurs when compelling visual motion is presented without corresponding physical motion cues. The resulting discomfort can negatively affect user comfort, usability, and sustained engagement with VR systems. Consequently, understanding and reducing VIMS is an important consideration in the design of VR applications, e.g., gaming and training systems.

Despite its importance, investigating MS in real driving environments is often costly, time-consuming, and difficult to control experimentally. Recent evidence suggests that VIMS may provide a useful laboratory model for studying MS mechanisms relevant to AV travel. VIMS commonly occurs in immersive virtual environments, driving simulators, and AV-related displays, where compelling visual motion is presented without corresponding physical motion cues. Irmak et al., 2025 demonstrated that individual susceptibility to VIMS is strongly associated with susceptibility to car sickness in real driving conditions ($R^2 = 0.81$), supporting the use of VIMS as a controlled laboratory model for investigating MS mechanisms relevant to AV travel. Therefore, investigating the relationship between postural sway and VIMS provides an efficient approach to characterizing individual differences in MS susceptibility and establishing on-road real-time MS detection systems.

Although postural sway has been linked to MS susceptibility, its relationship with VIMS remains insufficiently understood. Given the strong correspondence between VIMS and on-road MS, examining postural sway before and during VIMS exposure may provide a practical laboratory model for developing objective indicators of MS relevant to future AV applications.

2

RELATED WORK

VECTION, an illusionary perception of self-motion, was initially hypothesized to provide a link between postural instability and VIMS. However, the literature as described below reveals inconsistent evidence regarding the relationship between vection and MS, preventing a direct connection from being established. These findings, together with limitations in existing experimental paradigms, motivate the need for direct investigation of postural responses during VIMS exposure and form the basis of the research gaps discussed in this chapter.

2.1. VECTION AS A COMMON MECHANISM LINKING POSTURAL RESPONSE AND VIMS

Research investigating the relationship between vection and MS has produced mixed findings. Positive associations have been reported in studies showing that stronger individual vection experiences are accompanied by greater VIMS severity (Diels et al., 2007; Nooij et al., 2017; Kovalev et al., 2020; Teixeira et al., 2022). However, other studies demonstrated that vection and MS can become partially dissociable, particularly under complex visual-motion conditions where vection was suppressed while oculomotor persisted, thereby still encountering MS (Ji et al., 2009; Nooij et al., 2017).

Optic flow is known not only to account for vection and MS, but also to induce systematic postural responses. Foundational moving-room experiments established that visual motion can directly influence postural control even in the absence of physical movement (Lee and Lishman, 1975; Bronstein, 1986). Subsequent studies demonstrated relationships between vection and body sway (Kuno et al., 1999; Kawakita et al., 2000; Fushiki et al., 2005), demonstrating a clear effect of the direction and magnitude of stimuli on postural responses. In addition, Guerraz and Bronstein, 2008 proposed that visually induced postural responses may arise from both automatic visuomotor mechanisms - leading to visually evoked postural response, or VEPR - and vection. Although the findings about VEPR were consistent, the body sway responding to vection onset, which usually takes more than 5 seconds, differed between individuals.

2.2. HEAD MOTION UNDER SEATED CONDITIONS

Although visually induced postural responses have been extensively investigated under standing conditions, studies under seated conditions, which are closer to the occupants' posture in AVs and VR, have been limited. The findings from investigations conducted under standing conditions cannot be directly generalized to seated situations because the underlying postural control mechanisms differ substantially. Compared to standing, a seated posture requires considerably fewer degrees of freedom to maintain balance. At the same time, somatosensory information relevant to postural control is largely restricted to the head and neck region. Consequently, visually induced responses in seated observers are likely to rely on different control strategies and may even alter the perceived direction of self-motion.

Supporting this view, Fujimoto and Ashida, 2020 reported that expansion optic flow, which was predominantly interpreted as forward self-motion during standing, was no longer consistently perceived as forward motion when participants were seated. Likewise, the perceived direction of lateral optic flow, which was relatively consistent across participants while standing, surprisingly differed under seated conditions. Similar observations were reported by Held et al., 1975, who employed a rod-and-disk paradigm to examine visual influences on perceived verticality in seated participants. After prolonged roll-axis visual rotation ceased, participants consistently exhibited a small compensatory head tilt opposite to the direction of the preceding visual motion, suggesting a persistent visually induced bias in perceived verticality.

Together, these findings indicate that seated responses to visual motion differ fundamentally from standing postural responses, not only in motor behavior but also in perceptual interpretation. Since automated driving, driving simulators, and training systems or gaming using VR are typically operated in seated environments, understanding visually induced head motion under seated conditions is therefore essential for characterizing visually driven behavior in these applications.

2.3. HEAD-TRUNK STABILIZATION AND SENSORY WEIGHTING

Head and neck motion during visual motion exposure is not governed solely by visually driven responses but emerges from the interaction of multiple stabilization mechanisms. Keshner and Peterson, 1995 proposed that head stabilization is achieved through a combination of voluntary motor control, vestibular reflexes—primarily the vestibulocollic reflex (VCR)—and cervicocollic reflexes (CCR) driven by neck proprioception, together with the passive mechanical properties of the head–neck system. The relative contribution of these mechanisms is not fixed, but depends on the dynamics of external perturbations. In general, voluntary control predominates at low-frequency disturbances, while reflexive mechanisms such as the VCR and CCR become more influential in the intermediate frequency range, providing rapid compensation to maintain head stability relative to space and the trunk, respectively. At higher frequencies, however, the head–neck system is increasingly influenced by its intrinsic mechanical properties, which may lead to resonance effects and amplified head motion relative to the trunk.

Within the context of visually induced motion, these stabilization mechanisms suggest that cervical responses are shaped not only by visual input, but also by individual

differences in sensory weighting between visual, vestibular, and proprioceptive cues. Accordingly, variability in cervical motion during vection may partly reflect differences in underlying head–trunk stabilization strategies rather than purely differences in visual motion processing. To capture these intrinsic differences in control strategy, a separate head–trunk stabilization assessment will be included to characterize each participant's baseline cervical control behavior prior to visual motion exposure.

2.4. MOTIVATION FOR CONTINUOUS VECTION MEASUREMENT

Although vection has been extensively investigated, several important gaps remain in the current literature.

First, studies that quantify vection incidence have predominantly employed highly simplified visual stimuli, such as optic-flow patterns composed of random dots. While these paradigms provide excellent experimental control and are effective for isolating low-level visual mechanisms, their findings cannot be readily generalized to more ecologically valid environments, including immersive VR applications and commercial VR games. Vection is widely considered to arise from multisensory integration and higher-level perceptual interpretation rather than visual input alone. Consequently, simplified laboratory stimuli may primarily reflect the characteristics of visual motion processing while underrepresenting the contribution of cognitive factors involved in self-motion perception.

Second, in studies employing continuous forward-motion visual stimuli (e.g., contracting random-dot optic flow), the simulated self-motion is almost always presented at a constant velocity. As a result, it remains largely unknown how temporal changes in velocity, such as acceleration and deceleration without changes in the direction of travel, influence the onset and temporal dynamics of vection. This represents an important yet underexplored aspect of visually induced self-motion.

Finally, although vection and visually induced VIMS frequently co-occur, the causal relationship between them remains unclear. Individuals who develop MS typically report experiencing vection; however, it is not known whether vection and MS arise from the same underlying mechanisms or whether vection is merely a by-product of MS progression. Most previous studies have continuously recorded vection using button presses or rating sliders, whereas MS has typically been assessed only intermittently with subjective questionnaires, resulting in a substantial mismatch in temporal resolution between the two measures. Collecting high-temporal-resolution measurements of both vection and MS under a broader range of visual stimuli may therefore provide new insights into their temporal relationship and facilitate the incorporation of vection into future models of MS progression.

2.5. RESEARCH OBJECTIVES AND HYPOTHESIS

The objectives of this study are:

1. To quantify individual baseline *head sway* motion during unperturbed standing and seated conditions under both eyes-open and eyes-closed conditions.
2. To assess individual *head-trunk stabilization* performance during controlled yaw

rotational visual or motion perturbations.

3. To continuously quantify *VIMS* with high temporal resolution during exposure to VR.
4. To investigate the relationship between pre-exposure head-trunk stabilization performance and *VIMS* during VR exposure.

Accordingly, the following hypothesis is proposed:

Hypothesis Individual differences in pre-exposure head-trunk stabilization performance are significantly associated with the severity of *VIMS* during VR exposure.

The relationship between baseline head sway and *VIMS* severity (Objectives 1 and 3) provides a means of examining the postural instability theory of MS. In particular, previous work by Stoffregen and colleagues has demonstrated an association between pre-exposure postural instability and susceptibility to subsequent MS (Stoffregen and Smart, 1998; Smart Jr. et al., 2002). However, this relationship has not been consistently replicated across subsequent studies, with several investigations providing evidence that challenges the proposed role of pre-exposure postural instability in predicting individual MS (Dennison and D’Zmura, 2017).

Whereas Objective 1 characterizes spontaneous head sway under eyes-open and eyes-closed conditions, Objective 2 evaluates the ability to stabilize the head relative to the trunk during controlled visual and/or motion perturbations. The comparison across these conditions is intended to characterize individual differences in reliance on visual information to maintain head-trunk stability along the yaw axis. Together, Objectives 1 and 2 provide complementary measures of individual postural control characteristics, which are subsequently examined in relation to *VIMS* severity to determine whether pre-exposure head-trunk stabilization can account for individual differences in susceptibility to *VIMS*.

3

METHOD

3.1. PARTICIPANTS

The participants consisted of 25 adults comprising 14 males (56%) and 11 females (44%). The mean age of the sample was 25.2 years (mean = 25.2 years, $SD = 2.8$ years), with an age range from 19 to 33 years. The average height was 170.3 cm (mean = 170.3 cm, $SD = 8.6$ cm), and the mean body weight was 63.9 kg (mean = 63.9 kg, $SD = 13.0$ kg). The histogram of these data can be found in Figure 3.1. Participants self-reported being healthy with no history of stroke or dementia, and no musculoskeletal, cognitive, psychiatric, or vestibular impairments at the time of participation. The study was approved by the Human Research Ethics Committee of Delft University of Technology (ID 7376). Before participation, all participants were provided with the "Informed Consent Form" (Appendix C) and were instructed to fast and refrain from consuming any caffeine products for 2 hours prior to participation. Participants were free to terminate the experiment at any time without argumentation.

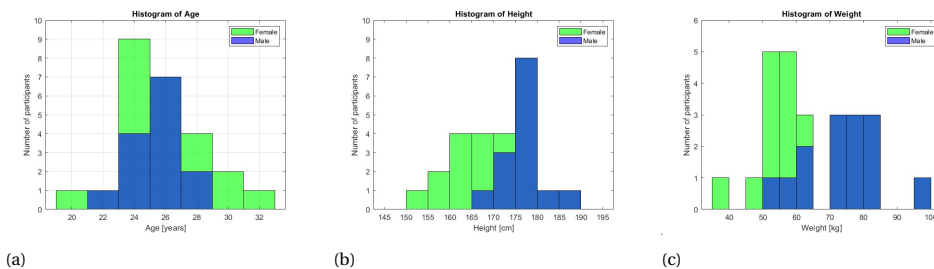


Figure 3.1: (a) The age distribution of participants per sex. The male participants were distributed in a relatively narrow age range (21-28 years). (b) The height distribution per sex shows that the male participants were predominantly taller than the female participants. (c) The weight of male participants was distributed within a wider range and significantly higher than that of the female participants ($p < 0.001$). An additional analysis of the effect of lower weights was conducted because two female participants were lighter than 50 kg.

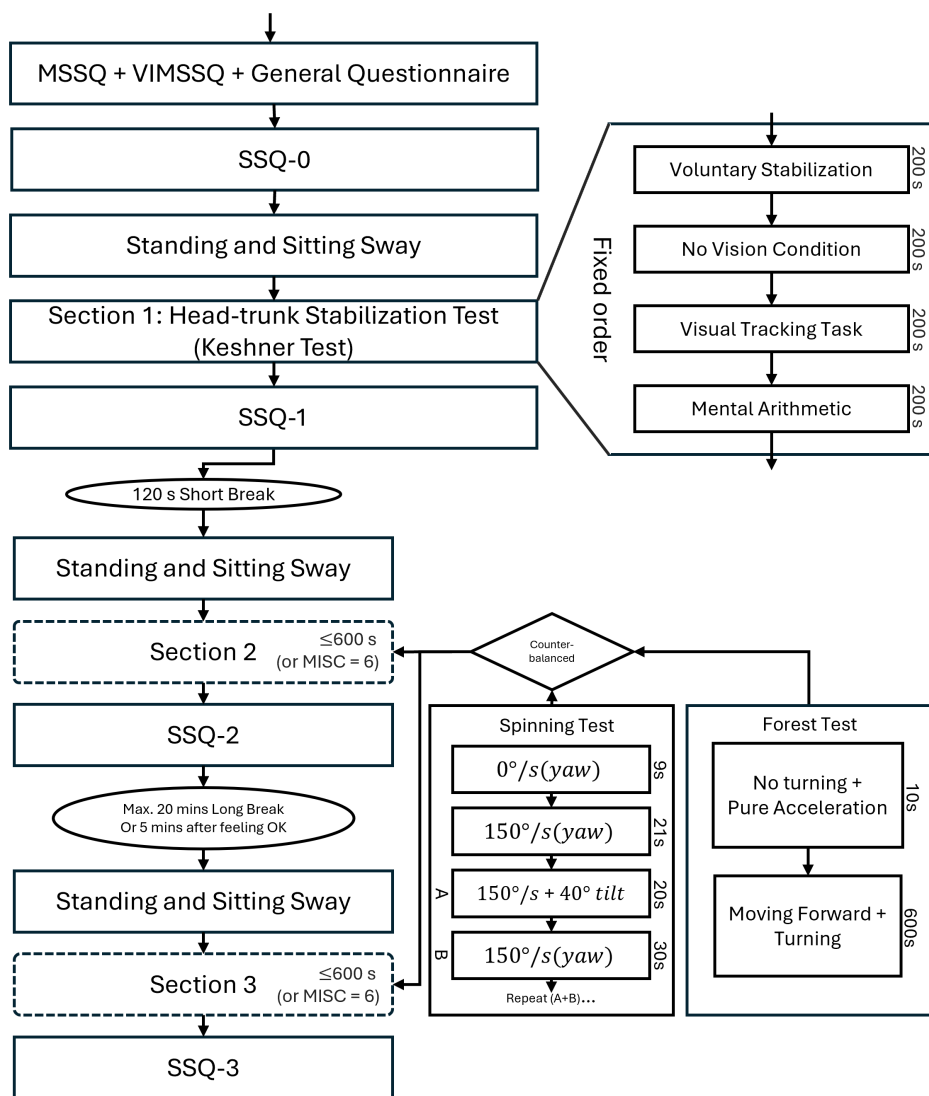


Figure 3.2: Experimental procedure. Participants first completed the MSSQ, VIMSSQ, and a general questionnaire. The experiment consisted of three sections, each of which had a Standing and Sitting Sway Measurements before and a Simulator Sickness Questionnaire (SSQ) after. SSQ-0 was administered before any test. In Section 1, participants completed a head-trunk stabilization test comprising four 200-s tasks presented in a fixed order: voluntary stabilization (VS), no-vision (NV), visual tracking (VT), and mental arithmetic (MA). SSQ-1 and a short 120-s break followed Section 1. In the forest test, participants completed a driving simulation that showed a 10-minute forest road scene, including trees, barriers, and other vehicles. In the spinning test, participants were presented with a 360-degree video, continuously rotating but not moving the view angle. Both tests were terminated if the participant's Misery Scale (MISC) score reached 6, exposure time reached 600 seconds, or upon participant request. The order of the last two tests was counterbalanced across the participants. SSQ-2 and SSQ-3 were administered immediately after completion or termination of Section 2 and Section 3, respectively.

3.2. APPARATUS

3.2.1. HEAD-MOUNTED DISPLAY (HMD)

Visual stimuli were presented through a standalone mixed reality HMD, Meta Quest 3 (Fig 3.3b, refresh rate = 120 Hz, resolution = 2064 x 2208 pixels per-eye, visible field of view = 103.8° horizontal & 96.4° vertical). The experimental procedure was programmed and embedded in a standalone application installed in the HMD. The Meta Quest 3 provides 6-Degree-of-Freedom (6-DoF) head tracking and color passthrough for mixed-reality viewing. However, Meta does not publicly disclose the headset-tracking sampling rate or the end-to-end latency of tracking-driven display updates, so these parameters were recorded but not analyzed in this study. In addition to the HMD, one of the paired hand controllers was given to participants to interact with the application. In the remainder of this report, the controller refers to the paired controller connected to the HMD. The refresh rate of rendering in each trial was 120 fps, except for the forest test.

3.2.2. ROTATIONAL SEAT

Figure 3.4a presents the rotational seat setup with a participant on it. Motion stimuli were generated using a motorized rotational chair equipped with a four-point safety harness, adjustable backrest, armrests, and foot restraints. The chair was controlled via a motor controller, which received angular velocity commands transmitted from the computer at a rate of 50 Hz.

3.2.3. INERTIAL MEASUREMENT UNIT (IMU)

Movella XSENS DOT IMUs were mounted on the HMD and the rotational seat with sticky pads (brand: Pritt). The pads were renewed daily to prevent dysfunction of the adhesive. The kinematics of participants' HMD and the rotational seat were recorded, serving as the kinematics of heads and trunks of participants, respectively. The IMUs provided high-temporal-resolution, up to 800 Hz, tracking data of tri-axial angular velocity (sensing range: $\pm 2000^\circ/s$) and tri-axial acceleration (sensing range: $\pm 16g$ or $\pm 156.96m/s^2$). The device implemented a strapdown integration algorithm to reduce the rate to 60 Hz while preserving accuracy. The result was further fed to the sensor fusion algorithm (XKFCore) of Movella, a Kalman-filter-based proprietary algorithm that fuses the sensor modalities to calculate estimates of orientation to avoid drift (Movella, 2023). Finally, the data were exported to a personal computer via a USB cable.

3.3. PROCEDURE AND DESIGN

3.3.1. GENERAL SETUP

A schematic overview of the experimental procedure is presented in Fig. 3.2. The baseline Simulator Sickness Questionnaire (SSQ-0) was administered upon arrival. After completing SSQ-0, participants were instructed and assisted to sit in the rotational seat with their back fully supported by the backrest while facing forward. The seat position was adjusted such that the midpoint between the participant's ears was approximately aligned with the rotational axis of the chair, ensuring a distance of 185 cm from the wall to the participant's ear when they faced the wall and kept the head upright. A four-point safety



(a)



(b)

Figure 3.3: (a) Coordinate definition and attaching position of the IMU on the rotational seat. (b) Meta Quest 3 HMD set: A right-hand controller (left) was given to participants during Sections 2 and 3. A Movella XSSENS DOT IMU was attached to the HMD (right). It shows the coordinate definition of the IMU on the HMD, aligning with the one on the rotational seat when the participants were seated in the starting position.

harness was then fitted and adjusted to ensure both comfort and stability. To verify adequate fixation of the shoulders during head movements, the experimenter stood approximately 100° to the left and right of the participant and instructed the participant to turn their head toward the experimenter on each side.

Participants completed one Head-trunk Stabilization task, consisting of four subtasks (200 s per subtask), two VR environment exposure sessions (up to 10 min each), and three pre-exposure body sway measurements (5 min each). They were asked to report their subjective MS rating and vection before, during, and after the exposures. The order of the two VR exposure sessions was counterbalanced across participants.

Prior to Section 2, participants were familiarized with the MISC score and trained to report their current MISC score and vection using the controller joystick and button. MS severity was continuously reported in the form of MISC using a joystick: participants pushed the joystick forward or backward to increase or decrease their current rating. Changes in MISC levels were accompanied by auditory feedback via headphones. Participants were informed that the trial would be terminated when a MISC score of 6 was reached, and that the termination time would be included as an experimental response measure; therefore, they were instructed to report their symptoms as objectively as possible.

3.3.2. STANDING AND SITTING SWAY MEASUREMENT (PRE-EXPOSURE)

Standing and sitting sway measurements were conducted at the start of each experiment trial, consisting of 90-s and 60-s recordings of head IMU data, respectively. Both measurements contained eyes-open and eyes-closed conditions. During all measurements,

participants wore the HMD in passthrough mode, which provided a 30-fps streaming video of participants' surroundings.

For the standing sway assessment, participants stood upright on a rigid surface in a standardized posture, with their feet approximately hip-width apart and their arms resting alongside the body. For the sitting sway assessment, participants sat upright in the rotational seat, secured by the four-point safety harness. In both assessments, participants were instructed to keep their heads upright and minimize unnecessary movements while maintaining a stable posture for the duration of the recording. The instruction can be found in Appendix A.1.

3.3.3. HEAD-TRUNK STABILIZATION TEST (YAW)

The head-trunk stabilization test was adopted from the study by Keshner and Peterson, 1995, in which the participants stabilized their head during yaw-rotational perturbation under four conditions, hereafter termed the *Keshner test*. The assessment focuses specifically on *yaw rotation* because it minimizes changes in head orientation relative to gravito-verticality, thereby reducing otolith involvement. In contrast, pitch and roll rotations directly modify the orientation of the head relative to gravito-verticality, generating substantial gravito-inertial cues that may dominate sensory reweighting processes. By preferentially employing yaw rotation, the relative contribution of visual information can be magnified, allowing individual differences in visual reliance and visual-vestibular integration to be examined more clearly. Since VIMS is highly associated with visual-vestibular interactions, yaw-based stabilization behavior may provide a useful proxy for characterizing sensory weighting strategies that contribute to variability in cervical responses during vection.

Four conditions were included in this test: Voluntary Stabilization (VS), No Vision (NV), Visual Tracking (VT), and Mental Arithmetic (MA). In the VS condition, the participant was asked to keep the head direction marker coincident with a stationary tracking target while the seat was rotated. The NV condition was performed in the dark while the participant was given the task of stabilizing the head by imagining both the head direction marker and the stationary tracking target. Only under the NV condition, participants were put on headphones playing brown noise to cover the noise in the laboratory. Provided the same environment as the VS condition, the VT condition required that the participant align the head direction marker to the moving tracking target on a stationary seat. During MA, the participant's attention was removed from the task of stabilization by a series of mental calculation tasks in audio - listed in Appendix A.2.2 - while rotation in the dark was ongoing. The audio and on-screen instructions are in Appendix A.2.1 and A.2.3, respectively.

STIMULUS

For the NV and MA conditions, the display was set to solid black during the exposure, and the participants were asked to close their eyes. For the VS and VT conditions, the VR environment consisted of a simple horizon scene designed to provide minimal visual context. Two groups of depth-cued visual objects were presented in the scene: Head Direction Marker and Tracking Target (Fig. 3.5).

Within the scenes of VS and VT, the first group, the head direction marker, consisted



(a) A secured participant at the starting position of the Keshner test. His ears were adjusted close to the rotational axis of the seat to the experimenter's best. The HMD with IMU attached had already been equipped. The participant was asked to face ahead with reference of his proprioception. The headset was removed to avoid the HMD. The back, arms, and feet lay on the backrest, armrest, and footrest, respectively; thereby, the entire trunk was supported by the seat at most.

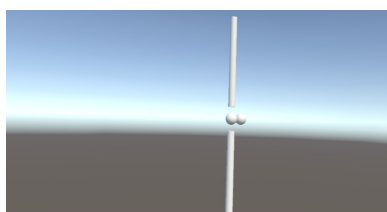


Figure 3.5: A screenshot showing the two groups of objects: head direction marker and tracking target. The tracking target, a white sphere a little further from the observer, was set to the center of the view at the beginning of each trial under the VS and VT conditions. The head direction marker, identical to the tracking target, was emphasized by two vertical bars above and below. This marker indicated the facing of the observer, always stayed at the same height as the tracking target, and indicated the gravito-verticality throughout the trial. The background showed a horizon, providing information about verticality as well.

Table 3.1: Parameters of the sum of 12 sinusoids. These frequencies are also denoted as f_k hereafter.

Prime Numbers	Frequency [Hz]	Amplitude [°/s]
37	0.185	18
49	0.245	18
71	0.355	18
101	0.505	17
143	0.715	17
211	1.055	17
295	1.475	15
419	2.095	15
589	2.945	13
823	4.115	12
1031	5.155	9
1741	8.705	7

of a white sphere (simulated to be 0.1 m in diameter) accompanied by two vertically aligned white bars positioned above and below the sphere. These bars emphasized the sphere and maintained a constant vertical orientation relative to gravity. The sphere was positioned along the participant's forward head-direction vector, while its vertical position remained constant. Its motion was constrained to the surface of an imaginary cylinder centered on the participant with a radius of 3 m.

The second group, tracking target, was a white sphere identical in size and color to the first sphere but without the accompanying vertical bars. This sphere served as the tracking target for the participant only under VS and VT conditions. Its motion was constrained to the surface of a concentric imaginary cylinder centered on the participant with a radius of 3.1 m.

The same time-series of velocity commands was provided to either the rotational seat (in VS, NV, and MA) or the tracking target (in VT) under different experimental conditions. The time-series of velocity commands was a sum of 12 sinusoids (SSN) that consisted of a relatively prime set of harmonics of a common base frequency, sharing no common divisors. The SSN waveform used for all subjects in this study was composed of the following harmonics: 37, 49, 71, 101, 143, 211, 295, 419, 589, 823, 1031, 1741. Multiplied by a fundamental frequency of 0.005 Hz, the complete range of the waveform in the frequency domain was from 0.185 to 8.705 Hz. Among these frequencies, those from 0.185 to 4.115 Hz were the same as the frequencies used by Keshner and Peterson, 1995, and the highest two frequencies were added to examine the human cervical response under a more demanding condition. The data will be further used for validation of neuromuscular models (see Happee et al., 2023). The amplitudes were subsequently scaled with a factor of 0.9 and rounded to whole numbers, to respect the maximum amplitude of 50°. The corresponding amplitude of the sinusoids is shown in Table 3.1.

PROCEDURE

Before the start of each subtask, the experimenter aligned both the head direction marker and tracking target with the participant's forward gaze based on their relaxed neck pos-

Table 3.2: Parameters of the sum of 4 sinusoids used for yaw rotation in the forest test

Frequency [Hz]	Amplitude [$^{\circ}/s$]
0.05	45
0.185	15
0.245	8
0.355	5

3

ture. Each subtask started with an audio briefing and an on-screen text instruction (see Appendix A.2.1), followed by a verbal countdown by the experimenter. An additional visual countdown was implemented at the beginning of the VT condition. The order of subtasks was fixed: VS, NV, VT, and MA. Each subtask lasted 200 seconds, and no rest period was provided between subtasks. After all trials, the participants were assisted out of the rotational seat and administered the SSQ-1.

3.3.4. FOREST TEST

STIMULUS

The forest test was conducted in a passive VR environment, simulating a road in a forest. It was designed to elicit both vection and VIMS in a setting comparable to gaming. The expected vection was elicited not only by the expanding optic flow but also by the rotation of the observer's VR view. The road scene provided contextual cues that allowed participants to anticipate upcoming visual motion, including objects that convey subjective verticality (e.g., barriers, trees, other vehicles, see Fig 3.6c). Each participant completed an at-most-10-minute journey on an identical route across participants, consisting of continuous movement forward and rotation of view in the yaw and pitch axes. The pitch rotation was programmed as a sinusoidal tilting with an amplitude of 5 degrees and a frequency of 0.067Hz, while the yaw rotation was composed as a sum-of-four-sine panning, consisting of 0.05, 0.185, 0.245, 0.355Hz (Table 3.2). These rotations defined the instantaneous viewing direction (Fig 3.7). At each simulation step (1/120s), the forward velocity was updated from a target speed of 30m/s under constraints of gravitational acceleration ($9.81m/s^2$) along the pitch direction and a maximum lateral acceleration of 0.6 g determined by the instantaneous turning radius. The displacement vector for each step was then obtained by multiplying the instantaneous forward direction by the updated velocity, and the complete trajectory was generated by integrating these stepwise displacements. The rendering refresh rate was set to 30 fps due to hardware limitations, and the observer's orientation was updated at 120 Hz.

The participants were instructed to stabilize their heads, and the HMD view of the observers was compensated for their head motion. Their trunks were constrained by the harness. The seat stayed stationary throughout the exposure, and the participants were told so.

PROCEDURE

After the standing and sitting sway measurements were conducted, participants stayed in the rotational seat and were assisted in fitting the HMD and holding a controller. Participants subsequently received standardized audio instructions accompanied by on-



(a)



(b)



(c)

Figure 3.6: The screenshots of stimuli in the forest test. The environment included roadside barriers, trees casting shadows, and stationary vehicles in the opposite direction. (a) The point of view at the beginning of the test. (b) The countdown text appears before the start of the visual motion. (c) The point of view during the exposure. The observer always drove on the right side of the road, positioned at a fixed displacement from the centerline of the road. The demonstration video can be found at <https://youtu.be/PoWZPQLkHO8>.

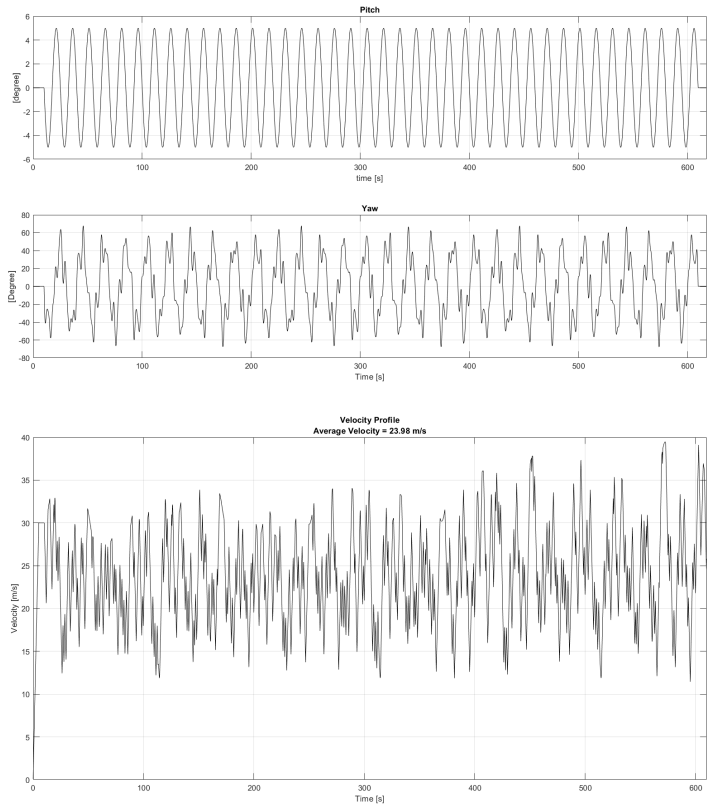


Figure 3.7: Orientation and velocity profile in the forest test

screen text explanations (see Appendix A.3) and were asked to adjust the MISC score to reflect their current condition. Once all preparations were completed, the instructional panel was hidden, and data recording was initiated. To facilitate temporal synchronization between the IMU and HMD datasets, the experimenter lightly tapped the HMD, creating a distinct vibration pattern that was identifiable in both data streams during subsequent analysis.

A 5-s visual countdown was presented immediately before the exposure began. The maximum duration of both tests was 610 s. The experiment terminated automatically when the participant reported a MISC score of 6. In addition, the experimenter could manually terminate the session using a controller if requested by the participant. Upon completion of the test, participants were assisted out of the rotational seat and seated in a stationary chair, where they completed the SSQ on a personal computer.

3.3.5. SPINNING TEST



(a) The point of view at the beginning of the spinning test.



(b) The point of view during the tilt.

Figure 3.8: The screenshots of stimuli in the spinning test. The environment was a pre-recorded 360 panorama video, looping every 2 minutes. The demonstration video can be found at <https://youtu.be/4PxFOO7v1M>.

STIMULUS

The spinning test combined a series of high-speed yaw-axis rotation ($150^\circ/\text{s}$, held for 30s) with intermittent roll-axis visual tilts (40° , held for 20s, Fig 3.8b), inspired by the paradigm proposed by Irmak et al., 2025. The visual motion strictly followed the one used in Irmak's original experiment. According to their results, this motion successfully raised VIMS in most participants within 10 minutes. In contrast to the original study, which employed an animated VR environment with 3D models, the present study used realistic 360-degree video recordings (Fig 3.8a). This modification aimed to enhance ecological validity while facilitating the rapid onset of VIMS, thereby enabling observation of the temporal relationship between VIMS severity and head motion within a shorter exposure duration.

PROCEDURE

The procedure of the spinning test was adopted from the forest test; however, no count-down was provided in this test. The maximum duration of this test was 600 s. The experiment terminated automatically when the participant reported a MISC score of 6. In addition, the experimenter could manually terminate the session using a controller if requested by the participant.

The order of the forest test and the spinning test was counterbalanced across participants. Of the 14 male participants, six completed the forest test first, and eight completed the spinning test first. Of the 11 female participants, six completed the forest test first, and five completed the spinning test first. Therefore, the experimental order was approximately balanced across the two sex groups.

3.4. RESPONSE MEASURES

3.4.1. MSSQ AND VIMSSQ (GENERAL SUSCEPTIBILITY)

The Motion Sickness Susceptibility Questionnaire (MSSQ) is one of the most widely used and established questionnaires for assessing individual susceptibility to MS in general. Because VIMS, however, represents a distinct form of MS associated with exposure to visual motion, MSSQ may not fully capture an individual's susceptibility to VIMS. The Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) was therefore developed as a specialized measure targeting susceptibility to VIMS. In the current study, both questionnaires were administered to characterize participants' general MS and VIMS susceptibility, respectively.

MSSQ scores were calculated following Golding, 1998, yielding a standardized susceptibility index. Participants reported their past experiences, divided into childhood (before 12 years old) and adulthood, across multiple transportation modes (car, train, boat, airplane, etc.), and a total susceptibility score was computed for use as a covariate. In addition, participants reported their prior experience related to VIMS by completing VIMSSQ, developed by Keshavarz et al., 2023. The questionnaire evaluates the frequency of five common VIMS-related symptoms, including nausea, headache, dizziness, fatigue, and eyestrain, experienced while using 11 types of visual displays and devices (e.g., smartphones, televisions, video games, movie theaters, simulators, and VR HMD). Participants rated each symptom on a four-point Likert scale ranging from 0 (never) to 3 (often). The questionnaire also includes items assessing the frequency of exposure to these visual devices and a single item measuring the extent to which participants avoid visual displays due to discomfort.

3.4.2. SSQ

Prior to the actual experiment, and after experiment sections 1-3, the Simulator Sickness Questionnaire (SSQ) was used to assess the various symptom clusters of VIMS following Kennedy et al., 1993. The SSQ was a standardized questionnaire containing 16 items, each rated on a 4-point Likert scale ranging from "not at all" to "severe". Three subscales—nausea (SSQ-N), oculomotor (SSQ-O), and disorientation (SSQ-D), as well as a total score (SSQ-TS), were calculated using pre-defined factor weightings. The details of the questionnaire can be found in Appendix B.1.

3.4.3. HEAD AND SEAT MOTION

Head and seat motion were recorded using an IMU attached to the HMD and the rotational seat firmly (Fig 3.3a), respectively. By implementing a four-point safety harness, the seat kinetics were assumed to represent the trunk kinetics. The sensor recorded tri-axial angular velocity and orientation estimates, which were used to characterize trunk motion during the experimental trials.

3.4.4. VECTION INCIDENCE

Participants were instructed to report their vection incidence during the forest and spinning tests. The data were a time series comprising 1 for indicating an affirmative of perceived vection at the moment, and 0 otherwise. Vection was explained with the "moving train illusion": when being in a stationary train and a nearby train begins to move, you may briefly feel as if your own train is moving in the opposite direction. The controller collected the triggered signal at a sampling rate of 60 Hz and passed the data to the HMD with a delay of less than 30 ms. The application in the HMD then recorded the triggered signal.

3.4.5. MISC

Participants were instructed to reflect on their MS severity during the forest and spinning tests with a sampling rate of 60 Hz. The MS severity was determined using the MISC (MIsery SCAle), for which the levels and corresponding symptoms are shown in Table 3.3. The test was stopped when the MISC reached a score of 6, which equals slight nausea.

Table 3.3: Misery Scale (MISC) and Associated Symptoms

MISC Score	Associated Symptoms	
0	No problems	
1	Uneasiness	
2	Vague	Dizziness, warmth, headache, stomach awareness, sweating
3	Slight	
4	Fair	
5	Severe	
6	Slight	Nausea
7	Fair	
8	Severe	
9	(Near) retching	
10	Vomiting	

3.5. DATA ANALYSIS

3.5.1. PREPROCESSING

DATA SYNCHRONIZATION

The two Movella Xsens DOT IMUs were synchronized before each experimental session using the built-in synchronization function of the Movella DOT application (ver-

sion 2023.6.0) running on an iOS device (version 26.5). The synchronization procedure aligned the internal clocks of both IMUs before data acquisition, enabling the head-mounted and trunk-mounted sensors to record data within a common time frame throughout the experiment.

Because the HMD and IMUs operated as independent recording systems, an additional synchronization procedure was performed at the beginning of some trials (VT condition in the Keshner test, forest test, and spinning test). After the recording functions of both systems were initiated and before the onset of the visual stimulus, the experimenter gently tapped the HMD to generate a distinct vibration signal detectable by both the HMD-mounted IMU and the HMD tracking system. The resulting vibration peak was subsequently used as a synchronization marker to align the time series from the two recording systems during offline processing.

The recording systems of IMUs sampled data at 60 Hz, while the one in the HMD did not record with a fixed time interval. Therefore, the temporal alignment accuracy was limited by the maximum sampling interval of 30 Hz, resulting in a maximum synchronization uncertainty of approximately 33.3 ms between HMD and IMU systems. Head and trunk motion analyses were performed exclusively using the synchronized IMU data. HMD-derived data were used only for visual stimulus presentation and behavioral event logging (i.e., MISC ratings and vection incidence).

MOTION SIGNAL PREPROCESSING

All motion signals obtained from the IMUs were preprocessed prior to further analysis. The signals were filtered using a zero-phase Butterworth band-pass filter to minimize sensor-related artifacts while preserving movement characteristics relevant to the experimental task. The filtering procedure consisted of a 2nd-order high-pass filter with a cutoff frequency of 0.1 Hz to remove slow sensor drift and low-frequency offsets, followed by a 4th-order low-pass filter with a cutoff frequency of 20 Hz to attenuate high-frequency measurement noise.

3.5.2. QUANTIFYING VIMS AND VECTION

SSQ

To account for individual differences in pre-existing symptoms, the baseline SSQ assessment (SSQ-0) administered before the experimental trials was treated as the baseline measurement. For each participant, baseline-corrected scores were calculated by subtracting the baseline score from each post-trial SSQ score, i.e., SSQ-1, -2, and -3. This procedure was applied to the SSQ Total Score (SSQ-TS) and to each symptom subscale, including nausea (SSQ-N), oculomotor disturbance (SSQ-O), and disorientation (SSQ-D).

The resulting change scores represented the symptom increase attributable to the experimental exposure and were used in all subsequent statistical analyses. Positive values indicated an increase in symptom severity relative to baseline, whereas negative values indicated symptom levels lower than the baseline measurement.

MISC

The MISC recordings were analyzed up to the time point when the VR exposure was terminated. It was only recorded during and shortly (5 s) before the start of the forest and

spinning tests. The recordings were stored in HMD's memory as soon as the application terminated. Because the experimental protocol specified termination when the MISC reached 6, the endpoint of each recording was defined as the first instance at which a score of 6 was reported, immediately before the VR environment was deactivated. In one trial, a participant (P16 in the spinning test) briefly reported a MISC of 6 before subsequently returning to a score of 5, resulting in the termination at the second instance at which MISC reached 6. To ensure a consistent definition of symptom progression across participants, the actual termination of application was therefore used as the endpoint for all analyses. For participants who did not reach a MISC of 6, the complete 600-s exposure was retained.

Four summary features were extracted from each MISC recording. First, the mean MISC was calculated to represent the overall symptom severity throughout the analyzed exposure period,

$$\text{MISC}_{\text{mean}} = \frac{1}{T} \int_0^T \text{MISC}(t) dt, \quad (3.1)$$

where T denotes the analyzed exposure duration.

Second, the peak MISC was calculated to represent the peak symptom severity,

$$\text{MISC}_{\text{max}} = \max_{0 \leq t \leq T} (\text{MISC}(t)). \quad (3.2)$$

Third, to quantify the rate of symptom development, the MISC rate was defined as the maximum MISC divided by the time at which that maximum was first reached:

$$\text{MISC}_{\text{rate}} = \begin{cases} \frac{\text{MISC}_{\text{max}}}{t_{\text{max,first}}}, & \text{if } \text{MISC}_{\text{max}} \neq 0, \\ 0, & \text{if } \text{MISC}_{\text{max}} = 0. \end{cases} \quad (3.3)$$

where MISC_{max} is the peak MISC recorded during the exposure, and $t_{\text{max,first}}$ is the elapsed time from the start of exposure to the first occurrence of MISC_{max} .

Finally, following the approach adopted in previous studies Irmak et al., 2025, the reciprocal of the termination time was calculated as an indicator of MS severity: $1/t_{\text{end}}$, where t_{end} corresponds to the analyzed exposure duration, i.e., the elapsed time until the experiment was terminated or the full exposure was completed. Participants who reached the termination criterion earlier exhibited larger values of $1/t_{\text{end}}$.

The extracted MISC-related features are summarized in Table 3.4.

Table 3.4: MISC-derived features used for statistical analysis.

Feature	
Mean MISC	$\text{MISC}_{\text{mean}}$
Peak MISC	MISC_{max}
MISC rate	$\text{MISC}_{\text{rate}}$
Inverse end time	$1/t_{\text{end}}$

VECTION INCIDENCE

The vection response was represented as a binary time series, $v(t)$, where $v(t) = 1$ indicated the presence of vection and $v(t) = 0$ indicated its absence. Each vection recording was truncated at the same endpoint as the corresponding MISC recording to ensure temporal alignment across measurements. Adapted from the *vection gain* used by Nooij et al., 2017, vection incidence was then quantified as the temporal average of the binary vection signal by integrating $v(t)$ over the recording duration and normalizing by the total recording time:

$$v_{mean} = \frac{1}{T} \sum_{t=0}^T v(t) \Delta t, \quad (3.4)$$

where T denotes the duration of the truncated recording and Δt denotes the time step to the next sample. Since $v(t)$ is binary, v_{mean} represents the proportion of time during which vection was experienced, with values ranging from 0 to 1.

3.5.3. QUANTIFYING SWAY MEASUREMENT (PRE-EXPOSURE)

Standing and sitting sway were quantified using the angular velocity signals of head motion recorded by the head-mounted IMU. All signals underwent the preprocessing procedures described previously, including synchronization and band-pass filtering. To eliminate transient movements associated with task initiation, the first 5 s of each recording were discarded. Consequently, 85 s of data from the standing sway assessment and 55 s from the sitting sway assessment were retained for subsequent analysis.

The angular velocity signals corresponding to the pitch and roll axes were obtained directly from the gyroscope measurements provided by the IMU. They were analyzed separately to characterize postural sway in the anterior–posterior (AP) and medial–lateral (ML) directions, respectively. The yaw axis was excluded because rotational movements about the vertical axis were not considered representative of postural sway during the standing and sitting balance tasks.

Both time-domain and frequency-domain characteristics of head sway were quantified. In the time domain, the root mean square (RMS) of the angular velocity was calculated to quantify the overall magnitude of head motion:

$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N \omega_i^2}, \quad (3.5)$$

where ω_i denotes the angular velocity at sample i , and N is the total number of samples. The RMS of the angular velocity is the metric associated with the mean velocity used by Stoffregen and Smart, 1998.

The peak angular velocity was defined as the maximum absolute value of the angular velocity signal:

$$\omega_{\text{peak}} = \max(|\omega_i|). \quad (3.6)$$

To quantify the cumulative amount of head movement over the entire recording period, the angular velocity integral (AVI) was computed as the time-integrated absolute angular velocity:

$$AVI = \sum_{i=1}^N |\omega_i| \Delta t, \quad (3.7)$$

where Δt represents the sampling interval. This measure reflects the total amount of rotational variability independent of direction, which is a widely used sway metric (Stoffregen and Smart, 1998; Smart Jr. et al., 2002; Keshavarz et al., 2014; Palmisano et al., 2014; Palmisano et al., 2018).

In the frequency domain, the power spectral density (PSD) of the angular velocity signal was estimated using Welch's method. Welch's method was adopted for spectral estimation using 20-s Hann-windowed segments with 50% overlap and a sampling frequency of 60 Hz. The PSD was used to characterize the distribution of signal power across frequencies:

$$P(f) = \text{PSD}\{\omega(t)\}, \quad (3.8)$$

where $P(f)$ denotes the power at frequency f .

A set of PSDs of pre-exposure head sway at the twelve characteristic frequencies, defined in the Keshner test, was extracted from the spectrum to compare with the same set of characterized features in the Keshner test. At each frequency, the bin width of the density estimation was 0.05 Hz. Furthermore, three summary measures were extracted. The peak frequency was defined as the frequency associated with the maximum spectral power:

$$f_{\text{peak}} = \arg \max_f P(f). \quad (3.9)$$

The mean frequency was computed as the power-weighted average frequency:

$$f_{\text{mean}} = \frac{\sum_f f \cdot P(f)}{\sum_f P(f)}. \quad (3.10)$$

The median frequency (f_{med}) of the signal is defined as the frequency that divides the total power of the spectrum into two halves, satisfying the following discrete equation:

$$\sum_{i=1}^M P(f_i) \Delta f_i = \frac{1}{2} \sum_{i=1}^N P(f_i) \Delta f_i \quad (3.11)$$

where $P(f_i)$ represents the estimated PSD at the i -th frequency bin, Δf_i is the frequency bin width, and N denotes the total number of bins within the analyzed frequency band. Because the exact half-power point rarely aligns perfectly with a discrete bin, linear interpolation is applied between bins M and $M + 1$ to determine the precise value of f_{med} .

Overall, the following sway features were extracted for each trial and computed separately for AP and ML angular velocity components:

Table 3.5: Summary of extracted head sway features based on angular velocity in AP and ML directions.

	Features	AP	ML
Time-domain	RMS	AP_{RMS}	ML_{RMS}
	Peak angular velocity	$AP_{\omega, \text{peak}}$	$ML_{\omega, \text{peak}}$
	Angular velocity integral (AVI)	AP_{AVI}	ML_{AVI}
Frequency-domain	Frequency-specific PSD	$AP_{P(f_k)}$	$ML_{P(f_k)}$
	Peak frequency	$AP_{f, \text{peak}}$	$ML_{f, \text{peak}}$
	Mean frequency	$AP_{f, \text{mean}}$	$ML_{f, \text{mean}}$
	Median frequency	$AP_{f, \text{med}}$	$ML_{f, \text{med}}$

3.5.4. QUANTIFYING NECK STABILIZATION (KESHNER TEST)

The angular velocities of the head and seat were obtained from the recorded Euler angle trajectories from the Keshner test, using a first-order finite difference approximation. The finite difference serves as a better proxy for yaw angular velocity than the recorded z-axis angular velocity because the recorded Euler angle about the yaw direction was strictly along the gravito-verticality and the only contributor to the movement of the head direction marker during tasks. Neck angular velocity was defined as the relative angular velocity between the head and the seat,

$$\omega_{\text{neck}}(t) = \omega_{\text{head}}(t) - \omega_{\text{seat}}(t), \quad (3.12)$$

where $\omega_{\text{head}}(t)$ and $\omega_{\text{seat}}(t)$ denote the head and seat angular velocity vectors, respectively. Since the experimental perturbation was restricted to the yaw axis, only the yaw component was included in subsequent analyses.

FREQUENCY-DOMAIN COHERENCE ANALYSIS

The auto-spectral densities of the seat and neck signals were denoted by $P_{ss}(f)$ and $P_{nn}(f)$, and the cross-spectral density was denoted by $P_{sn}(f)$.

The magnitude-squared coherence was calculated as

$$C_{sn}(f) = \frac{|P_{sn}(f)|^2}{P_{ss}(f)P_{nn}(f)}, \quad (3.13)$$

where

- $P_{ss}(f)$ is the power spectral density of the seat motion,
- $P_{nn}(f)$ is the power spectral density of the head motion,
- $P_{sn}(f)$ is the cross-power spectral density between the seat and head motion.

The coherence value ranges from 0 to 1, with values approaching 1 indicating a strong linear relationship between seat and neck motion at a given frequency. Auto-spectral densities and cross-spectral densities were estimated using Welch's averaged periodogram method with 50% overlapping rectangle window segments at the sampling rate of 60 Hz.

To facilitate comparisons between participants, coherence values were extracted, yielding a frequency-specific coherence profile for each participant.

FREQUENCY-DOMAIN GAIN AND PHASE ANALYSIS

Let $\omega_s(t)$ denote the yaw angular velocity of the seat and $\omega_n(t)$ denote the yaw angular velocity of the neck, where neck angular velocity was defined as the relative angular velocity between the head and the seat. The discrete Fourier transforms of the seat and neck angular velocity signals were computed using the Fast Fourier Transform (FFT):

$$S(f) = \mathcal{F}\{\omega_s(t)\}, \quad (3.14)$$

$$N(f) = \mathcal{F}\{\omega_n(t)\}. \quad (3.15)$$

Frequency-specific gain was calculated as

$$G(f) = \frac{|N(f)|}{|S(f)|}, \quad (3.16)$$

and the phase difference was calculated as

$$\Phi(f) = \angle N(f) - \angle S(f). \quad (3.17)$$

Gain and phase spectra were evaluated at the frequencies of SSN (see Table 3.1), to be comparable to the study by Keshner and Peterson, 1995. These spectra were used to characterize the frequency-dependent neck response under each experimental condition. At each stimulus frequency f , the neck-with-respect-to-trunk response of each subject i was represented as a complex number:

$$H_i(f) = a_i(f) + j b_i(f) = \mathcal{F}\{\omega_i(t)\}, \quad (3.18)$$

where $a_i(f)$ and $b_i(f)$ denote the real and imaginary components of the response, respectively.

The group vector average across N subjects was computed as

$$\bar{H}(f) = \bar{a}(f) + j \bar{b}(f), \quad \bar{a}(f) = \frac{1}{N} \sum_{i=1}^N a_i(f), \quad \bar{b}(f) = \frac{1}{N} \sum_{i=1}^N b_i(f). \quad (3.19)$$

The standard errors of the real and imaginary components were calculated separately as

$$SE_a(f) = \frac{\sigma_a(f)}{\sqrt{N}}, \quad SE_b(f) = \frac{\sigma_b(f)}{\sqrt{N}}, \quad (3.20)$$

where $\sigma_a(f)$ and $\sigma_b(f)$ are the standard deviations of $a_i(f)$ and $b_i(f)$ across subjects at frequency f .

These two standard errors define the half-widths of a rectangle centered on the vector-average point $\bar{H}(f)$ in the complex plane, i.e., an x - y error region given by $[\bar{a}(f) - SE_a(f), \bar{a}(f) + SE_a(f)]$ and $[\bar{b}(f) - SE_b(f), \bar{b}(f) + SE_b(f)]$.

The diagonal length of this rectangle was taken as a conservative estimate of the gain error:

$$SE_G(f) = \sqrt{(2 SE_a(f))^2 + (2 SE_b(f))^2}. \quad (3.21)$$

The corresponding phase error was estimated as the angle subtended between the vector average $\bar{G}(f)$ and the error-rectangle diagonal vector $D(f) = 2SE_a(f) + j2SE_b(f)$:

$$SE_{\Phi}(f) = |\angle \bar{G}(f) - \angle D(f)|. \quad (3.22)$$

Similar to coherence analysis, gain and phase values were extracted, yielding a frequency-specific gain and phase profile for each participant.

INDIVIDUAL DIFFERENCE FEATURES

For each participant and condition, the following feature set was extracted:

Table 3.6: Summary of extracted stabilization features.

Features	
Average magnitude-squared coherence	$C_{sn}(f_k)$
Frequency-specific average gain	$G(f_k)$
Frequency-specific average phase	$\Phi(f_k)$

where f_k is a series of octave-spaced frequency bins, identical to the frequencies forming the motion stimuli (see Table 3.1).

INDIVIDUAL STABILIZING METRICS

Marked inter-subject variability was observed in the difference between the VS and NV conditions at low frequencies (0.185-1.055 Hz). While the group-averaged frequency responses showed similar overall trends, individual participants exhibited substantially different magnitudes of visual benefit, as reflected by the differences in gain and phase between the two conditions.

Unlike the MA condition, in which coherence decreased considerably at low frequencies, both the VS and NV conditions maintained relatively high coherence throughout the low-frequency range. This indicates that the input-output relationship remained highly consistent during the measurements, allowing the observed differences between VS and NV to be interpreted as stable individual characteristics rather than trial-to-trial fluctuations.

To quantify individual differences in visually mediated sensorimotor control, five subject-specific features were extracted from the low-frequency range (0.185-1.055 Hz). The Fourier transfer coefficients at frequency f under the VS and NV conditions were computed using the FFT:

$$H_{VS}(f) = \mathcal{F}\{\omega_{VS}(t)\}, \quad (3.23)$$

$$H_{NV}(f) = \mathcal{F}\{\omega_{NV}(t)\}. \quad (3.24)$$

Gain and phase were subsequently computed from the complex ratio of the FFT responses between the VS and NV conditions at each frequency:

$$R(f) = \frac{H_{VS}(f)}{H_{NV}(f)}, \quad (3.25)$$

where $H_{VS}(f)$ and $H_{NV}(f)$ denote the complex Fourier coefficients at frequency f under the VS and NV conditions, respectively.

The gain ratio at each frequency was defined as the natural logarithm of the magnitude of the complex ratio,

$$\Delta G(f) = \ln|R(f)|, \quad (3.26)$$

and the phase difference was defined as the phase angle of the complex ratio,

$$\Delta\phi(f) = \angle R(f) \quad (3.27)$$

The subject-specific VS/NV gain ratio and mean phase difference were obtained by averaging across the low-frequency range,

$$G_{mean} = \frac{1}{N} \sum_{f \in f_{k,low}} \Delta G(f) \quad (3.28)$$

$$\phi_{mean} = \frac{1}{N} \sum_{f \in f_{k,low}} \Delta\phi(f) \quad (3.29)$$

where $f_{k,low}$ denotes the set of frequencies within 0.185-1.055 Hz and N is the number of frequencies.

To capture the largest phase discrepancy between conditions, the peak phase difference was defined as

$$\phi_{peak} = \max_{f \in f_{k,low}} |\Delta\phi(f)|. \quad (3.30)$$

Coherence was computed independently for the VS and NV conditions at each frequency,

$$C_c(f), \quad c \in \{VS, NV\}, \quad (3.31)$$

and the subject-specific coherence for each condition was obtained by averaging over the low-frequency range,

$$C_{c,mean} = \frac{1}{N} \sum_{f \in f_{k,low}} C_c(f), \quad c \in \{VS, NV\}. \quad (3.32)$$

Consequently, five subject-specific features were obtained: (1) the mean VS/NV gain ratio, (2) the mean VS-NV phase difference, (3) the peak VS-NV phase difference, (4) the mean coherence under the VS condition, and (5) the mean coherence under the NV condition.

Table 3.7: Subject-specific stabilization features used for statistical analysis.

Feature	
Mean VS/NV gain ratio	G_{mean}
Mean VS-NV phase difference	ϕ_{mean}
Peak VS-NV phase difference	ϕ_{peak}
Mean coherence under VS	$C_{VS,mean}$
Mean coherence under NV	$C_{NV,mean}$

3

3.5.5. QUANTIFYING SWAY MEASUREMENT IN THE FOREST AND SPINNING TEST (IN-EXPOSURE)

The same signal processing and feature extraction procedures described for the head motion analysis (Section 3.5.3) were applied. Because the visual stimulus was repetitive, PSD-based frequency-domain analysis was performed to characterize the spectral response. AVI was not calculated because the analyzed signal segment had variable durations for each participant, rendering this duration-dependent metric inappropriate for between-trial comparisons.

3.5.6. DATA EXCLUSION

Several datasets were excluded from specific analyses due to recording errors or protocol deviations. For participant P4, the IMU-recorded angular velocity data collected during the spinning test were corrupted. Consequently, the motion data recorded during the exposure period were excluded from all motion-related analyses.

For participant P21, a protocol misunderstanding occurred during the forest test. The participant believed that the MISC only needed to be reported at the beginning and end of the exposure. As a result, all MISC values recorded during the exposure period were zero and did not reflect the participant's subjective responses. Therefore, P21's MISC data from the exposure period were excluded from analyses involving continuous MISC measurements. However, the maximum MISC was considered to be 6 because the experiment was stopped due to nausea.

3.5.7. CORRELATION ANALYSIS

Table 3.8 summarizes the feature categories included in the correlation analysis. Each feature category was independently correlated with all VIMS- and vection-related features. Since the MISC is an ordinal scale and a linear relationship could not be assumed, the association was evaluated using Spearman's rank correlation coefficient. In addition, the demographic variables were correlated with all types of features using Spearman's correlation test.

To control the family-wise error rate arising from multiple comparisons, the statistical significance within each correlation matrix was adjusted using the Holm–Bonferroni correction developed by Holm, 1979. Each correlation coefficient in a given matrix was treated as an individual hypothesis test, with the total number of comparisons defined as the total number of cells in that matrix (e.g., a 3×5 matrix was treated as 15 simultaneous tests). The raw p-values were ranked in ascending order and sequentially compared

Table 3.8: All features used for Spearman's correlation analysis.

Type	Feature	
VIMS-related	SSQ scores	SSQ
	Mean MISC	$MISC_{mean}$
	Maximum MISC	$MISC_{max}$
	MISC rate	$MISC_{rate}$
	Inverse end time	$1/t_{end}$
Vection-related	Mean vection	v_{mean}
Sway Motion -related	RMS	RMS
	Peak angular velocity	ω_{peak}
	AVI	AVI
	PSD	P_{f_k}
	Mean frequency	f_{mean}
	Median frequency	f_{med}
VS/NV	Peak frequency	f_{peak}
	Mean gain ratio of VS to NV	G_{mean}
	Mean phase difference	ϕ_{mean}
	Peak phase difference	ϕ_{peak}
	Mean coherence under VS	$C_{VS,mean}$
	Mean coherence under NV	$C_{NV,mean}$

against progressively relaxed significance thresholds according to the Holm–Bonferroni procedure to determine statistical significance.

PRE-EXPOSURE HEAD MOTION VS. VIMS-RELATED FEATURES

To systematically compare the relationships between the pre-exposure postural sway features and VIMS-related outcomes under different experimental conditions, the correlation results were organized according to four experimental factors: test type (forest or spinning), posture (standing or sitting), visual condition (eyes-open (EO), eyes-closed (EC), and the change from EC to EO (EO-EC relative sway, similar to the Romberg quotients mentioned by Palmisano et al., 2014), and sway direction (anterior–posterior (AP) or medial–lateral (ML)). For each combination of posture and visual condition, the corresponding correlation table simultaneously included all AP and ML motion-related features from both the forest and spinning tests, resulting in an extended correlation matrix.

To facilitate comparisons across experimental conditions, three summary statistics were calculated for each posture–visual (e.g., sit-EO condition) condition pair. First, the absolute values of all Spearman's correlation coefficients were averaged to quantify the overall association strength, hereafter referred to as the mean ρ . In addition, the numbers of significant correlations *before* Holm–Bonferroni correction at the 0.05 and 0.01 significance levels were counted and denoted as S^* and S^{**} , respectively. These statistics are reported in the table header above each correlation matrix.

A similar correlation analysis was performed for the head motion recorded during the exposure period (in-exposure). The same set of motion-related features was analyzed, except for the Angular Velocity Integral (AVI), which was excluded. Each remaining

motion-related feature was correlated with the VIMS-related outcome measures, yielding an extended correlation matrix similar to that used for the pre-exposure analysis.

To account for individual differences in baseline head sway motion, the in-exposure motion features were baseline-corrected by subtracting the corresponding pre-exposure feature values before performing the correlation analysis. Four baseline conditions were examined independently, including stand-EO, stand-EC, sit-EO, and sit-EC, to compare the correlation strength obtained using different baseline references.

4

RESULT

4.1. STANDING AND SITTING SWAY MEASUREMENT (PRE-EXPOSURE)

Figure 4.1 shows the average power spectral density (PSD) of head angular velocity during the pre-test body sway measurements under four postural conditions (Sit-EO, Sit-EC, Stand-EO, and Stand-EC) before Sections 2 and 3. Overall, similar spectral patterns were observed before both experimental sessions.

In both the AP and ML directions, the standing conditions exhibited consistently higher spectral power than the sitting conditions across most of the analyzed frequency range. This difference was particularly evident below approximately 2 Hz, whereas the PSDs of all conditions gradually converged at higher frequencies.

Within the standing conditions, the EC condition generally resulted in slightly higher AP spectral power than the EO condition at the lowest frequency bands before Section 2, whereas the two standing conditions showed largely comparable spectra in the remaining frequency range. In contrast, the ML direction showed consistently higher power in the Stand-EO condition than in the Stand-EC condition over much of the low-frequency range in both pre-test measurements.

For the sitting conditions, the AP spectra of Sit-EO and Sit-EC exhibited similar frequency-dependent profiles, with a local maximum around 1.055 Hz. In the ML direction, Sit-EO generally showed higher spectral power than Sit-EC, although the pattern was not obvious before spinning tests and after forest tests (Fig 4.1b). Across all six conditions, spectral power decreased markedly above approximately 2 Hz, with relatively little power remaining in the highest analyzed frequency bands.

Figure 4.2 summarizes the distributions of the time- and frequency-domain features extracted from the pre-exposure body sway measurements under the four baseline conditions. The distributions obtained before the forest and spinning tests showed substantial overlap (t-test result: $p > 0.4$ in all features), indicating good consistency between the two experimental sessions.

Among the time-domain features, the standing baseline generally exhibited larger angular motion than the sitting baseline. AVI (sitting: $20.39 \pm 7.47^\circ$; standing: $57.35 \pm$

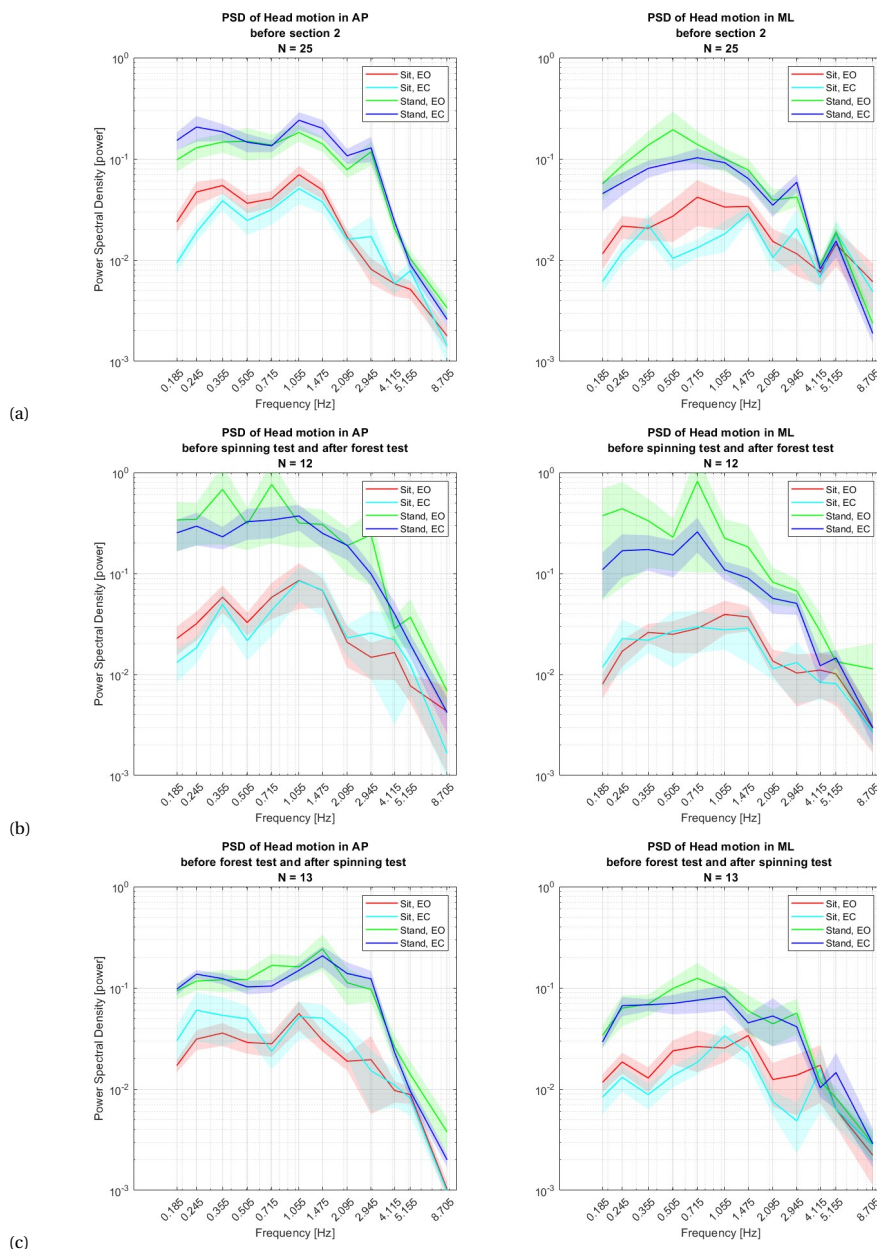


Figure 4.1: Mean power spectral density (PSD) of head angular velocity during pre-test body sway measurements (a) before Section 2, (b) before the spinning test but after the forest test, and (c) before the forest test but after the spinning test. The left column shows anterior-posterior (AP, pitch angular velocity) motion, and the right column shows medio-lateral (ML, roll angular velocity) motion. Four postural conditions were evaluated: sitting with eyes open (Sit-EO), sitting with eyes closed (Sit-EC), standing with eyes open (Stand-EO), and standing with eyes closed (Stand-EC). Solid lines represent the group means, and shaded regions indicate the standard error (SE). The PSD of head motion acted similarly to a low-pass filter under every condition. Between EO and EC, the mean power values of head motion were similar. A common mean power drop of AP head motion between 0.505 and 0.715 Hz, which is neither clearly inspected under standing in both directions nor under sitting in ML.

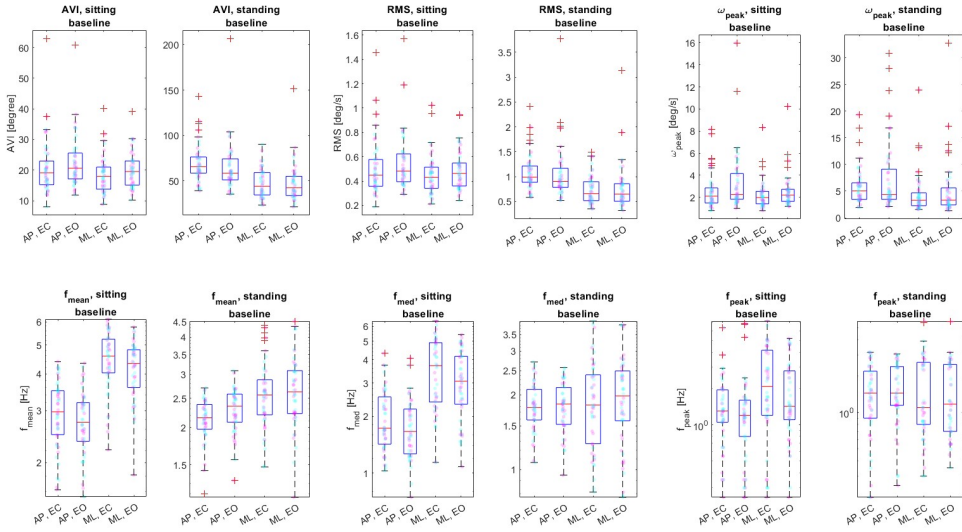


Figure 4.2: Distributions of time- and frequency-domain features extracted from the pre-test body sway measurements under the sitting and standing baseline conditions. Time-domain features include angular velocity integral (AVI), root mean square angular velocity (RMS), and peak angular velocity (ω_{peak}). Frequency-domain features include the PSD-weighted mean frequency (f_{mean}), median frequency (f_{med}), and peak frequency (f_{peak}) computed over the 0.1–20 Hz frequency range. Boxplots summarize the distributions across participants, while individual data points represent measurements collected before the forest test (light purple) and spinning test (light cyan). AP and ML denote the anterior-posterior (pitch angular velocity) and medio-lateral (roll angular velocity) directions, respectively, under both eyes-open (EO) and eyes-closed (EC) conditions.

23.85°), RMS (sitting: $0.50 \pm 0.20^\circ/s$; standing: $0.91 \pm 0.45^\circ/s$), and peak angular velocity (sitting: $2.67 \pm 1.88^\circ/s$; standing: $5.70 \pm 5.07^\circ/s$) were consistently higher in the AP direction than in the ML direction during standing (p-values in t-tests were all below 0.001), whereas the differences between AP and ML were smaller during sitting. Within each posture, the eyes-open and eyes-closed conditions produced largely comparable distributions, although modest increases in AP motion were observed in the eyes-open condition for several features under the sitting condition.

The frequency-domain features showed distinct differences between the AP and ML directions. During sitting, the ML direction generally exhibited higher mean frequency (AP: $2.92 \pm 0.71\text{ Hz}$; ML: $4.36 \pm 0.93\text{ Hz}$), median frequency (AP: $1.93 \pm 0.74\text{ Hz}$; ML: $3.43 \pm 1.35\text{ Hz}$), and peak frequency (AP: $1.54 \pm 1.31\text{ Hz}$; ML: $2.29 \pm 1.62\text{ Hz}$) than the AP direction (p-values in t-tests were all below 0.001). In contrast, the standing baseline showed more comparable frequency distributions between AP and ML, with only small directional differences (f_{mean} : $p < 0.001$; f_{med} : $p = 0.03$; f_{peak} : $p = 0.84$). Compared with the time-domain features, the frequency-domain features demonstrated greater inter-subject variability, particularly for the sitting baseline.

In summary, the baseline body sway measurements showed clear inter-subject variability across conditions, but the magnitude of this variability depended on posture and feature domain. Standing generally exhibited larger dispersion in time-domain measures, indicating greater individual differences and more extreme sway responses than sitting, whereas sitting showed greater inter-subject variability in frequency-domain features. By contrast, the EO and EC conditions largely overlapped within each posture,

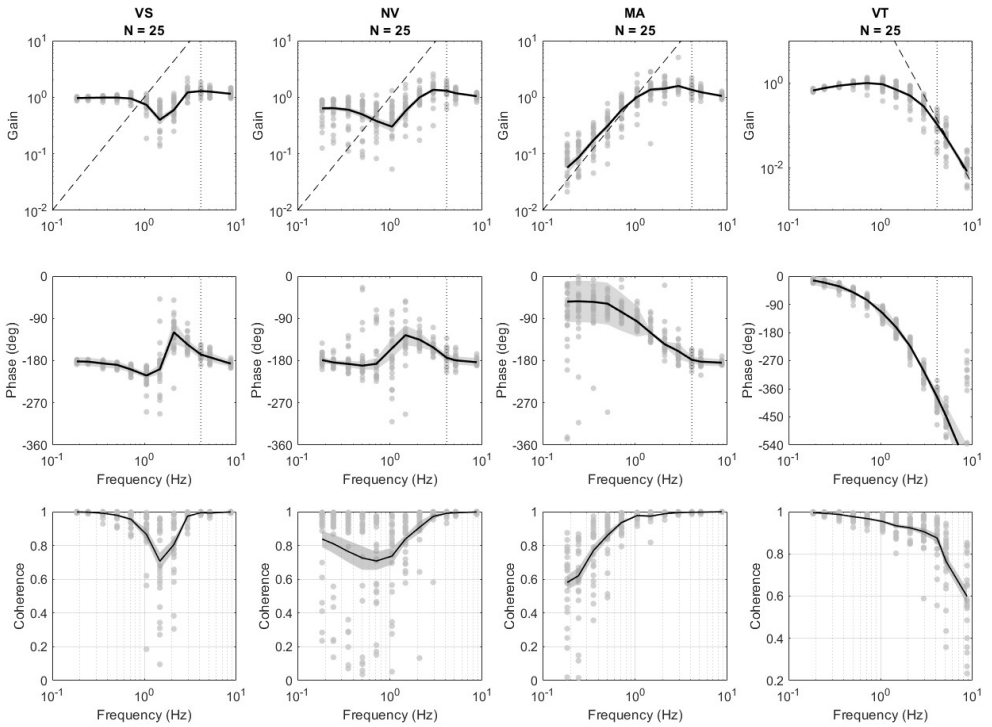


Figure 4.3: Frequency-domain analysis of the head motion relative to trunk motion in VS, NV, MA, and VT conditions. Gain represents the amplitude ratio (Equation 3.16), and phase represents the phase difference between trunk yaw rotation (input) and neck yaw rotation (output; head yaw rotation relative to trunk yaw rotation, Equation 3.17). The vertical dash lines in gain plots indicate the maximum frequency used by Keshner and Peterson, 1995, 4.115Hz. The solid black line and the grey shaded area show the average and $\pm 1SE$ of the average across participants at each frequency, respectively. The tilted dashed lines in the gain plots under VS, NV, and MA present a slope of 20 dB/decade, indicating a second-order mechanical dynamic of the neck.

suggesting that vision contributed relatively little to the overall individual variability compared with the stronger effect of posture.

4.2. KESHNER TEST

Figure 4.3 summarizes the frequency responses of the trunk-neck system under the four experimental conditions. In this analysis, the seat rotation served as the input, while the rotation of the head relative to the seat represented the system output. A gain of one with a phase of -180° represents that the head motion fully compensated for the seat motion, corresponding to an ideally stabilized head in space. A gain below one indicates undercompensation, such that the head moves with a smaller angular velocity than the seat, whereas a gain greater than one indicates an amplified head response. In terms of phase, a phase near 0° indicates that the head moves in the same direction as the seat and therefore provides little compensation, whereas a phase approaching $\pm 180^\circ$ indicates motion in the opposite direction that compensates for the seat rotation. For the VT condition, the seat did not rotate during the task, and the head motion is more relevant than that relative to the seat. Hence, the input and the output of the frequency

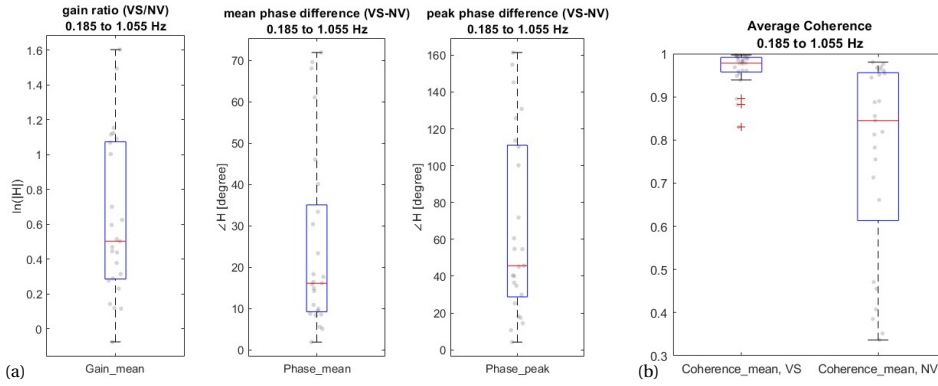


Figure 4.4: Distribution of the frequency-domain metrics averaged over 0.185–1.055 Hz. (a) The left three panels show the mean gain ratio between the voluntary stabilization (VS) and no vision (NV) conditions, the mean phase difference, and the peak phase difference (VS-NV), respectively. (b) The right panel compares the average magnitude-squared coherence between VS and NV. Boxes indicate the interquartile range (IQR), the red line denotes the median, whiskers extend to $1.5 \times \text{IQR}$, individual participants are shown as gray dots, and outliers are marked with red crosses. Overall, gain ratio and phase difference exhibited positively skewed distributions with greater dispersion above the median, whereas coherence remained consistently high during VS but showed substantially larger inter-subject variability during NV.

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response were represented as the tracking target and the head velocity, respectively. In the VT condition, the ideal tracking is represented as a gain of one and phase of 0° to indicate that the head is moving fully in phase with the tracking target.

Mean coherence exceeded 0.9 over most of the measured frequencies in the VS, MA, and VT conditions, except near the transition frequencies, where coherence decreased to approximately 0.7. The NV condition exhibited the lowest coherence (0.708 ± 0.265) at 0.715 Hz, indicating larger individual variability without visual feedback.

Under the two voluntary stabilization conditions (VS and NV), the frequency response of neck motion relative to trunk motion exhibited a pronounced reduction in gain around 1 Hz. The mean gain reached a minimum value of 0.399 ± 0.229 at 1.475 Hz in the VS condition and 0.301 ± 0.262 at 1.055 Hz in the NV condition. The largest between-subject variability in gain occurred both at 2.945 Hz in the VS condition (1.217 ± 0.341) and in the NV condition (1.353 ± 0.407), indicating considerable between-subject variability in the effectiveness of voluntary head stabilization near 3 Hz when visual information was unavailable.

Overall, these observations are consistent with the findings of Keshner and Peterson, 1995, who reported a reduction in gain around 1 Hz and suggested that the voluntary compensation mechanism of human head movements can only contribute to accurate head stabilization for frequencies below approximately 1 Hz. Beyond this frequency range, from approximately 1.475 to 2.945 Hz, the gain increased with an approximate slope of 40 dB/decade, indicating a transition from active voluntary compensation to passive mechanical behavior.

Figure 4.4 summarizes the inter-subject distributions of the VS/NV gain ratio, phase difference, and coherence averaged over the 0.185–1.055 Hz frequency range.

For the mean gain ratio, most participants exhibited a positive ratio, indicating a

higher neck gain during VS than during NV ($G_{mean} = 0.629 \pm 0.454$). Only one participant (P8) showed a negative gain ratio ($G_{mean,P8} = -0.0758$), indicating a slightly higher mean gain in NV than in VS. The gain ratio distribution was positively skewed, with most observations clustered below the median and a relatively larger spread among participants with higher gain ratios.

The mean phase difference between VS and NV was $\phi_{mean} = 25.059 \pm 21.861^\circ$. All participants exhibited mean phase differences smaller than 90° , indicating generally consistent phase relationships between the two conditions. Although the median was located at 16.129° , the 75th percentile and maximum reached 35.090° and 71.951° , respectively, reflecting greater inter-subject variability among participants with larger phase differences.

The peak phase difference was $\phi_{peak} = 65.866 \pm 49.129^\circ$ and showed substantially larger variability than the mean phase difference. While the maximum value remained below 180° , approximately one-third of the participants ($N = 8/25$) exhibited peak phase differences exceeding 90° . Similar to the gain ratio and mean phase difference, the distribution was characterized by a concentration of observations below the median and a wider dispersion toward larger values.

The average coherence was high in VS and moderate in the NV condition ($C_{mean,VS} = 0.964 \pm 0.041$; $C_{mean,NV} = 0.764 \pm 0.226$). However, coherence values during VS were tightly clustered near unity, indicating a highly consistent visual sensorimotor control system within participants. In contrast, coherence during NV exhibited substantially greater inter-subject variability, with several participants showing markedly reduced coherence despite the group means remaining relatively high.

Conclusively, almost every participant exhibited higher gain in VS than in NV, indicating that visual feedback generally enhanced head stabilization responses. Mean phase differences between VS and NV remained below 90° for all participants, suggesting broadly consistent temporal relationships across conditions. However, peak phase differences showed substantially greater dispersion, with some participants exhibiting large phase shifts under VS relative to NV. Coherence was consistently high and tightly clustered in VS, whereas NV showed markedly greater inter-subject variability despite moderate average coherence. Overall, these results indicate that VS was associated with a more uniform stabilization pattern across participants in the low frequencies, whereas NV involved more heterogeneous control characteristics in both response magnitude and phase.

4.3. FOREST AND SPINNING TESTS

4.3.1. MISC AND VECTION OVER EXPOSURE ACROSS PARTICIPANTS

Figure 4.5 presents the time profile of MISC in the forest and spinning tests. In the forest test (only 24 participants' MISC data were analyzed because P21 was excluded), the mean MISC across participants increased smoothly and reached MISC 2 around 150 s. On the other hand, in the spinning test, the mean MISC across participants shows a steeper slope at the start of the exposure, rising more intensely around 30 s (the first roll-tilting), and reaching MISC 2 around 100 s. This indicates a stronger effect in MS symptom progression of the visual stimuli in the spinning test.

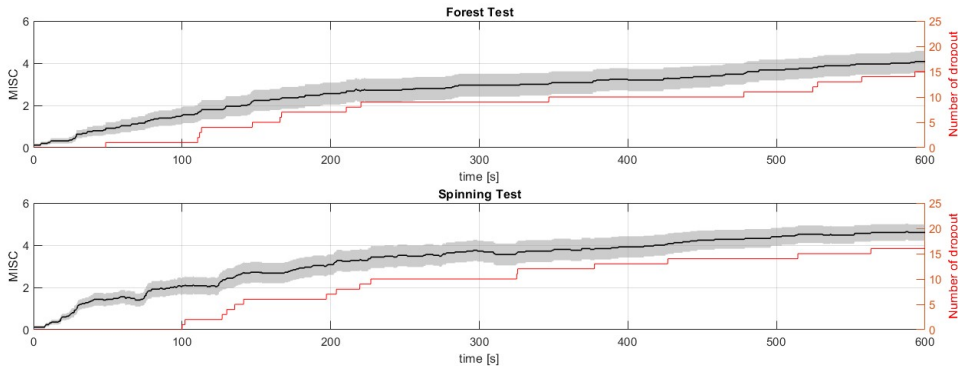


Figure 4.5: MISC profile across 25 participants (only 24 participants were included in the forest test; P21 was excluded) with a solid black line as the mean MISC, and a shaded area as ± 1 standard error at a specific time. The MISC data from the prematurely terminated participants were assumed to be 6 after the trial was terminated. The trials that terminated prematurely resulted in dropouts, and the counts of dropouts along the timeline are overlaid in the plots. In the forest test, average VIMS progression was relatively smooth and monotonically increasing, while the mean MISC developed rapidly at the early stage of exposure in the spinning test. The mean MISC in the spinning test showed more decreasing moments than in the forest test.

Two more rapid MISC-increasing timings were also observed in the spinning test: around 80 s and 130 s (at the second and the third roll-tilting), and the progression went relatively smoothly beyond 150 s. A brief drop in progression can be observed between 300 and 330 s. Although the progression continues growing, the curve shows a plateau coinciding with the periods without the observer's roll-tilted. This suggests that the visual stimulus during tilting and tilted predominantly contributes to VIMS over the timeline.

Both tests reached a 20% dropout rate ($N = 5/25$) around 140 s (forest: 147 s; spinning: 135 s). However, the dropout rate in the spinning test reached 50% earlier than the one in the forest test (forest: 528 s; spinning: 377 s). At the end of the tests, the dropout rate in the spinning test was one person more than in the forest test (forest: $N = 15$; spinning: $N = 16$). The final mean misc in the spinning test was higher, but not significantly, than in the forest test (forest: 4.32 ± 2.41 ; spinning: 4.60 ± 1.94 ; $p = 0.65$).

Figure 4.6 demonstrates the mean vection incidence throughout the timeline. The incidence was generally higher in the spinning test (forest: 0.181 ± 0.034 ; spinning: 0.446 ± 0.074 ; $p = 0.02$). The variability of mean vection incidence (i.e., change in mean vection over time) in the forest test was surprisingly higher than in the spinning test (forest: 13.32; spinning: 12.72). This could be an effect of dropout because fewer participants can contribute to the vection variability with more dropouts at the moment. Therefore, the dropout-corrected variability was calculated by dividing the mean vection incidence by the number of active participants. The corrected vection variability was higher in the spinning test than in the forest test (forest: 0.739; spinning: 0.748).

4.3.2. INDIVIDUAL VIMS FEATURES

SSQ

Figure 4.7 summarizes the SSQ scores after the VIMS-inducing tests across participants. To present the difference within individuals between the forest and spinning tests, the

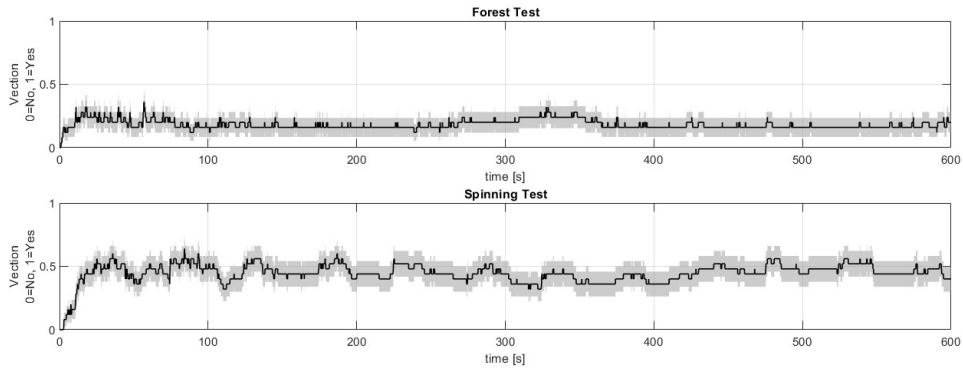


Figure 4.6: Vection profile across 25 participants with a solid black line as the mean vection incidence, and a shaded area as $\pm 1SE$ at a specific time. The participants generally perceived more vection throughout the spinning tests than the forest tests (forest: 0.181 ± 0.034 ; spinning: 0.446 ± 0.074 ; $p = 0.02$). Although the mean vection incidence oscillated more drastically in the spinning test (variability = 12.72), the total vection variability was higher in the forest test (variability = 13.32).

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individual results in the forest test were sorted by SSQ total scores across participants (Fig 4.7a). Subsequently, the results in the spinning tests (Fig 4.7b) were illustrated in the same order.

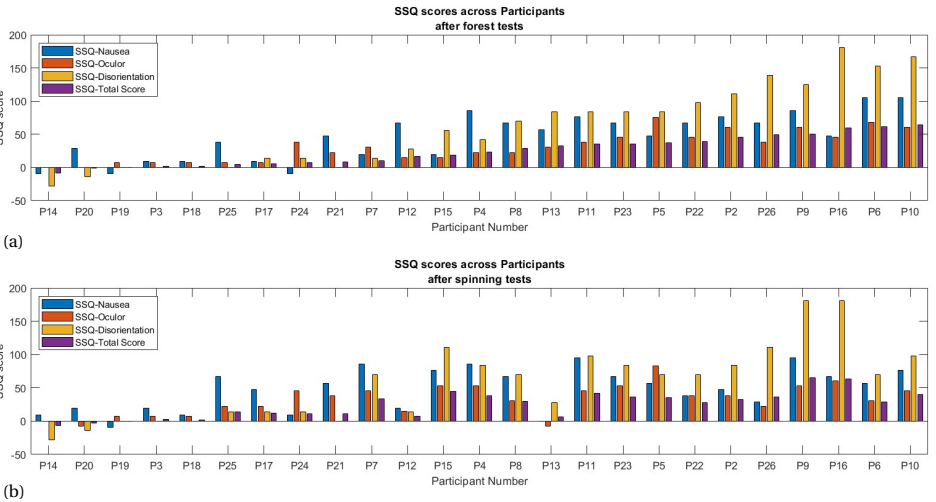


Figure 4.7: The SSQ results in (a) forest tests and (b) spinning tests. The order of participants was determined by the sorted order of SSQ total scores in forest tests.

The descriptive statistics of the SSQ scores for all participants are summarized as follows. In the forest test, the mean ($\pm$ SD) scores were 46.94 ± 34.94 for SSQ-Nausea (SSQ-N), 30.93 ± 22.52 for SSQ-Oculomotor (SSQ-O), 60.13 ± 61.43 for SSQ-Disorientation (SSQ-D), and 25.16 ± 21.91 for the total SSQ score (SSQ-TS). In the spinning test, the corresponding scores were 47.70 ± 31.40 (SSQ-N), 32.14 ± 22.87 (SSQ-O), 56.79 ± 56.39 (SSQ-D), and 24.50 ± 19.91 (SSQ-TS), respectively.

Across both experimental conditions, SSQ-D exhibited the highest mean score among

the three subscales, followed by SSQ-N and SSQ-O, whereas the total SSQ score remained comparable between the forest and spinning tests. The mean SSQ scores were generally similar across the two experimental conditions.

MISC AND t_{end}

Figure 4.8 presents $MISC_{mean}$ across participants. The average $MISC_{mean}$ across participants in spinning tests (2.13 ± 1.26) was slightly higher than in forest tests (1.64 ± 1.14). The participant-specific $MISC_{max}$ can be found in Figure 4.9. The average $MISC_{max}$ in both tests (forest: 4.44 ± 2.22 ; spinning: 4.72 ± 1.86) was slightly higher than the mean MISC at the end of the tests, indicating that the VIMS progression in both tests was not strictly increasing during exposure. The average MISC rate in the forest tests was slightly higher than that in the spinning tests and was accompanied by greater inter-subject variability, as reflected by the larger standard deviation (forest: 0.0230 ± 0.0272 ; spinning: 0.0238 ± 0.0179 , Fig. 4.10). $1/t_{end}$ values across participants are summarized in Figure 4.11. The mean end time in the forest test was 412.90 ± 215.31 s, whereas the spinning condition yielded a slightly lower mean end time of 380.56 ± 204.81 s.

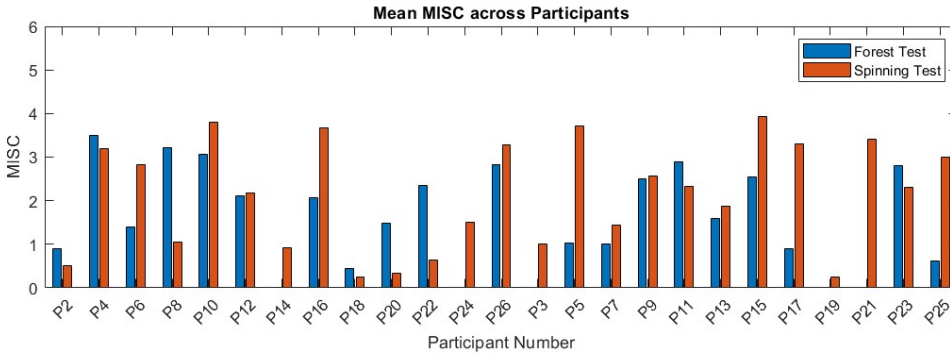


Figure 4.8: Mean MISC across participants shows no clear effect of experiment order. Even-numbered participants (left-half, P2–P26) completed the spinning tests in Section 2, and odd-numbered participants (right-half, P3–P25) completed the forest tests in Section 2.

4.4. CORRELATION ANALYSIS

4.4.1. VIMS-FEATURE BETWEEN FOREST AND SPINNING TESTS

Figure 4.12 shows the Spearman correlations between VIMS-related measures obtained from the forest and spinning tests. Overall, the measures exhibited moderate to strong positive associations across the two tests. For the SSQ measures, correlations were generally stronger when the same symptom dimensions were compared across tests. The strongest association was observed for SSQ-D subscores ($\rho = 0.855$, $p_{bonf} < 0.01$), followed by the SSQ-TS ($\rho = 0.767$, $p_{bonf} < 0.01$). SSQ-N and -O subscores also showed significant within-domain correlations (SSQ-N: $\rho = 0.556$; SSQ-O: $\rho = 0.656$), although their associations were weaker than those observed for SSQ-D and -TS. Cross-domain correlations were generally moderate, with the strongest associations involving SSQ-D in the forest test and SSQ-TS in the spinning test ($\rho = 0.748$, $p_{bonf} < 0.01$), while forest SSQ-TS was correlated with spinning SSQ-D ($\rho = 0.841$, $p_{bonf} < 0.01$).

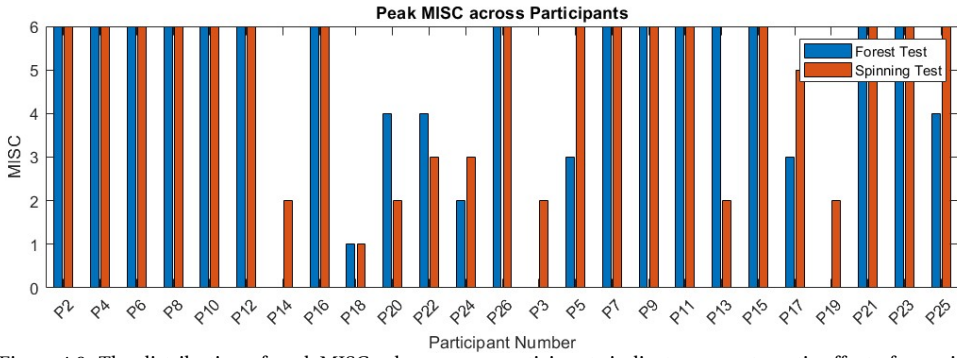


Figure 4.9: The distribution of peak MISC values across participants indicates no systematic effect of experimental order. Most participants who attained a MISC of 6 in at least one of the two tests also achieved a MISC of 6 in the other test. Only two participants (P5 and P25) completed the forest test without reaching a MISC of 6 in the spinning test. Conversely, only one participant achieved a MISC of 6 in the forest test but not in the spinning test.

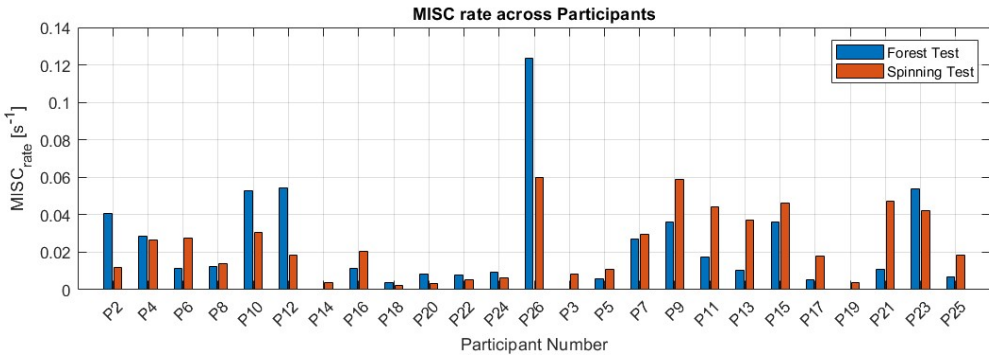


Figure 4.10: Individual MISC rates for each participant in the forest and spinning tests. The MISC rate was calculated as the peak MISC divided by the elapsed time from the start of exposure to the first occurrence of the peak MISC, representing the rate of symptom development during the exposure.

The MISC-related measures showed a broader pattern of moderate-to-strong positive correlations between the two tests. Correlations ranged from $\rho = 0.376$ to 0.800 , with particularly strong associations observed for peak MISC and MISC rate ($\rho = 0.714$ to 0.800 , $p_{\text{bonf}} < 0.01$). The inverse time-to-end measure also showed consistently positive associations with the other MISC-related measures, reaching $\rho = 0.708$ ($p_{\text{bonf}} < 0.01$) with each other test. These findings indicate that individual differences in VIMS severity and symptom development were relatively consistent between the forest and spinning exposures, with the strongest cross-test consistency observed for SSQ-D, overall SSQ scores, peak MISC, and MISC rate.

Figure 4.13a and Figure 4.13b show the Spearman correlations between the SSQ scores and MISC measure characteristics within the forest test and the spinning test, respectively. Peak MISC and MISC rate exhibited generally strong associations with all SSQ scores across tests. Only the correlation between MISC rate and SSQ-O in both tests and between peak MISC and SSQ-O in the forest test showed moderate significance ($\rho = 0.422$ to 0.521 , $p_{\text{bonf}} < 0.05$); otherwise exhibited strong significance ($\rho = 0.616$ to 0.796 , $p_{\text{bonf}} < 0.01$). The strongest correlations within both tests were observed for

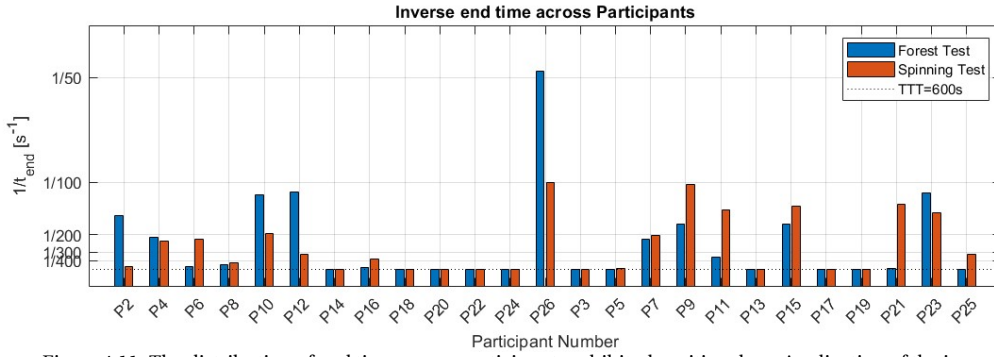


Figure 4.11: The distribution of end time across participants exhibited positive skew. Application of the inverse enhanced the sensitivity of the measure for lower end time, resulting in a steeper linear change in the transformed variable at higher levels of $1/t_{end}$.

peak MISC and SSQ-N subscores (Forest: $\rho = 0.756$; Spinning: $\rho = 0.796$). The weakest correlations were observed for SSQ-O subscores within both tests.

EFFECT OF EXPOSURE ORDER ON VIMS-RELATED FEATURES

Table 4.1: The VIMS-related features in the Spinning and the Forest tests when the tests were in Sections 2 and 3. The table represents the data in the form of mean $\pm$ SD.

	In Section 2		In Section 3	
	Forest	Spinning	Forest	Spinning
SSQ_N	39.0 ± 29.7	41.1 ± 27.4	54.3 ± 38.8	54.9 ± 35.0
SSQ_O	29.1 ± 22.6	29.2 ± 20.7	32.7 ± 23.2	35.4 ± 25.5
SSQ_D	45.2 ± 45.3	57.8 ± 58.5	73.9 ± 72.4	55.7 ± 56.6
SSQ_{TS}	20.1 ± 17.3	23.7 ± 20.2	29.9 ± 25.2	25.4 ± 20.5
$MISC_{mean}$	1.326 ± 1.117	1.857 ± 1.346	1.796 ± 1.203	2.428 ± 1.131
$MISC_{max}$	3.833 ± 2.588	4.538 ± 1.984	4.538 ± 2.184	4.917 ± 1.782
$MISC_{rate}$	0.017 ± 0.018	0.018 ± 0.016	0.028 ± 0.034	0.030 ± 0.018
$1/t_{end} [s^{-1}]$	0.0033 ± 0.0025	0.0033 ± 0.0024	0.0049 ± 0.0055	0.0047 ± 0.0031

To examine whether the order in which the Forest and Spinning tests were presented influenced MS severity, the VIMS-related features of each exposure were compared between the two counterbalanced presentation sequences. The descriptive statistics are summarized in Table 4.1. Across the two exposure positions, MS severity generally tended to be higher during the second exposure than during the first exposure. For example, mean MISC increased from 1.326 ± 1.117 to 1.796 ± 1.203 for the Forest exposure when it was presented second, and from 1.857 ± 1.346 to 2.428 ± 1.131 for the Spinning exposure. A similar increase was observed for MISC rate, which increased from 0.017 ± 0.018 to 0.028 ± 0.034 for Forest and from 0.018 ± 0.016 to 0.030 ± 0.018 for Spinning. The inverse end time also increased for both exposures when presented second, from 0.0033 ± 0.0025 to 0.0049 ± 0.0055 for Forest and from 0.0033 ± 0.0024 to 0.0047 ± 0.0031 for Spinning. The SSQ measures showed a similar tendency for SSQ-N, SSQ-O, and SSQ-TS, whereas SSQ-D showed a more exposure-dependent pattern, increasing from 45.2 ± 45.3 to 73.9 ± 72.4 .

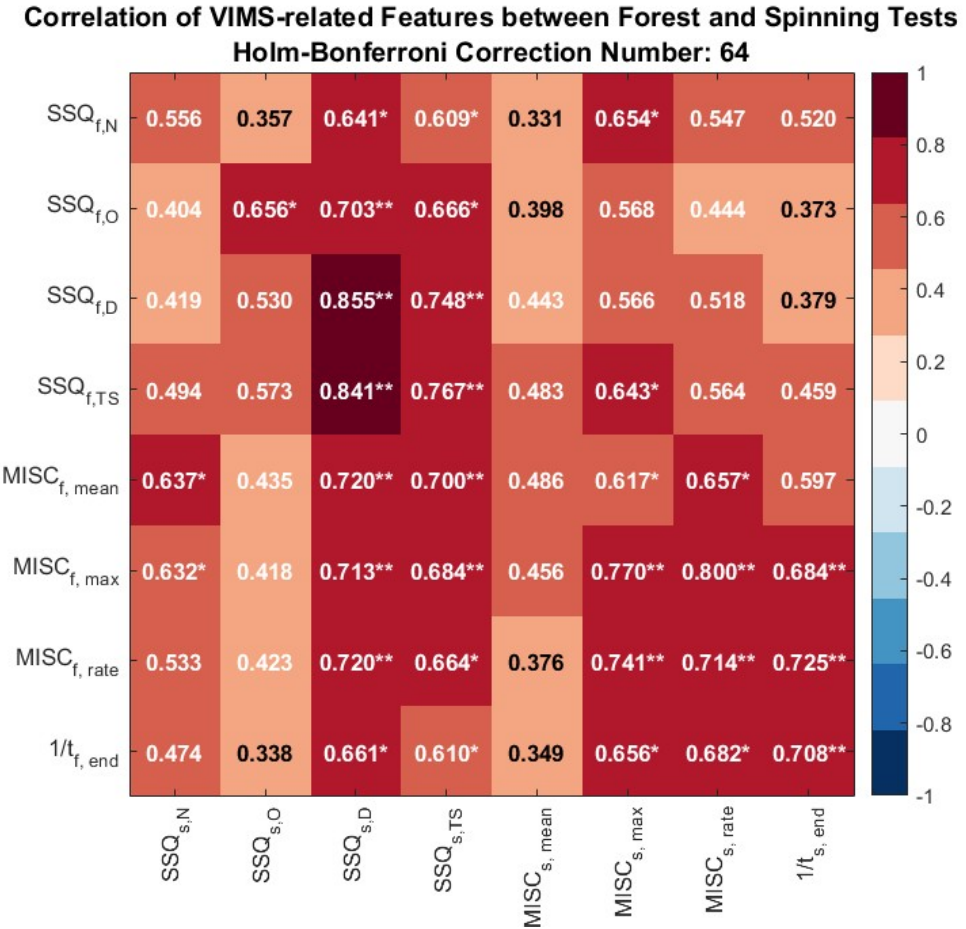


Figure 4.12: Spearman correlation matrix of VIMS-related measures between the forest and spinning tests. The first four columns represent SSQ measures from the spinning test, including Nausea (N), Oculomotor (O), Disorientation (D), and Total Score (TS), while the corresponding first four rows represent the same measures from the forest test. The last four columns and rows represent MISC-related measures, including mean MISC, peak MISC, MISC rate, and inverse time to the end of the test ($1/t_{end}$), from the spinning and forest tests, respectively.

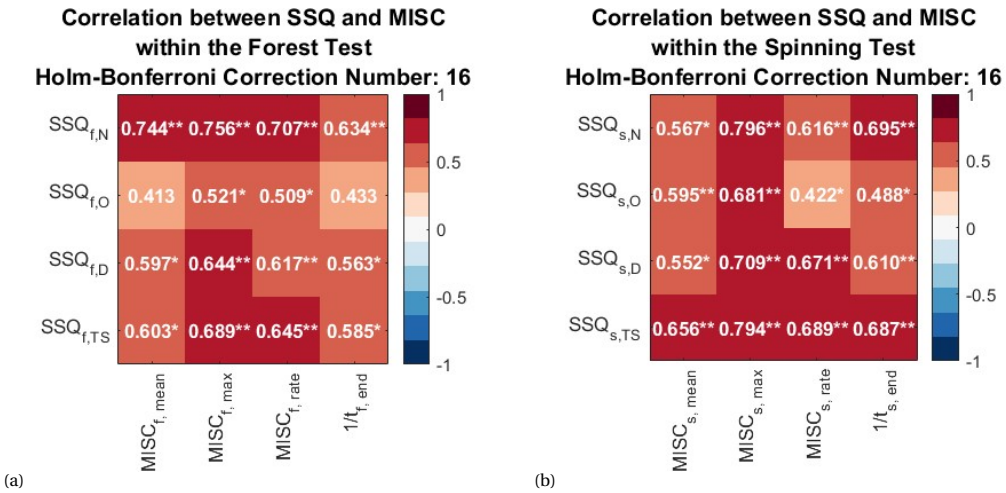


Figure 4.13: The association of SSQ scores with MISC in (a) forest tests and (b) spinning tests. * $p_{bonf} < 0.05$, ** $p_{bonf} < 0.01$.

for Forest but decreasing from 57.8 ± 58.5 to 55.7 ± 56.6 for Spinning.

Table 4.2 exhibits the multiple-comparison-corrected p-values of the effects of exposure order on VIMS-related features. To statistically assess these patterns while accounting for the repeated measurements within participants, linear mixed-effects models were fitted with exposure, presentation order, and their interaction as fixed effects and participant as a random intercept. No significant main effect of presentation order was identified for any of the VIMS-related features ($p > 0.05$ for all measures), indicating that the overall MS severity did not differ systematically between participants who experienced Forest first and those who experienced Spinning first. This finding suggests that the counterbalanced presentation sequences did not introduce a general shift in MS severity.

However, significant exposure-by-order interactions were observed for SSQ-N ($p = 0.010$), SSQ-D ($p = 0.040$), SSQ-TS ($p = 0.027$), MISC rate ($p = 0.002$), and inverse end time ($p = 0.013$) before multiple-comparison correction. After Holm-Bonferroni correction across the eight motion sickness measures, the interaction remained significant only for MISC rate ($p_{bonf} = 0.014$). Descriptively, MISC rate increased for both visual exposures when they were presented second, with the increase being comparable between Forest and Spinning (Table 4.1). This result indicates that the rate of symptom development was sensitive to the position of the exposure within the experimental sequence, even though no overall main effect of presentation order was detected. Therefore, the effect of exposure order appears to be more specific to the MS progression rate rather than representing a uniform increase in all measures of symptom severity. The absence of a significant order main effect, with the only interaction observed for MISC rate, suggests that the counterbalanced design was generally effective in preventing a systematic order-related bias in the overall VIMS-related features.

These findings were considered when interpreting the subsequent analyses of VIMS-related outcomes. Because no significant main effect of presentation order was identi-

Table 4.2: Results of the linear mixed-effects models examining the effects of visual exposure, presentation order, and their interaction on VIMS-related features. Participants were included as a random intercept. Holm-Bonferroni-corrected p-values are reported with the corresponding raw p-value in the following bracket.

Measure	Exposure	Order	Exposure $\times$ Order
SSQ-N	0.287 (0.048)	1.000 (0.233)	0.071 (0.010)
SSQ-O	0.605 (0.203)	1.000 (0.686)	0.309 (0.155)
SSQ-D	0.605 (0.253)	1.000 (0.215)	0.158 (0.040)
SSQ-TS	0.605 (0.150)	1.000 (0.233)	0.136 (0.027)
Mean MISC	0.068 (0.009)	1.000 (0.520)	0.198 (0.066)
Peak MISC	0.605 (0.147)	1.000 (0.799)	0.309 (0.293)
MISC rate	0.095 (0.014)	1.000 (0.232)	0.014* (0.002)
Inverse end time	0.605 (0.121)	1.000 (0.257)	0.080 (0.013)

* Holm-Bonferroni-adjusted p-value $p_{bonf} < 0.05$.

fied across the evaluated measures, there was no evidence of systematic order-related bias that would require excluding either exposure sequence from the subsequent analyses. However, the significant exposure-by-order interaction observed for MISC rate after Holm–Bonferroni correction indicates that the temporal development of VIMS may be influenced by the position of the exposure within the experimental sequence. Therefore, results involving MISC rate were interpreted with caution because of the significant order interaction, whereas the absence of a general order effect supported the use of the counterbalanced exposure data in the subsequent analyses.

4.4.2. MSSQ AND VIMSSQ

Figure 4.14 presents the correlations of the susceptibility questionnaire scores (MSSQ and VIMSSQ) with the VIMS-related outcome measures obtained from the forest and spinning tests. Overall, the susceptibility questionnaires showed moderate to strong positive correlations with most VIMS features, indicating that higher susceptibility scores were generally associated with greater VIMS severity.

In the forest test, all SSQ subscales, except SSQ-O, exhibited significant positive correlations with MSSQ (SSQ-N: $\rho = 0.639$, $p_{bonf} = 0.004$; SSQ-O: $\rho = 0.378$, $p_{bonf} = 0.13$; SSQ-D: $\rho = 0.543$, $p_{bonf} = 0.02$; SSQ-TS: $\rho = 0.573$, $p_{bonf} = 0.02$). Notably, MSSQ demonstrated significant correlations with both the mean and peak MISC scores (mean: $\rho = 0.578$, $p_{bonf} = 0.02$; peak: $\rho = 0.538$, $p_{bonf} = 0.02$), whereas the corresponding correlations with VIMSSQ were comparatively weaker. In contrast, $1/t_{end}$ was not significantly correlated with any MSSQ-derived measure.

In the spinning test, VIMSSQ exhibited significant positive correlations with all VIMS features, including all SSQ subscales (SSQ-N: $\rho = 0.582$, $p_{bonf} = 0.009$; SSQ-O: $\rho = 0.623$, $p_{bonf} = 0.005$; SSQ-D: $\rho = 0.586$, $p_{bonf} = 0.01$; SSQ-TS: $\rho = 0.641$, $p_{bonf} = 0.005$), the mean, peak MISC scores, and MISC rate (mean: $\rho = 0.535$, $p_{bonf} = 0.007$; peak: $\rho = 0.529$, $p_{bonf} = 0.01$; rate: $\rho = 0.518$, $p_{bonf} = 0.009$), and $1/t_{end}$ ($\rho = 0.538$, $p_{bonf} = 0.02$). By comparison, the correlations between the MSSQ measures and VIMS features were

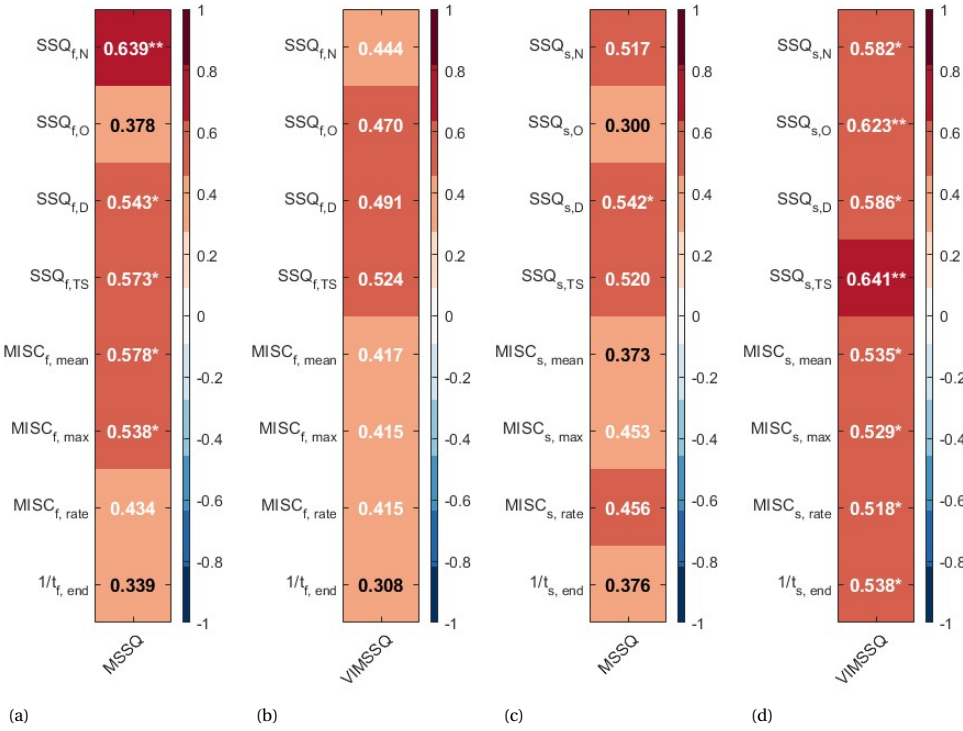


Figure 4.14: The correlation table between VIMS features and the results of susceptibility questionnaires. (a) and (b) present the results of the forest test, in which MSSQ demonstrated a more significant correlation with VIMS-related features. In contrast, (c) and (d) show that VIMSSQ was correlated more significantly with VIMS-related features in the spinning test. Asterisks indicate statistical significance after Holm–Bonferroni correction: * $p < 0.05$, ** $p < 0.01$.

less consistent. Although several SSQ measures remained significantly correlated with MSSQ (SSQ-N: $\rho = 0.517$, $p_{bonf} = 0.04$; SSQ-D: $\rho = 0.542$, $p_{bonf} = 0.04$; SSQ-TS: $\rho = 0.520$, $p_{bonf} = 0.046$), not all associations reached statistical significance.

4.4.3. DEMOGRAPHIC DATA

Figure 4.15 presents the only significant correlation between demographic variables and VIMS features. In the spinning test, the correlation between $1/t_{end}$ and height showed the significance ($\rho = -0.533$, $p_{bonf} = 0.04$), indicating that taller participants generally exhibited lower $1/t_{end}$ values. In addition, significant differences in $1/t_{end}$ ($p < 0.001$) and participant height were observed between male and female participants. In contrast, in the forest test, height showed moderate correlations with $MISC_{mean}$ ($\rho = -0.424$, $p_{bonf} = 0.27$), $MISC_{rate}$ ($\rho = -0.549$, $p_{bonf} = 0.07$) and $1/t_{end}$ ($\rho = -0.408$, $p_{bonf} = 0.26$). Weight also demonstrated moderate correlations with $1/t_{end}$ ($\rho = -0.448$, $p_{bonf} = 0.20$), $MISC_{mean}$ ($\rho = -0.443$, $p_{bonf} = 0.18$), $MISC_{rate}$ ($\rho = -0.470$, $p_{bonf} = 0.191$), and SSQ_N ($\rho = -0.405$, $p_{bonf} = 0.22$) in the forest test. Nonetheless, no measures in the forest test

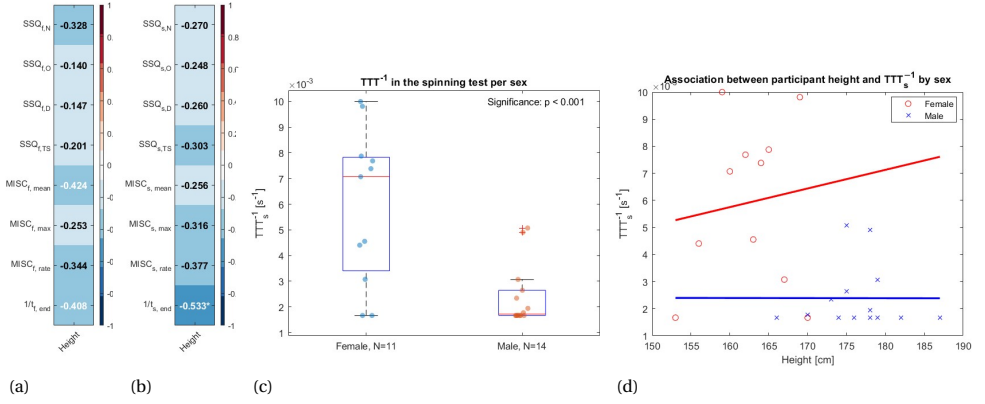


Figure 4.15: The correlation table between VIMS-related features and participants' height (a) in the forest test and (b) in the spinning test. (c) Significant difference in $1/t_{end,s}$ between male and female participants. (d) Relationship between participant height and $1/t_{end,s}$ stratified by sex. Scatter points represent individual participants, and solid lines indicate linear regression fits for each sex. The nearly horizontal regression line within male participants and the slightly positive correlation within female participants indicate that the overall negative correlation between height and $1/t_{end,s}$ was primarily driven by the difference between male and female participants rather than by an independent effect of height.

correlated significantly with any demographic variables.

Figure 4.16a shows that SSQ_N in females ($SSQ_{N,female} = 63.3 \pm 28.4$) was significantly higher than the same subscores in males ($SSQ_{N,male} = 34.1 \pm 35.0$) in the forest test. Similarly in Figure 4.16b, $MISC_{mean}$ in females ($N = 10$, P21 was omitted; $MISC_{mean,female} = 2.29 \pm 0.98$) were significantly higher than in males ($MISC_{mean,male} = 1.17 \pm 1.04$). In spinning tests (MISC rate: Fig 4.16c and inverse end time: Fig 4.15c), sex showed significant effects on $MISC_{rate}$ and $1/t_{end}$. The MISC rate was generally lower in male participants ($MISC_{rate,male} = 0.015 \pm 0.011 s^{-1}$) than in female participants ($MISC_{rate,female} = 0.035 \pm 0.019 s^{-1}$). The inverse end time in males ($1/t_{end,male} = 2.4 \times 10^{-3} \pm 1.2 \times 10^{-3} s^{-1}$) were significantly lower than in females ($1/t_{end,female} = 5.9 \times 10^{-3} \pm 3.0 \times 10^{-3} s^{-1}$). Although participant height was negatively correlated with $1/t_{end}$, further analysis revealed that both participant height and $1/t_{end}$ differed significantly between sexes. After accounting for sex, height was no longer significantly associated with $1/t_{end}$, indicating that the apparent correlation was attributable to the sex difference rather than an independent effect of height (Fig. 4.15d).

4.4.4. PRE-EXPOSURE HEAD MOTION

Figure 4.17 presents the correlations between VIMS-related features and baseline standing sway motion features across tests. For the standing condition, the EC trials (Fig. 4.17a) yielded a mean ρ of 0.146, with 23 significant correlations before Holm-Bonferroni correction ($S^* = 23$; $S^{**} = 3$). Under EO (Fig. 4.17b), the mean ρ increased slightly to 0.150, whereas the number of significant correlations before Holm-Bonferroni correction decreased to 13 ($S^* = 13$; $S^{**} = 2$). In contrast, the EO-EC relative sway (Fig. 4.17c) exhibited substantially stronger associations, with the mean ρ increasing to 0.163 ($S^* = 27$; $S^{**} = 7$).

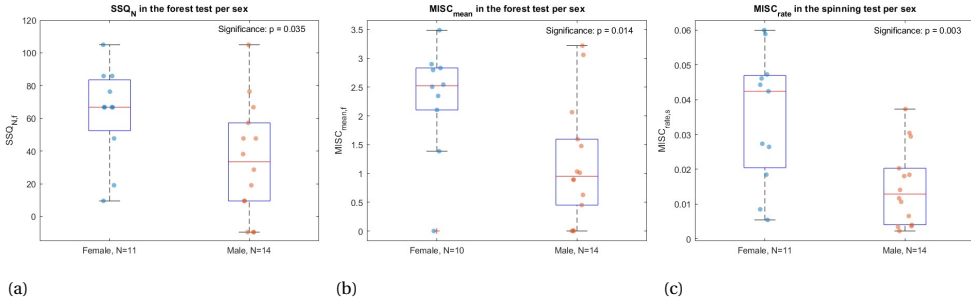


Figure 4.16: The effects of sex in (a) SSQ-Nausea subscore, SSQ_N , (b) the mean MISC, $MISC_{mean}$, in forest tests, and (c) the MISC rate, $MISC_{rate}$, in spinning tests.

For the standing EO-EC relative sway, two notable correlation patterns were observed. First, in the spinning test, the PSD in ML at the 11th frequency component (5.155 Hz) showed a strong negative correlation with the mean MISC score ($\rho = -0.592$; $p = 0.002$; $p_{bonf} = 0.52$; on the bottom right of Fig. 4.17c). Second, the low-frequency AP PSD generally exhibited stronger correlations with VIMS-related features in both experimental tests. In particular, the PSD at the 4th AP frequency component (0.505 Hz) during the spinning test was significantly (without Holm-Bonferroni correction) correlated with the SSQ Nausea subscore ($\rho = -0.575$; $p = 0.003$; $p_{bonf} = 0.76$).

Figure 4.18 shows tables of correlations between baseline sway motion-and VIMS-related features under the seated condition, demonstrating a different pattern. Under EC (Fig. 4.18a), the mean ρ was 0.155, although only 12 significant correlations were observed ($|\rho|_{mean} = 0.155$; $S^* = 12$; $S^{**} = 0$), fewer than in the corresponding standing condition. Under EO (Fig. 4.18b), the overall correlation strength decreased to a mean ρ of 0.148, with only 9 significant correlations ($|\rho|_{mean} = 0.148$; $S^* = 9$). Similar to the standing condition, however, the EO-EC relative sway (Fig. 4.18c) produced the strongest overall associations, with a mean ρ of 0.188, 43 significant correlations before Holm-Bonferroni correction, and 10 correlations reaching $p < 0.01$ ($|\rho|_{mean} = 0.188$; $S^* = 43$; $S^{**} = 10$).

Several prominent correlations were identified in the relative EO-EC sway while sitting. During the forest test, the ML peak angular ($ML\omega_{peak}$) velocity was strongly negatively correlated with the SSQ Nausea subscore ($\rho = -0.721$; $p < 0.001$; $p_{bonf} = 0.01$). This correlation is the only significant result after Holm-Bonferroni correction among all associations. In addition, the median frequency of head motion in AP exhibited significant positive correlations (before Holm-Bonferroni correction) with all SSQ measures, including SSQ-N ($\rho = 0.605$; $p = 0.001$; $p_{bonf} = 0.39$), SSQ-O ($\rho = 0.531$; $p = 0.006$; $p_{bonf} = 1.76$), SSQ-D ($\rho = 0.628$; $p < 0.001$; $p_{bonf} = 0.23$), and SSQ-TS ($\rho = 0.626$; $p < 0.001$; $p_{bonf} = 0.23$).

Overall, EO-EC relative sways consistently in both standing and sitting postures produced stronger associations between postural sway features and VIMS-related outcomes than either the EO or EC conditions. Furthermore, opposite correlation trends were observed between the forest and spinning tests. In the sitting EO-EC relative sway, the majority of motion-related features were negatively correlated with the VIMS-related out-

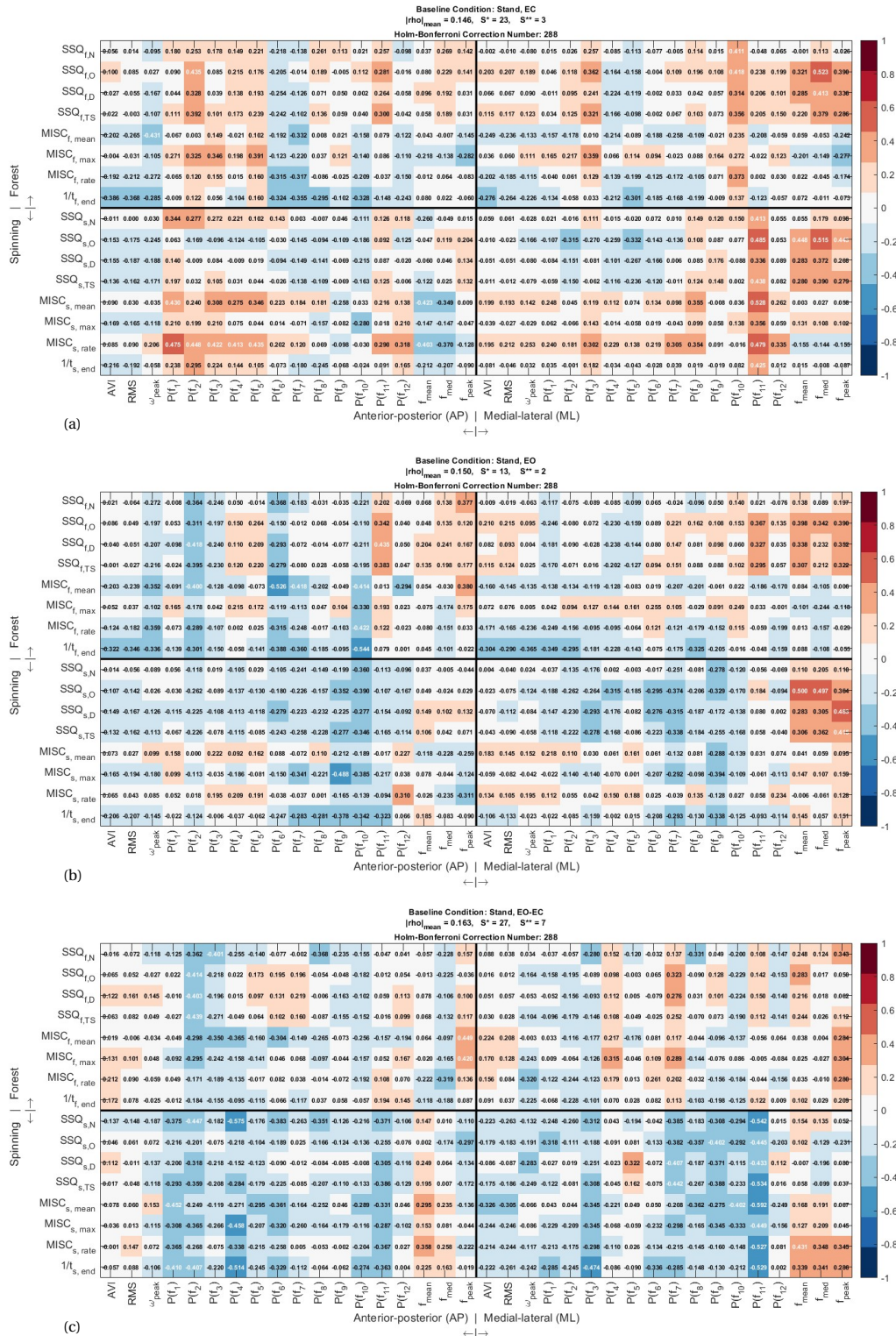


Figure 4.17: Correlation tables between VIMS-related features and pre-exposure motion-related features during standing posture under (a) eyes-closed (EC) and (b) eyes-open (EO) conditions, with (c) EO-EC relative sway.

comes obtained from the forest test, and the only statistically significant correlations existed in this test (upper half of Fig. 4.18c). Conversely, correlations in the spinning test were predominantly positive. A similar contrast was also observed in the standing EO-EC relative sway. However, the distribution of significant correlations (before Holm-Bonferroni correction) was reversed. Specifically, the spinning test contained most of the negative correlations, whereas the forest test primarily exhibited positive correlations.

4.4.5. VS/NV FEATURES

The Spearman's correlations of the VS/NV features with VIMS-related measures and vection incidence are summarized in Fig. 4.19. Among the five VS/NV features, the mean VS/NV gain ratio (G_{mean}) showed a moderate positive correlation with the inverse end time during the spinning test ($1/t_{s,\text{end}}$, $\rho = 0.408$, $p = 0.04$; $p_{\text{bonf}} = 1.66$). The peak phase difference (ϕ_{peak}) was positively correlated with the inverse end time in both the forest test ($1/t_{f,\text{end}}$, $\rho = 0.409$; $p = 0.04$; $p_{\text{bonf}} = 1.73$) and the spinning test ($1/t_{s,\text{end}}$, $\rho = 0.432$, $p = 0.03$; $p_{\text{bonf}} = 1.24$). No significant correlations were observed between the mean gain ratio (G_{mean}), the mean phase difference (ϕ_{mean}), or the condition-specific coherence measures ($C_{VS,\text{mean}}$ and $C_{NV,\text{mean}}$) and the remaining VIMS severity measures, including the SSQ subscales and MISC.

None of the stabilization features showed significant correlations with vection incidence scores. Overall, significant associations were observed only for selected phase- and coherence-related features, and the mean VS/NV gain ratio only exhibited a significant relationship with the inverse end time in the spinning test.

4.4.6. IN-EXPOSURE HEAD MOTION

Figure 4.20 summarizes the correlations of VIMS-related features with the in-exposure sway motion features, corrected with the Sit-EC baseline sway. Overall, the motion-related features derived from the in-exposure head motion exhibited substantially weaker associations with the VIMS-related features than those obtained from the pre-exposure head motion. None of the baseline conditions produced a correlation reaching the $p < 0.05$ significance level after Holm-Bonferroni correction. Among the four baseline conditions, the Sit-EC baseline yielded the strongest overall performance, with a mean ρ of 0.151 and 15 significant correlations ($|\rho|_{\text{mean}} = 0.151$; $S^* = 15$; $S^{**} = 0$).

Although the baseline-corrected in-exposure motion features generally showed weaker explanatory power than the pre-exposure features, one correlation pattern remained consistent across three out of four conditions, except the Stand-EO condition. Specifically, the peak angular velocity in the AP direction ($AP_{\omega_{\text{peak}}}$) was negatively correlated with $\text{MISC}_{\text{rate}}$ in the forest test (Sit-EC: $\rho = -0.421$, $p = 0.04$, $p_{\text{bonf}} = 9.66$; Sit-EO: $\rho = -0.508$, $p = 0.01$, $p_{\text{bonf}} = 2.58$; Stand-EC: $\rho = -0.457$, $p = 0.02$, $p_{\text{bonf}} = 5.91$). This finding indicates that the AP peak angular velocity is a relatively robust motion-related feature associated with the forest test.

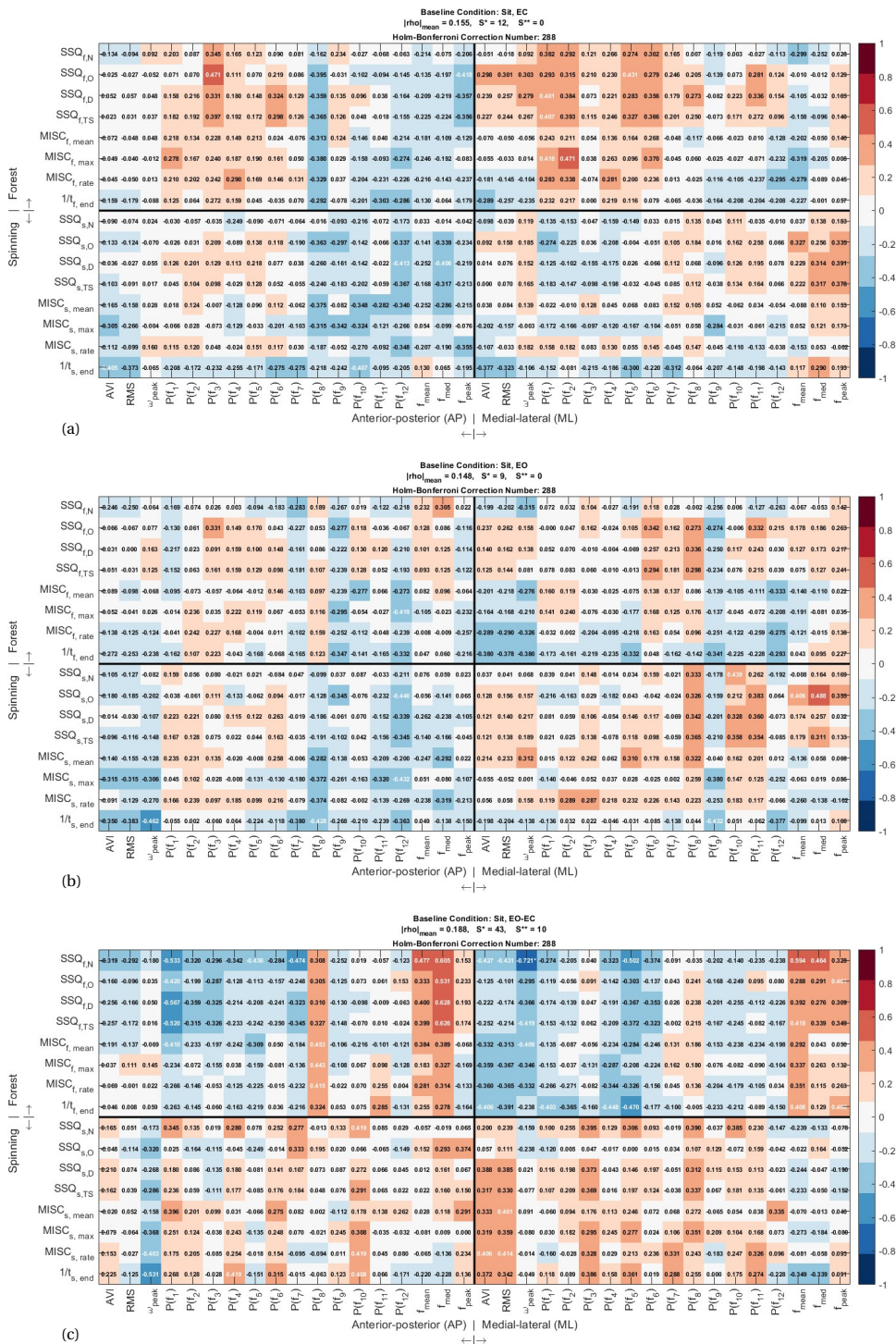


Figure 4.18: Correlation tables between VIMS-related features and pre-exposure motion-related features during sitting posture under (a) eyes-closed (EC) and (b) eyes-open (EO) conditions. (c) The EO-EC relative sway showed the greatest number of significant associations before Holm-Bonferroni correction among all conditions. The correlation between the SSQ-Nausea subscore in the forest test and the peak angular velocity in ML was the strongest among all observed associations. The median frequency of head motion in AP showed strong correlations with all the SSQ scores.

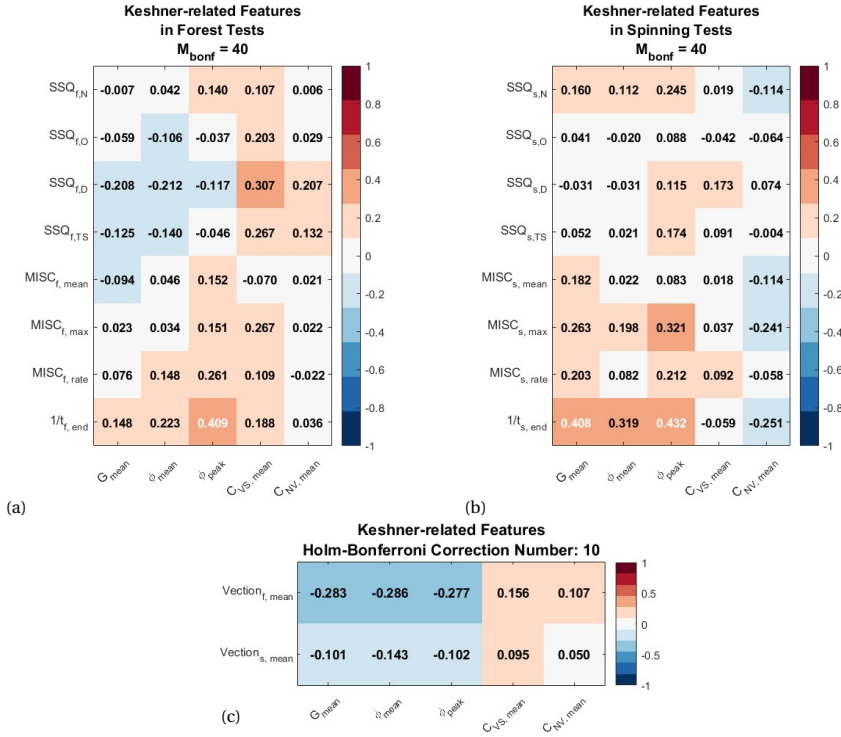


Figure 4.19: Spearman correlation coefficients between the VS/NV features and VIMS-related features. The VS/NV features include the mean VS/NV gain ratio (G_{mean}), mean VS-NV phase difference (ϕ_{mean}), peak VS-NV phase difference (ϕ_{peak}), mean coherence under the voluntary stabilization condition ($C_{VS, \text{mean}}$), and mean coherence under the no-vision condition ($C_{NV, \text{mean}}$). VIMS-related features include Simulator Sickness Questionnaire (SSQ) scores, Misery Scale (MISC), inverse end time ($1/t_{\text{end}}$), and vection incidence. Subscripts s and f denote the spinning test and forest test, respectively. SSQ_N , SSQ_O , SSQ_D , and SSQ_{TS} represent the nausea, oculomotor, disorientation, and total scores of the SSQ, respectively. Values shown are Spearman's correlation coefficients. M_{bonf} is the Holm-Bonferroni correction number for the correlation table.

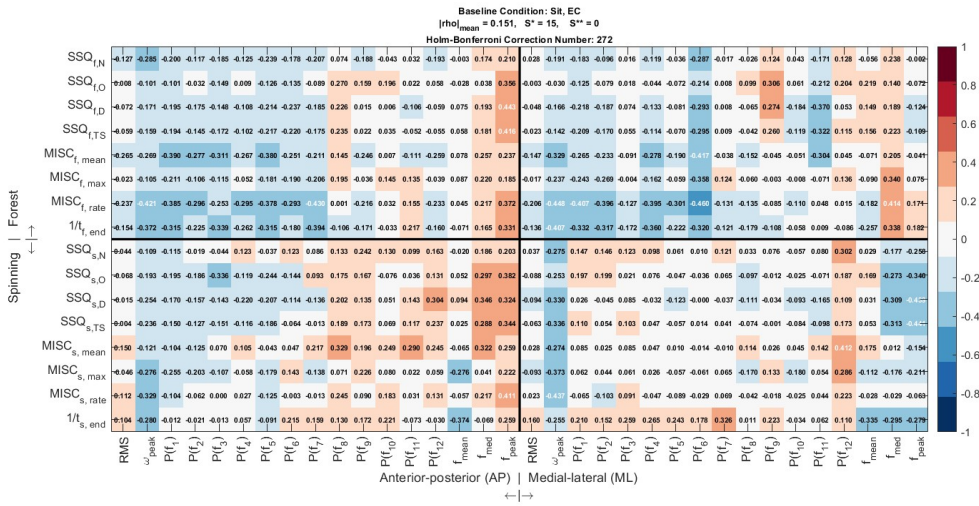


Figure 4.20: The correlation table between baseline-corrected in-exposure motion-related features and VIMS-related features. The baseline data were collected under the Sit-EC condition.

5

DISCUSSION

5.1. EFFECTS OF POSTURE AND VISUAL CONDITION ON THE ASSOCIATION OF PRE-EXPOSURE POSTURAL SWAY AND VIMS

The present results provide evidence that individual differences in pre-exposure head sway are associated with VIMS-related outcomes, with the strength of these associations depending on posture and visual condition. Crucially, this association is not uniform across all testing paradigms but is highly modulated by the specific posture and visual conditions used during baseline assessment.

Specifically, the EO-EC relative sway features obtained in the sitting posture (Fig. 4.18c) exhibited stronger overall correlations with the VIMS-related features than those obtained in the standing posture. This finding is consistent with the experimental setup, in which all visual exposures were performed in a seated position. Therefore, the sitting pre-exposure sway may better reflect the postural control strategy adopted during the subsequent VIMS exposure.

This observation is also consistent with the findings of Fujimoto and Ashida, 2020, who reported substantial differences in visually evoked postural responses (VEPRs) between standing and sitting conditions. Specifically, Fujimoto highlighted that AP sway response exhibited opposite directions between the two postures, while the magnitude of postural sway was markedly reduced in the sitting condition. Furthermore, participants were more likely to perceive vection in the opposite direction when seated compared with standing. These posture-dependent differences suggest fundamentally distinct postural control mechanisms between sitting and standing. In the current study, in-exposure head sway represents the VEPRs elicited by the passive VR environment. Accordingly, sway features related to movement amplitude (except for f_{peak} and f_{mean}) showed stronger associations with VIMS-related outcomes in the sitting condition, as they better reflect the postural behavior during exposure.

Another notable finding is that the EO-EC relative sway consistently demonstrated stronger overall correlations with VIMS-related features than either the EO or EC condition alone, regardless of posture. This enhancement primarily originated from the EC

condition: greater postural sway under EC was linked to more severe individual MS. This is supported by the low-frequency PSD under EC showing generally positive, although non-significant, correlations with SSQ scores, unlike the weaker and less consistent relationships found in EO. Consequently, EO-EC relative sway features predominantly showed negative correlations with VIMS measures, suggesting not only that these associations were tied more closely to the EC component than to the EO component but also that a larger power density of sway without perturbation in EC precedes more severe MS within-subject.

Importantly, the magnitude of EO-EC relative sway, in both the time and frequency domains, may provide a useful index of visual dependency in postural control. Individuals who exhibited greater pre-exposure sway under the EC condition, together with smaller sway under the EO condition, tended to show stronger sickness progression, a pattern consistent with postural instability theory. From this perspective, EO-EC relative sway may be interpreted not simply as a measure of visual dependency, but more specifically as an indicator of the form of instability emphasized in postural instability theory, because it reflects how much postural stabilization relies on visual input. Accordingly, a larger EO-EC relative sway suggests greater reliance on visual input for stabilization, and the present results indicate that individuals with stronger pre-exposure reliance on visual input tend to experience more severe motion sickness.

Notably, this interpretation was also supported in the sitting posture, where similar associations with VIMS-related features were observed. This suggests that reliance on visual input for stabilization remains a relevant factor even when postural demands are reduced under seated conditions. This point also helps clarify the relationship between the current findings and previous standing-posture studies that used EO-EC relative sway in the form of the Romberg quotient (Palmisano et al., 2014; Palmisano et al., 2018). Although the Romberg quotient has been associated with vection strength, no clear relationship with VIMS has been reported. In the present study, AVI is conceptually similar to the total path integral used in the Romberg quotient, and it showed correlations of no more than 0.4 with any VIMS-related or vection-related feature. This result further suggests that this type of sway metric has limited explanatory value for VIMS.

The stronger association between VIMS-related features and EC condition pre-exposure measurement is related to the sensory information available during immersive VR exposure. When an HMD presents strong optic flow, visual information may become less reliable for estimating subjective verticality. Under such conditions, postural stability relies increasingly on non-visual sensory inputs, including vestibular and proprioceptive information. Consequently, individuals exhibiting greater postural sway under the EC condition may possess less effective non-visual postural control, making them more vulnerable to sensory conflict during vection. This interpretation is consistent with the observed associations between EC-derived sway features and the VIMS-related outcomes. However, further studies incorporating direct measurements of sensory weighting would be required to confirm this hypothesis.

From a methodological perspective, this study further demonstrates that postural sway in a seated posture can be effectively quantified using head kinematics. While conventional assessments rely on force plates to measure CoP displacement in standing, such approaches are not directly applicable to sitting. By using head angular velocity

in pitch and roll as proxies for AP and ML sway, the present study captured meaningful sway characteristics that were significantly associated with VIMS outcomes. This result highlights a practical and scalable alternative for assessing postural stability in seated VR paradigms, and supports the use of head-based metrics as a sensitive indicator in future VIMS research.

5.2. ROBUSTNESS AND PREDICTIVE VALUE OF THE VIMS ASSOCIATIONS

Although several associations were observed between pre-exposure sway features and VIMS-related outcomes, their statistical robustness should be interpreted with caution. In particular, the application of the Holm-Bonferroni correction for multiple comparisons substantially reduced the number of associations that remained statistically significant. This finding indicates that the observed correlations should primarily be interpreted as evidence of systematic relationships between individual postural characteristics and VIMS, rather than as evidence that any single sway feature provides a robust standalone predictor of MS. The relatively large number of tested features and VIMS-related outcomes also increases the likelihood of observing nominally significant associations by chance. Therefore, the uncorrected correlations are useful for identifying potential relationships and generating hypotheses, whereas the corrected results provide a more conservative assessment of their statistical reliability.

The relationships between the VIMS measures were also not fully consistent. In particular, associations with MISC-derived outcomes were not always accompanied by corresponding associations with SSQ scores. This discrepancy is not necessarily unexpected because the two measures characterize different aspects of the MS. MISC provides a time-resolved measure of symptom severity and therefore captures the temporal development of sickness during the exposure, whereas the SSQ provides a multidimensional assessment of symptoms obtained before and after the exposure. Consequently, a physiological characteristic may be related to the onset or progression of sickness without producing a proportional change in the final SSQ score. Although previous studies have reported stronger correspondence between MISC and SSQ measures, the present results suggest that these measures should not be assumed to be interchangeable indicators of VIMS severity.

The present findings also do not demonstrate that any individual sway or Keshner-derived metric is a superior predictor of VIMS compared with established susceptibility measures. In the present dataset, MSSQ and VIMSSQ provided comparatively direct information about individual susceptibility, whereas the motion-related features showed more condition-dependent and less statistically robust associations with VIMS outcomes. This distinction is important because MSSQ and VIMSSQ characterize susceptibility at the questionnaire level, while the motion measures provide objective information about an individual's sensorimotor behavior. Thus, the value of the proposed motion measures may not be to replace questionnaire-based susceptibility measures, but rather to provide complementary physiological information that may help explain why individuals with similar self-reported susceptibility exhibit different responses to a given sensorimotor control task.

Similarly, the Keshner test revealed substantial individual differences in head stabilization and sensorimotor control, but these characteristics should not be interpreted as direct proxies for MS susceptibility. The head motion measures during the Keshner test describe the individual's ability to transform trunk or visual input into an appropriate head response, whereas VIMS reflects the interaction of sensory conflict and symptom accumulation. The absence of a strong and statistically robust relationship between a particular head-stabilization metric and VIMS would therefore suggest that head stabilization represents one component of the underlying sensorimotor phenotype rather than a sufficient predictor of sickness by itself.

Taken together, these results suggest that the predictive value of postural and head-stabilization measures is more likely to emerge from their combined characterization of individual sensorimotor behavior than from any single metric. Future studies should therefore evaluate multivariate predictive models incorporating multiple motion features together with MSSQ or VIMSSQ, rather than assessing each physiological measure independently. Importantly, such models should be evaluated using out-of-sample validation to determine whether these measures provide predictive information beyond established susceptibility questionnaires.

5.3. KESHNER TEST

Overall, the Bode plots demonstrate distinct control characteristics depending on the sensorimotor task. The VS and NV conditions exhibit active head stabilization at low frequencies, followed by a transition toward passive neck dynamics at higher frequencies. In contrast, the MA condition is predominantly governed by the passive mechanical dynamics of the head-neck system, whereas the VT condition exhibits the characteristics of a visually driven tracking system with a limited control bandwidth.

Across all four task conditions, the mean coherence remained above 0.6 over most of the measured frequency range, indicating that trunk (or target) motion explained a substantial proportion of the variance in neck motion and that the linear frequency-response model provided an adequate representation of the measured behavior. Although coherence decreased within specific frequency bands, particularly near the transition regions, the overall coherence values support the interpretation of the estimated gain and phase responses.

5.3.1. INTERPRETATION OF THE COHERENCE RESULTS

The coherence analysis provides an indication of the linearity and repeatability of the input-output relationship across frequencies. A coherence value close to 1.0 indicates that neck motion can be well explained by trunk motion using a linear frequency-response model, whereas a lower coherence suggests greater nonlinear behavior or larger variability in motor control strategies.

VS

In the VS condition, coherence remained close to 1.0 at both low and high frequencies but decreased to approximately 0.75 near 1–2 Hz. This frequency range corresponds to the region where voluntary head stabilization is most active, suggesting that individual differences in voluntary control strategies contribute to the reduced consistency of the

frequency response. The relatively large spread of individual coherence values around the minimum further indicates substantial inter-subject visual sensory variability in active head stabilization.

NV

The NV condition exhibited the lowest coherence among the four conditions over a broad frequency range, particularly below approximately 1 Hz. This result suggests that removing visual feedback increased the variability of individuals' stabilization strategies, resulting in a less consistent linear relationship between trunk and neck motion throughout the entire trial within the individual. Lower coherence than in any other condition may also imply that the participants attempted to tackle the task with different strategies in a single trial. The wide distribution of coherence values across subjects further indicates pronounced individual differences in the absence of visual information.

MA

In contrast, coherence in the MA condition increased monotonically with frequency and approached 1.0 above approximately 1.5 Hz. This indicates that not only did the stabilizing strategy vary across participants, but also an inconsistent voluntary stabilizing strategy existed within subjects. The relatively small spread of data points in the high frequencies indicates that participants responded in a highly consistent manner under these conditions and further suggests that neck motion became increasingly dominated by the passive mechanical dynamics of the head-neck system rather than voluntary control.

VT

Above approximately 2–3 Hz, coherence declined noticeably, reaching values of approximately 0.6 at the highest excitation frequencies. This reduction suggests that participants were no longer able to accurately track the visual target, leading to a less consistent input-output relationship. The increased spread of individual coherence values at higher frequencies further indicates greater inter-subject variability in visual tracking performance once the task exceeded the effective bandwidth of the visual-motor control system.

The coherence analysis clearly distinguishes between variability arising from voluntary control and variability arising from the limitations of the sensorimotor system. The lowest coherence in VS and NV occurs where active stabilization strategies differ across and/or within individuals. The reduced coherence in VT, however, reflects the inability of the visual tracking system to compensate for increasing target frequency. In contrast, the high coherence observed in the MA condition at higher frequencies indicates that participants responded in a mechanically consistent manner when voluntary neck motion was minimized.

5.3.2. COMPARING WITH THE STUDY BY KESHNER AND PETERSON, 1995

For all three experimental conditions with seat motion input (i.e., VS, NV, and MA), the gain no longer increased substantially above 2.945 Hz and gradually converged toward

1.0. In the present study, two additional higher-frequency excitation signals were included (in Figure 4.3, the frequencies to the left of the vertical dashed line are identical to those used by Keshner and Peterson, 1995). The resulting gain converged toward 1.0, while the phase simultaneously approached -180° at high frequencies, indicating that the head's inertia was holding itself still in space, resulting in a perfect compensation. These findings provide further evidence that the human neck behaves as a second-order low-pass system with a resonant frequency of approximately 2 to 3 Hz. The MA condition provided even clearer evidence supporting this interpretation. The mean gain exhibited a resonant overshoot above 1.475 Hz, followed by a gradual decrease toward 1.0 at higher frequencies, which is characteristic of an underdamped second-order system.

Under VT, the gain margin at the phase crossover frequency was approximately 0.5–0.7, which is slightly higher than the 0.2–0.4 reported by Keshner and Peterson, 1995. Nevertheless, the overall gain and phase characteristics closely resembled those reported in the reference study. This suggests that although participants in the present study maintained slightly higher tracking gains near the control bandwidth, the effective frequency range over which visual feedback can accurately guide head motion remains below approximately 2 Hz. This interpretation is also consistent with the results obtained under the VS and NV conditions, where voluntary head stabilization became ineffective above approximately 1–2 Hz. Conclusively, these findings indicate that the bandwidth of visually mediated sensorimotor control of the head is inherently limited to frequencies below approximately 2 Hz, beyond which the response becomes increasingly dominated by the passive mechanical dynamics of the head-neck system.

5.3.3. DIFFERENCES FROM KESHNER AND PETERSON, 1995

The most noticeable difference from the results reported by Keshner and Peterson, 1995 was observed in the MA condition at low frequencies (0.185–0.355 Hz). Compared with the reference study, the mean phase lag was substantially smaller (i.e., closer to 0°), suggesting that participants maintained a smaller delay between trunk and neck motion under this condition. However, this difference should be interpreted cautiously because the between-subject variability at these frequencies was considerable, with a standard deviation of approximately 79.5° , indicating that individual responses differed markedly.

The Keshner test therefore provides a complementary characterization of the sensorimotor pattern underlying the VIMS response. Whereas pre-exposure sway quantifies the individual's spontaneous postural behavior, the Keshner-derived measures characterize the dynamic transformation of external motion or visual information into head motion. Together, these measurements provide information at different levels of the postural-control system. Although the present results do not support interpreting any single Keshner-derived feature as a direct predictor of VIMS, the characterized features may serve as mechanistic descriptors in future individualized MS models.

5.4. POTENTIAL TASK-DEPENDENT MODULATION OF NECK MECHANICAL IMPEDANCE

An interesting observation is that the transition from active control to passive neck dynamics occurred at a higher frequency in the VS condition than in the MA condition. If

voluntary stabilization simply added an active feedback controller to an otherwise unchanged mechanical system, the overall frequency response would be expected to resemble a combination of the VT and MA responses. However, a distinct transition gap was observed, suggesting that the underlying neuromechanical properties of the head-neck system differed between the two tasks.

One possible explanation of the transition gap between 1.055 and 2.945 Hz under VS and NV conditions is task-dependent modulation of neck mechanical impedance. During the MA condition, participants were instructed to maintain a fixed head-to-trunk relationship. To fix the head orientation with respect to the trunk, one could have achieved this through increased muscle co-contraction, which results in greater effective neck stiffness and damping. In contrast, the VS condition required continuous relative motion between the head and trunk to stabilize the head in space. Such a task may favor a lower effective mechanical impedance, allowing faster and more compliant neck movements over a wider frequency range. Consequently, the transition from active stabilization to passive mechanical behavior was shifted toward higher frequencies in the VS condition.

Taken together, these findings suggest that more precise inference of sensory reweighting may require experimental paradigms that minimize task-dependent variation in neck mechanical impedance. In addition, direct assessment of neck muscle activity, for example, through EMG recordings during visual exposure, would enable comparison of co-contraction levels across conditions and provide stronger evidence regarding the relationship between mechanical impedance and the observed frequency-dependent responses.

5.5. INDIVIDUAL DIFFERENCES IN SENSORY INTEGRATION AND IMPLICATIONS FOR MOTION SICKNESS MODELLING

Beyond the individual associations with VIMS, the present findings provide insight into individual differences in sensory integration and postural control. The stronger relationships observed for EC-derived sway features suggest that the ability to maintain postural stability in the absence of visual information may be relevant to individual susceptibility to VIMS. However, the dependence of these relationships on posture, visual condition, and frequency indicates that susceptibility cannot be reduced to a simple measure of overall postural instability. Instead, the results are more consistent with the view that individuals differ in how sensory information is weighted and integrated during postural control.

The EO-EC relative sway provides a potential behavioural indicator of this individual sensory weighting. A larger relative sway may indicate a greater contribution of visual information to postural stabilization, whereas relatively small differences may indicate greater reliance on non-visual sensory information. The fact that EO-EC relative sway features obtained during sitting were associated with VIMS-related outcomes is particularly relevant to seated VR and automated-vehicle applications, where the trunk is mechanically constrained, and visual motion may become an important source of sensory conflict. Nevertheless, the present study cannot determine the underlying sensory weights directly. The EO-EC relative sway should therefore be regarded as an indirect

behavioural marker of sensory dependence rather than a direct measurement of sensory integration.

These findings provide partial support for the postural instability theory of MS, which proposes that visually induced sway can generate postural instability that is related to subsequent sickness. The present results demonstrate that individual pre-exposure postural behavior is associated with subsequent VIMS, which is compatible with the proposed relationship between postural control and sickness susceptibility. However, the absence of a consistent relationship across all sway measures and VIMS outcomes argues against interpreting postural instability as a universal direct predictor of MS. Instead, postural instability may represent one observable consequence of differences in multisensory integration and sensorimotor control that contribute to, but do not fully determine, MS susceptibility.

This interpretation also provides a potential connection between the present findings and individualized computational models of MS. Recent work by Kotian et al., 2025 demonstrated that individual differences in MS responses can be captured by introducing individualized parameters into an MS accumulation model. Their results showed that personalized models can substantially improve the representation of individual sickness responses compared with group-averaged models. The present findings suggest a complementary direction for such modelling approaches: in addition to personalizing the accumulation of sickness symptoms, individual differences in sensory integration and sensorimotor control may provide physiological information for parameterizing the generation of sensory conflict.

In this framework, MSSQ and VIMSSQ may provide information about an individual's baseline susceptibility, while pre-exposure sway and Keshner-derived measures may characterize individual sensorimotor behavior. The Keshner-derived gain, phase, coherence, and frequency-dependent transition characteristics could further quantify how effectively an individual stabilizes the head in response to motion or visual inputs. These physiological measures could potentially be incorporated into a personalized sensory-conflict model to investigate whether differences in sensory weighting or head-control dynamics explain part of the between-subject variability in VIMS. Such an approach would shift the interpretation of these measurements from standalone predictors toward physiological parameters that describe individual differences in the sensory-motor processes underlying MS.

A particularly important implication is that individual differences may occur at multiple stages of the MS pathway. An individual may differ in baseline susceptibility, sensory integration, sensorimotor control, and the subsequent accumulation of sickness symptoms. Therefore, a future individualized model could combine questionnaire-based susceptibility measures, objective postural and head-motion characteristics, and time-resolved MISC responses within a single framework. Such a model could help determine whether the observed motion features provide predictive information beyond MSSQ and VIMSSQ.

5.6. EXPERIMENTAL PROTOCOL CONSIDERATIONS

Overall, the experimental protocol was implemented successfully. Following the pilot test, the experimental instructions and visual stimuli were refined to improve clarity

and usability before the formal data collection. Nevertheless, several hardware- and protocol-related factors should be considered when interpreting the results.

First, the Movella XSENS DOT IMUs exhibited noticeable DC drift throughout data collection. To mitigate this issue, a high-pass filtering procedure was applied, which inevitably removed signal components below 0.1 Hz. As very low-frequency head movements may contribute to the development of MS, the filtering process may also have removed motion information that was relevant to the investigated phenomenon. In addition, a severe data corruption occurred during data retrieval for P4 in the VIMS-inducing test, where the recorded angular velocity contained unrealistic values exceeding $10^9^\circ/\text{s}$. Consequently, this dataset could not be included in the analysis.

The Meta Quest 3 data logging also showed inconsistencies in sampling frequency. Although the intended sampling rate was 60 Hz, several recordings were stored effectively at 30 Hz. This issue primarily affected the MISC and vection incidence recordings, as these measurements relied solely on the HMD data. Furthermore, the reduced sampling frequency increased the uncertainty of the synchronization between the IMU and HMD data streams. Since synchronization was performed using synchronization markers, the temporal synchronization error increased to approximately 1/30 s in recordings sampled at 30 Hz.

Environmental conditions may also have influenced the experimental outcomes. Data collection for Participants 13 to 20 (P13–P20) took place during a heatwave in the Netherlands. Elevated ambient temperatures may have affected participants' MS symptoms independently of the experimental stimuli. For example, higher baseline scores were observed for the sweating item in the baseline Simulator Sickness Questionnaire (SSQ-0). However, because the laboratory temperature was not continuously monitored throughout the experiment, the potential influence of temperature could not be quantified or controlled.

Finally, variability in participants' interpretation of the vection instructions may have affected the vection recordings. Although standardized instructions were provided, post-experiment interviews revealed differences in how participants understood the reporting task. Some participants pressed the response button only when they first experienced vection, whereas others held or repeatedly pressed the button only during periods in which the sensation of vection was actively present. This inconsistency resulted in markedly different temporal patterns of vection recordings across participants and may have introduced additional variability into the vection-related analyses.

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CONCLUSION

This study investigated the relationship between individual postural and head-stabilization characteristics and VIMS-related outcomes, with and without controlled motion perturbations. In addition, a Keshner-inspired frequency-response approach was used to characterize the frequency-dependent control behavior of the head-neck system under different sensorimotor task conditions. Overall, the findings indicate that the association between pre-exposure postural sway and VIMS-related outcomes depends on the posture and visual condition in which sway is assessed.

Pre-exposure sway measured in the seated posture, particularly using the EO-EC relative sway, showed stronger overall associations with VIMS-related outcomes than sway measured during standing. Because the subsequent visual exposures were performed in a seated posture, this finding suggests that baseline measurements obtained in a posture matching the exposure context may better characterize the postural control strategy relevant to the subsequent task. Across both postures, EO-EC relative sway measures generally showed stronger associations with VIMS-related outcomes than EO or EC measures alone. This pattern is consistent with the interpretation that EO-EC relative sway may provide an indirect behavioural indicator of individual differences in visual dependency during postural control. The relatively stronger contribution of EC-derived sway further suggests that individual differences in non-visual postural control may be relevant to VIMS susceptibility during immersive visual motion. However, because sensory weighting was not measured directly, this interpretation should be considered as a hypothesis for future investigation rather than a direct demonstration of altered sensory integration.

Importantly, the present study did not identify a single sway or Keshner-derived metric that can be considered a robust standalone predictor of VIMS. Although several associations were observed in the correlation analyses, application of the Holm-Bonferroni correction substantially reduced the number of statistically significant relationships. Furthermore, the associations were not fully consistent across MISC- and SSQ-derived outcomes, reflecting the different temporal and phenomenological aspects captured by these measures. Hence, the present findings provide evidence of condition-dependent asso-

ciations rather than evidence for a universal physiological predictor of VIMS. In comparison, MSSQ and VIMSSQ provided complementary information on individual susceptibility. The potential value of objective sway and head-stabilization measures may consequently lie not in replacing questionnaire-based susceptibility measures, but in providing physiological information about the sensorimotor characteristics underlying individual MS progression. The findings further suggest that individual VIMS susceptibility cannot be explained by overall postural instability alone. Instead, the dependence of the observed associations on posture, visual condition, and motion characteristics is more consistent with differences in multisensory integration and sensorimotor control. In this context, the results are compatible with the postural instability theory, but do not support the interpretation that greater postural sway is a universal direct determinant of VIMS. Rather, postural behavior may represent one observable component of the individual sensory-motor processes that contribute to susceptibility.

The Keshner-inspired analysis revealed clear task-dependent differences in gain, phase, and coherence. Across the tested conditions, visually mediated head stabilization was primarily effective at frequencies below approximately 2 to 3 Hz, whereas higher-frequency responses increasingly reflected the passive mechanical dynamics of the head-neck system. The difference between the VS response and the responses observed in the VT and MA conditions further suggests that effective neck mechanical impedance may be modulated according to task demands. This observation highlights the importance of considering task-dependent changes in neck stiffness and damping when interpreting frequency-response characteristics of head stabilization and sensory reweighting.

From a methodological perspective, the present study demonstrates the feasibility of using head angular velocity to characterize postural behavior during seated VR exposure, where conventional CoP displacement is less directly applicable. Although the present results do not establish head-based sway as a superior predictor of VIMS compared with established susceptibility measures, they demonstrate its potential as an objective descriptor of individual sensorimotor behavior in seated VR environments.

These findings also provide a potential direction for individualized MS modelling. Recent work has demonstrated that individual differences in MS responses can be represented using personalized model parameters (Kotian et al., 2025). The present results suggest that objective measures of postural sway, sensory dependency, and head-stabilization performance may provide complementary physiological descriptors for such individualized models. Future studies could therefore investigate whether combining MSSQ and/or VIMSSQ with objective measures of sensory integration and head control improves prediction of individual VIMS responses beyond questionnaire-based susceptibility alone, using multivariate models and out-of-sample validation.

Several limitations should be acknowledged, including IMU drift, inconsistencies in HMD sampling frequency, possible environmental influences such as elevated ambient temperature, and variability in participants' interpretation of the vection reporting task. These factors may have introduced additional variability into the measurements and should be addressed in future experimental designs.

In conclusion, the strongest statistically significant association after Holm-Bonferroni correction was observed between seated EO-EC ML peak angular velocity and SSQ-Nausea in the forest test, indicating that posture- and visual-condition-dependent characteris-

tics of pre-exposure postural control are associated with individual differences in VIMS-related responses. More broadly, the findings suggest that VIMS susceptibility is better understood as an interaction between individual sensory integration, postural control, head stabilization, and symptom accumulation rather than as a consequence of a single measure of postural instability. The present study therefore provides a physiological framework for future research aimed at characterizing individual differences in VIMS and developing more individualized models of MS.

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INSTRUCTIONS

A.1. STANDING AND SITTING SWAY

A.1.1. THE SPOKEN CONTENT

Now, the following are the standing and sitting head motion measures during stabilization.

STANDING

The head motion will be measured during still standing with eyes open for 90 seconds, and another 90 seconds with eyes-closed. I will notify you when you need to close your eyes.

Please naturally stand still with your feet as wide as your hips and let your hands relax on both sides of you.

During the measurement, please keep your head upright and try your best to stabilize your entire body.

SITTING

The head motion will be measured during still sitting with eyes open for 60 seconds, and another 60 seconds with eyes-closed. I will notify you when you need to close your eyes.

During the measurement, please keep your head upright and try your best to stabilize your head.

A.2. KESHNER TEST – INSTRUCTIONS

A.2.1. AUDIO

GENERAL SETUP

During the experiment, please keep your back against the backrest, your hands on the armrests, and your feet on the footrest.

In the following tasks, you will see two spheres. One sphere will remain fixed in position, while the other will move to track your head position. Please try to keep both

A

spheres aligned at the center of your view and maintain your head in an upright position. The sphere that tracks your head has vertical lines above and below it to help you judge vertical alignment.

If you experience any discomfort or need to stop the experiment at any time, please raise your hand or notify the experimenter immediately.

TRIAL 1 (EYES OPEN, CHAIR ROTATING)

The first trial is about to begin. Please relax your shoulders, back, and all trunk muscles, and let your body rest naturally against the backrest.

(Trial begins)

TRIAL 2 (EYES CLOSED, CHAIR ROTATING)

Next, we will begin the second trial. The display will be turned off in this trial. Imagine that you are still facing the fixed sphere. You will experience a similar procedure as before, but you will now rely only on your internal sense of position.

The trial is about to begin. Please close your eyes and try not to look at anything. Relax your shoulders, back, and all trunk muscles, and let your body rest naturally against the backrest.

(Trial begins)

TRIAL 3 (EYES OPEN, CHAIR STATIC, VISUAL TARGET MOVING)

In the third trial, you will again use your head movements to align the two spheres. However, this time the chair will not rotate. Instead, the previously fixed sphere will move.

The trial is about to begin. Please relax your shoulders, back, and all trunk muscles, and let your body rest naturally against the backrest.

(Trial begins)

TRIAL 4 (EYES CLOSED, MENTAL ARITHMETIC)

For the final trial, please maintain your head in an upright, forward-facing position aligned with your body.

During the experiment, in addition to keeping your head stable, you will periodically hear simple mental arithmetic questions through the headphones. Please calculate the answer mentally and say your answer out loud so that the experimenter can record it.

The trial is about to begin. Please keep your eyes closed and relax your shoulders, back, and all trunk muscles, and allow your body weight to rest naturally against the backrest.

A.2.2. MENTAL ARITHMETIC

3-second pauses were placed between every two questions.

- | | |
|------------------|--------|
| $2 + 5 = ?$ | (A.1) |
| $8 - 3 = ?$ | (A.2) |
| $4 \times 3 = ?$ | (A.3) |
| $7 + 2 = ?$ | (A.4) |
| $9 - 4 = ?$ | (A.5) |
| $5 \times 2 = ?$ | (A.6) |
| $3 + 6 = ?$ | (A.7) |
| $8 - 2 = ?$ | (A.8) |
| $6 \times 3 = ?$ | (A.9) |
| $4 + 4 = ?$ | (A.10) |
| $7 - 5 = ?$ | (A.11) |
| $9 \times 2 = ?$ | (A.12) |
| $5 + 3 = ?$ | (A.13) |
| $6 - 1 = ?$ | (A.14) |
| $4 \times 2 = ?$ | (A.15) |
| $8 + 1 = ?$ | (A.16) |
| $9 - 2 = ?$ | (A.17) |
| $3 \times 3 = ?$ | (A.18) |
| $2 + 7 = ?$ | (A.19) |
| $8 - 5 = ?$ | (A.20) |
| $5 \times 3 = ?$ | (A.21) |
| $6 + 2 = ?$ | (A.22) |
| $7 - 3 = ?$ | (A.23) |
| $4 \times 4 = ?$ | (A.24) |
| $1 + 8 = ?$ | (A.25) |
| $9 - 6 = ?$ | (A.26) |
| $2 \times 5 = ?$ | (A.27) |
| $3 + 5 = ?$ | (A.28) |
| $8 - 1 = ?$ | (A.29) |
| $7 \times 2 = ?$ | (A.30) |
| $2 + 5 = ?$ | (A.31) |
| $8 - 3 = ?$ | (A.32) |
| $4 \times 3 = ?$ | (A.33) |
| $7 + 2 = ?$ | (A.34) |
| $9 - 4 = ?$ | (A.35) |
| $8 - 2 = ?$ | (A.36) |
| | (A.37) |

A

A.2.3. ON-SCREEN**GENERAL SETUP**

Sit back fully against the backrest. Place hands on armrests and feet on footrest. Keep your head upright and centered.

TRIAL 1 (EYES OPEN, CHAIR ROTATING)

Align the two spheres using head movement. Keep both spheres centered and maintain an upright head.

TRIAL 2 (EYES CLOSED, CHAIR ROTATING)

Close your eyes. IMAGINE the fixed sphere and keep your head aligned and upright.

TRIAL 3 (EYES OPEN, CHAIR STATIC, VISUAL TARGET MOVING)

Align the two spheres using head movement. The chair will not move; the sphere will move instead.

TRIAL 4 (EYES CLOSED, MENTAL ARITHMETIC)

Keep eyes closed and head upright. Answer simple math questions aloud when prompted.

A.3. FOREST AND SPINNING TEST - INSTRUCTIONS**AUDIO**

In the next experiment, the focus will be on your motion sickness level. Please keep your gaze fixed on the red cross displayed on the screen. Although the chair will not rotate during this test, you should still maintain your head in an upright and stable position.

Use the joystick on the controller to adjust your current MISC level by pushing it forward or backward. At any time, if you wish to stop the experiment, please raise your hand and close your eyes while waiting for the experimenter to assist you in removing the equipment.

If your MISC level reaches 6 (Slight Nausea), a 3-second countdown will begin automatically. If the MISC level remains at 6 when the countdown ends, the experiment will terminate automatically. At that point, please close your eyes and wait for the experimenter to assist you in removing the equipment.

ON-SCREEN**TIPS FOR CONTROLLER**

- Joystick Up/Down: MISC Score Up/Down
- Index Trigger: Vection Perceived

TASK DESCRIPTION

- Try to push Joystick UP/DOWN to match your current MISC score
- Pull the trigger whenever you feel self-motion



Joystick Up/Down:
MISC Score Up/Down

Index Trigger:
Vection Perceived

Try to push Joystick UP/DOWN to match your current MISC score

Pull the trigger whenever you feel self-motion

MISC Score	Associated Symptoms
0	No problems
1	Unsettled
2	Vague
3	Slight
4	Fair
5	Severe
6	Slight
7	Fair
8	Severe
9	(Near) reaching
10	Swimming

Figure A.1: Instruction Panel shown in the Application

B

QUESTIONNAIRES

B.1. SIMULATOR SICKNESS QUESTIONNAIRE

INSTRUCTIONS

Below is a list of symptoms often associated with using simulators or virtual reality environments. For each symptom, please indicate the degree to which it affects you **at this moment** by checking the appropriate box. Please be as objective as possible.

RESEARCHER'S SCORING NOTE

The SSQ scores are typically calculated using the following weights: **None = 0, Slight = 1, Moderate = 2, Severe = 3**. Symptoms are divided into three sub-scales (Nausea, Oculomotor, and Disorientation). A template of SSQ is shown in Table B.1.

RESEARCHER'S COMPUTATION NOTES

The following table (Table B.2) follows the scoring weights and formulas defined by Kennedy et al., 1993 to calculate the sub-scale and total scores.

B

No.	Symptom	Not at all	Slight	Moderate	Severe
1	General discomfort	☐	☐	☐	☐
2	Fatigue	☐	☐	☐	☐
3	Headache	☐	☐	☐	☐
4	Eye strain	☐	☐	☐	☐
5	Difficulty focusing	☐	☐	☐	☐
6	Increased salivation	☐	☐	☐	☐
7	Sweating	☐	☐	☐	☐
8	Nausea	☐	☐	☐	☐
9	Difficulty concentrating	☐	☐	☐	☐
10	Fullness of head	☐	☐	☐	☐
11	Blurred vision	☐	☐	☐	☐
12	Dizzy (eyes open)	☐	☐	☐	☐
13	Dizzy (eyes closed)	☐	☐	☐	☐
14	Vertigo ^a	☐	☐	☐	☐
15	Stomach awareness ^b	☐	☐	☐	☐
16	Burping	☐	☐	☐	☐

^a**Vertigo:** Experienced as a loss of orientation with respect to vertical upright.

^b**Stomach awareness:** A feeling of discomfort which is just short of nausea.

Table B.1: Content of SSQ

SSQ Symptom ^a	Weight		
	Nausea (N)	Oculomotor (O)	Disorientation (D)
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Column Sum^b	[1]	[2]	[3]
Nausea Score = [1] × 9.54			
Oculomotor Score = [2] × 7.58			
Disorientation Score = [3] × 13.92			
Total Score (TS) = [1] + [2] + [3] × 3.74			

^aScored 0, 1, 2, 3.

^bThe Sum obtained by adding symptom scores. Omitted scores are zero.

Table B.2: Computation of SSQ Score

C

INFORMED CONSENT

Informed Consent Form

You are being invited to participate in a research study titled “*Visually Induced Cervical Motion to Indicate Motion Sickness.*” This study is conducted by Hsiang-Yu Chen from Delft University of Technology.

The purpose of this research study is to investigate how cervical (neck) movement and postural stabilization are related to visually induced motion sickness during exposure to VR environments. The study also aims to examine how visual cues, sensory reliance, and Vection influence motion sickness responses. Participation will take place will require less than 60 minutes to complete. The data collected will be used for Hsiang-Yu Chen’s master’s thesis.

We will be asking you to complete several questionnaires related to motion sickness susceptibility and simulator sickness, and to participate in experimental tasks while wearing a virtual reality head-mounted display and sitting on a rotating chair. During the experiments, you will experience virtual environments, perform head and trunk stabilization tasks under eyes-open and eyes-closed conditions, and report your level of motion sickness and vection throughout the sessions.

As with any online activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. We will minimize any risks by de-identifying the data in the first place. All data will be encrypted, and access will be strictly managed.

Your participation in this study is entirely voluntary **and you can withdraw at any time**. You are free to omit any questions. The contact details will be removed from the storage at TU Delft as soon as the project ends.

Corresponding Researcher:
Hsiang-Yu Chen

Responsible Researcher:
Riender Happee

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
1. I have read and understood the study information dated [_____], or it has been read to me. I have been able to ask questions about the study, and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves completing questionnaires related to motion sickness and simulator sickness, wearing a virtual reality head-mounted display, sitting on a rotating chair while experiencing virtual environments with different visual-motion conditions, performing head and trunk stabilization tasks under eyes-open and eyes-closed conditions, and reporting my perceived level of motion sickness and vection during the experiments.	☐	☐
4. I understand that I will be compensated for my participation by being entered into a prize draw as compensation for the time spent participating in the study. The prize draw will be conducted on July 10 after all participants have completed the study, and the winners will be notified and contacted regarding the prize collection arrangements.	☐	☐
5. I understand that the study is anticipated to end on August 31, 2026, upon completion of the master's thesis defense.	☐	☐
6. I understand that taking part in the study involves exposure to visually induced motion and physical rotation in a rotating chair within a virtual reality environment, which may lead to temporary discomfort such as dizziness, nausea, eye or muscle fatigue, and in rare cases vomiting. The experiment also involves physical restraint in a seated position during rotation, which may cause discomfort, and there is a minor risk of instability or falling when entering or exiting the rotating chair while experiencing dizziness. In very rare cases, participants may experience severe discomfort or fainting during the trial.	☐	☐
7. I understand that these risks will be mitigated by ensuring that participation is voluntary and that I may withdraw from the study at any time without providing a reason. Regular monitoring of motion sickness symptoms will be conducted, and the experiment will be stopped if symptoms reach a predefined threshold (e.g., mild nausea). Participants will be able to take breaks at any time and will be assisted when entering or exiting the rotating chair using a dedicated platform and hand supports. The chair is equipped with adjustable restraints for safety and comfort, and emergency stop buttons are available to both the participant and the experimenter. In addition, the rotating chair is programmed to decelerate smoothly with a controlled maximum angular acceleration to minimize physical risk in case of interruption or emergency.	☐	☐
8. I understand that the study will collect limited personally identifiable information (PII), including participant contact information (e.g., email address for recruitment and scheduling purposes), basic demographic information (e.g., age and gender), and a participant identification code assigned for the purpose of data management.	☐	☐
9. I understand that the study will also collect personally identifiable research data (PIRD), including motion capture data of head and cervical movements, rotational chair movement data, virtual reality interaction data, questionnaire responses (including motion sickness susceptibility and simulator sickness ratings), and self-reported vection and motion sickness ratings.	☐	☐
10. I understand that all research data will be pseudonymised using participant codes, and that direct identifiers will be stored separately from research data. I understand that while the risk of re-identification is considered low, there remains a minimal residual risk that data could potentially be linked back to an individual if combined with other information.	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
11. I understand that some of the collected personally identifiable research data (PIRD) may be considered sensitive under GDPR, as it includes information related to participants' physical and psychological state, specifically motion sickness symptoms (e.g., dizziness, nausea, and discomfort) and related subjective responses.	☐	☐
12. I understand that no data related to religion, political views, criminal activity, or other unrelated sensitive categories will be collected or processed in this study.	☐	☐
13. I understand that a Data Protection Impact Assessment (DPIA) has been conducted (or is in place where required) to ensure that appropriate safeguards are implemented to protect participant data, and that all data will be stored securely and handled in accordance with applicable GDPR regulations and institutional data management policies.	☐	☐
14. I understand that several measures will be taken to minimise the risk of a data breach and to protect my identity in the event of such an occurrence. All collected data will be pseudonymised, meaning that personal identifiers (such as contact information) will be stored separately from research data and linked only through a participant code. Where possible, data will be anonymised or aggregated prior to analysis and reporting.	☐	☐
15. I understand that all research data will be stored on secure, access-restricted institutional servers in accordance with university data management and GDPR requirements. Only authorised members of the research team will have access to the data. Data will not be shared in identifiable form, and results will be reported in aggregated form only, ensuring that individual participants cannot be identified in any publication or presentation.	☐	☐
16. I understand that no audio or video recordings requiring transcription, blurring, or voice modification will be used; however, any raw data will be processed and stored in a secure and de-identified format to further reduce identification risks.	☐	☐
17. I understand that personal information collected about me that can identify me, such as contact information, will not be shared beyond the study team.	☐	☐
18. I understand that the (identifiable) personal data I provide will be destroyed after the prize draw is done, anticipated to be done on July 10.	☐	☐
19. I understand that after the research study the de-identified information I provide will be used for Hsiang-Yu Chen's master's thesis.	☐	☐
20. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
21. I give permission for the de-identified head and cervical motion data, motion sickness response, vection incidence response, questionnaire, and demographic data that I provide to be archived in <i>Master Thesis HsiangYu Chen</i> repository so it can be used for future research and learning.	☐	☐
22. I understand that access to this repository is restricted only to corresponding and responsible researchers. The data will be deleted in 5 years.	☐	☐

Participant No.:

Participant e-mail (if joining the prize draw):

Signatures

Name of participant [printed]

Signature

Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Hsiang-Yu Chen

Researcher name [printed]

陳翔翕

Signature

13/06/2026

Date

D

TABLES

Table D.1: Index table of the supplemental data of the only significant correlation after Holm-Bonferroni correction of VIMS-related features with sway motion-related features (peak angular velocity in the ML direction vs. SSQ-Nausea subscore in the forest test).

Individual data	Linear regression
Table D.6	Figure E.1

Table D.2: Index table of results of Keshner tests.

Feature Type	VS	NV	MA	VT
Motion	D.7	D.8	D.9	D.10
VS/NV		D.11		

D

Table D.3: Index table of correlations of VIMS-related features with the sway motion features during Keshner tests.

VS	NV	MA	VT	VS/NV
E.2	E.3	E.4	E.5	E.6

Table D.4: Index table of motion-related features of pre-exposure head motion.

Pre-exposure Features				
	Forest		Spinning	
	EC	EO	EC	EO
Standing	D.12	D.13	D.16	D.17
Sitting	D.14	D.15	D.18	D.19

Table D.5: Index table of features during VIMS exposures.

In-exposure Features		
Feature Type	Forest	Spinning
VIMS and vection	D.20	D.21
Motion	D.22	D.23

Table D.6: The individual data table of the strongest significant correlation in this study. The motion-related features were pre-exposure-derived. The Spearman correlation is -0.721 , and the p-value after Holm-Bonferroni correction shows a moderate significance of it ($p_{bonf} = 0.02$, $M_{bonf} = 288$).

	$\omega_{peak,ML}$	$SSQ_{f,N}$
P2	-0.029	76.320
P3	0.399	9.540
P4	-0.560	85.860
P5	0.822	47.700
P6	-0.385	104.940
P7	1.926	19.080
P8	0.022	66.780
P9	-0.147	85.860
P10	-0.771	104.940
P11	0.252	76.320
P12	0.396	66.780
P13	0.344	57.240
P14	0.811	-9.540
P15	0.998	19.080
P16	3.013	47.700
P17	0.010	9.540
P18	0.932	9.540
P19	0.716	-9.540
P20	0.526	28.620
P21	0.147	47.700
P22	0.072	66.780
P23	0.402	66.780
P24	0.604	-9.540
P25	0.030	38.160
P26	0.106	66.780

Table D.7: Table of sway motion-related features in Keshner tests under the Voluntary Stabilization (VS) condition across participants.

Voluntary Stabilization Condition in Keshner tests												
P#	AP						ML					
	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	760.6	4.790	26.878	3.138	3.030	4.10	1407.9	8.816	48.748	2.902	2.898	2.95
3	1152.7	7.114	29.569	3.314	4.005	4.10	1972.0	12.719	63.866	2.402	2.122	4.10
4	917.2	6.015	41.798	2.379	1.662	1.50	1455.2	9.205	43.523	2.008	1.235	2.95
5	797.9	4.976	35.343	3.712	4.024	4.10	934.5	5.807	29.099	2.405	1.692	2.95
6	1192.6	7.440	39.395	3.298	3.413	4.10	1178.4	7.525	52.538	2.591	2.118	2.95
7	755.3	4.871	38.090	2.623	2.702	2.95	1700.7	10.284	34.418	2.727	2.297	4.10
8	853.1	5.494	29.208	3.027	2.571	4.10	1371.5	8.629	46.604	2.538	2.083	2.95
9	1382.0	8.686	40.712	3.734	4.101	4.10	1443.5	9.110	50.284	2.656	1.710	2.95
10	925.5	5.796	24.693	2.792	2.469	2.10	1600.8	10.052	63.331	2.292	2.100	2.10
11	1150.5	7.327	52.686	3.349	3.651	4.10	1427.0	8.934	41.351	3.051	2.881	2.95
12	978.6	6.059	24.894	3.588	3.976	4.10	968.4	6.029	22.975	2.828	2.111	2.10
13	1338.4	8.353	34.752	4.140	4.120	4.10	1134.6	6.917	28.655	2.941	2.584	2.95
14	948.9	6.196	45.594	3.059	2.921	4.10	1947.6	12.080	65.345	2.493	2.086	2.10
15	889.8	5.651	34.160	2.611	2.399	4.10	1628.4	10.166	51.452	2.425	2.094	2.10
16	979.6	6.131	28.853	3.523	3.857	4.10	972.9	6.061	27.099	2.657	2.085	2.10
17	1700.5	10.697	42.591	2.774	2.933	2.95	1001.0	6.391	33.680	2.275	1.677	0.70
18	861.7	5.317	24.804	3.376	3.494	4.10	1204.8	7.483	33.141	2.567	1.689	1.05
19	725.3	4.637	28.792	3.552	3.720	4.10	1034.1	6.458	28.742	2.015	1.455	2.10
20	869.1	5.568	27.928	3.435	3.135	5.05	1586.5	10.580	72.897	1.565	1.257	2.10
21	655.4	4.184	40.388	2.572	2.102	2.95	989.9	6.050	22.563	2.993	2.140	2.10
22	1379.3	8.546	38.540	3.367	2.994	5.15	1521.1	10.671	99.509	2.235	1.396	5.15
23	877.2	5.668	34.920	3.454	2.612	5.15	2034.5	13.401	70.094	2.788	1.349	0.35
24	1200.3	7.567	36.597	3.528	4.081	4.10	1811.1	11.364	53.541	2.590	2.313	2.95
25	1339.6	8.414	37.558	3.465	4.047	4.10	1877.3	11.827	65.616	1.825	1.473	1.45
26	1504.6	9.405	56.674	3.037	2.963	4.10	2047.2	13.086	52.582	1.849	1.249	2.95

Table D.8: Table of motion-related features in Keshner tests under the No-Vision (NV) condition across participants.

No-Vision Condition in Keshner tests												
P#	AP						ML					
	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	831.6	5.244	24.324	2.686	2.893	4.10	1800.1	11.285	52.504	2.170	2.029	2.10
3	1370.7	8.419	29.570	3.522	3.984	4.10	1226.5	7.584	32.968	2.584	2.890	2.95
4	686.2	4.397	27.959	2.933	2.377	5.05	1143.0	7.028	31.434	2.562	2.916	2.95
5	802.6	5.041	29.736	2.609	2.088	2.10	1348.4	8.668	48.264	1.318	0.961	1.05
6	1363.5	8.368	36.269	3.903	4.113	4.10	1386.3	8.731	38.638	2.514	2.073	2.10
7	888.8	5.590	26.825	2.645	2.895	2.95	1810.1	11.089	36.973	2.078	1.498	1.45
8	1409.9	8.972	40.897	2.766	1.942	2.95	1954.4	12.396	57.088	1.932	1.059	0.70
9	1077.9	6.833	30.692	3.918	4.109	4.10	1075.3	6.653	27.284	3.036	2.881	2.95
10	1125.2	7.385	72.387	2.391	2.100	2.10	1662.7	10.414	43.338	2.134	2.084	2.10
11	1328.2	8.292	36.068	2.277	1.538	4.10	1381.0	8.468	38.806	2.764	2.630	2.10
12	1009.0	6.266	23.759	3.299	3.023	4.10	961.3	5.971	28.767	2.809	2.137	5.15
13	1045.3	6.703	33.366	3.923	4.105	4.10	964.3	5.960	25.981	2.762	2.444	2.95
14	1098.9	7.096	35.805	2.511	2.115	2.95	2295.9	14.113	55.039	2.227	1.623	1.05
15	1139.3	7.121	29.808	2.460	2.337	2.95	1722.9	10.514	41.721	2.026	2.061	2.10
16	941.0	5.859	22.972	3.061	2.953	2.95	1071.6	6.689	33.129	2.785	2.925	2.95
17	2098.7	13.017	45.767	2.452	2.542	2.95	1636.9	10.001	41.317	2.191	2.057	2.95
18	696.5	4.402	21.973	2.847	2.940	2.95	960.8	5.983	25.962	2.584	2.827	2.95
19	1314.9	8.261	34.244	3.643	4.090	4.10	1202.2	7.897	46.999	1.778	1.048	0.50
20	1256.6	7.758	32.747	3.129	2.961	4.10	1785.2	11.067	45.642	1.647	1.440	2.10
21	917.1	5.774	24.435	2.680	2.665	2.95	1265.5	7.915	32.541	2.902	2.953	4.10
22	1495.9	9.468	53.801	2.751	2.278	4.10	1583.8	9.994	42.242	2.780	2.095	4.10
23	952.0	5.910	25.259	3.884	4.103	5.15	1184.6	7.318	27.519	4.290	4.616	5.15
24	1096.6	6.825	33.448	2.696	2.861	4.10	1755.6	10.755	41.893	2.872	2.113	2.10
25	1673.6	10.556	45.914	2.793	2.912	2.95	1339.6	8.554	48.038	2.234	1.617	2.95
26	1236.0	7.619	36.202	2.749	2.896	2.95	2175.3	13.729	47.444	1.330	0.923	1.05

Table D.9: Table of motion-related features in Keshner tests under the Mental Arithmetic (MA) condition across participants. The ML data of P3 was assumed to be not applicable because the RMS value was over $10^{24} [^{\circ}/s]$.

D

Mental Arithmetic Condition in Keshner tests												
P#	AP						ML					
	AVI [$^{\circ}$]	RMS [$^{\circ}/s$]	ω_{peak} [$^{\circ}/s$]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [$^{\circ}$]	RMS [$^{\circ}/s$]	ω_{peak} [$^{\circ}/s$]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	669.8	4.234	21.156	2.453	2.294	2.95	2350.1	14.198	50.071	1.692	1.457	2.10
3	1263.1	7.726	27.790	3.751	4.110	4.10	N/A	N/A	N/A	N/A	N/A	N/A
4	840.3	5.313	31.815	2.632	1.711	5.05	1955.3	12.185	44.301	1.367	0.681	0.50
5	762.2	4.912	40.355	2.832	2.237	4.10	2227.2	14.071	60.326	1.626	1.124	1.05
6	960.0	6.000	26.908	3.707	4.153	5.05	1768.0	11.197	63.786	1.367	0.724	0.70
7	842.7	5.272	25.004	2.427	2.297	2.95	2953.6	17.917	54.848	1.593	1.379	1.05
8	1220.0	7.853	53.429	2.010	1.263	2.95	1899.5	11.958	56.396	1.453	0.802	0.50
9	902.0	5.814	37.982	2.642	2.543	4.10	1831.6	11.382	51.222	1.614	0.724	0.50
10	1173.9	7.330	30.242	2.315	2.106	2.10	2401.6	14.919	65.515	2.014	2.088	2.10
11	1017.9	6.357	33.655	1.502	1.031	1.05	1472.3	9.182	50.871	2.587	2.116	2.10
12	1656.8	11.413	87.161	2.534	2.201	4.10	1919.3	12.007	64.614	1.703	0.795	0.35
13	996.8	6.339	56.242	3.273	3.675	4.10	1198.3	7.549	52.055	1.932	1.161	0.70
14	733.8	4.692	23.678	2.377	1.518	1.05	2430.0	14.647	51.250	1.850	1.737	2.10
15	901.0	5.526	20.482	2.284	1.428	4.10	1932.3	11.788	41.058	2.173	2.081	2.10
16	813.1	5.066	23.302	3.657	4.092	5.15	1109.1	6.853	26.199	2.586	2.085	2.10
17	2112.2	12.986	55.685	2.638	2.923	2.95	1323.6	8.108	31.675	2.327	1.962	1.05
18	566.1	3.540	16.067	2.922	2.927	1.05	1217.6	7.462	31.104	2.768	2.925	2.95
19	830.3	5.521	49.176	2.630	2.278	0.35	2144.2	13.651	62.847	1.206	0.869	1.05
20	958.4	6.061	27.799	4.542	4.684	6.20	1541.6	9.570	37.953	2.586	2.111	2.10
21	1026.7	6.477	38.605	2.697	2.913	4.10	1485.3	9.144	32.347	3.084	2.962	2.95
22	1223.6	8.831	87.301	2.053	1.603	0.50	1841.3	11.275	41.043	1.710	1.122	1.05
23	1126.9	6.953	26.463	3.330	4.066	5.15	1584.0	9.675	35.467	4.175	4.150	5.15
24	1214.0	7.609	31.921	2.171	1.446	1.05	2567.6	15.707	88.433	2.299	2.095	2.10
25	1417.7	8.817	51.074	2.646	2.448	0.70	2517.7	15.594	73.514	1.467	1.066	1.05
26	1498.7	9.043	35.411	2.868	2.930	2.95	2380.6	14.444	54.776	1.189	0.752	0.70

Table D.10: Table of motion-related features in Keshner tests under the Visual Tracking (VT) condition across participants. The ML data of P3 was assumed to be not applicable because the RMS value was over $10^{24} [^{\circ}/s]$.

Visual Tracking Condition in Keshner tests												
P#	AP						ML					
	AVI [$^{\circ}$]	RMS [$^{\circ}/s$]	ω_{peak} [$^{\circ}/s$]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [$^{\circ}$]	RMS [$^{\circ}/s$]	ω_{peak} [$^{\circ}/s$]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	669.8	4.234	21.156	2.453	2.294	2.95	2350.1	14.198	50.071	1.692	1.457	2.10
3	1263.1	7.726	27.790	3.751	4.110	4.10	N/A	N/A	N/A	N/A	N/A	N/A
4	840.3	5.313	31.815	2.632	1.711	5.05	1955.3	12.185	44.301	1.367	0.681	0.50
5	762.2	4.912	40.355	2.832	2.237	4.10	2227.2	14.071	60.326	1.626	1.124	1.05
6	960.0	6.000	26.908	3.707	4.153	5.05	1768.0	11.197	63.786	1.367	0.724	0.70
7	842.7	5.272	25.004	2.427	2.297	2.95	2953.6	17.917	54.848	1.593	1.379	1.05
8	1220.0	7.853	53.429	2.010	1.263	2.95	1899.5	11.958	56.396	1.453	0.802	0.50
9	902.0	5.814	37.982	2.642	2.543	4.10	1831.6	11.382	51.222	1.614	0.724	0.50
10	1173.9	7.330	30.242	2.315	2.106	2.10	2401.6	14.919	65.515	2.014	2.088	2.10
11	1017.9	6.357	33.655	1.502	1.031	1.05	1472.3	9.182	50.871	2.587	2.116	2.10
12	1656.8	11.413	87.161	2.534	2.201	4.10	1919.3	12.007	64.614	1.703	0.795	0.35
13	996.8	6.339	56.242	3.273	3.675	4.10	1198.3	7.549	52.055	1.932	1.161	0.70
14	733.8	4.692	23.678	2.377	1.518	1.05	2430.0	14.647	51.250	1.850	1.737	2.10
15	901.0	5.526	20.482	2.284	1.428	4.10	1932.3	11.788	41.058	2.173	2.081	2.10
16	813.1	5.066	23.302	3.657	4.092	5.15	1109.1	6.853	26.199	2.586	2.085	2.10
17	2112.2	12.986	55.685	2.638	2.923	2.95	1323.6	8.108	31.675	2.327	1.962	1.05
18	566.1	3.540	16.067	2.922	2.927	1.05	1217.6	7.462	31.104	2.768	2.925	2.95
19	830.3	5.521	49.176	2.630	2.278	0.35	2144.2	13.651	62.847	1.206	0.869	1.05
20	958.4	6.061	27.799	4.542	4.684	6.20	1541.6	9.570	37.953	2.586	2.111	2.10
21	1026.7	6.477	38.605	2.697	2.913	4.10	1485.3	9.144	32.347	3.084	2.962	2.95
22	1223.6	8.831	87.301	2.053	1.603	0.50	1841.3	11.275	41.043	1.710	1.122	1.05
23	1126.9	6.953	26.463	3.330	4.066	5.15	1584.0	9.675	35.467	4.175	4.150	5.15
24	1214.0	7.609	31.921	2.171	1.446	1.05	2567.6	15.707	88.433	2.299	2.095	2.10
25	1417.7	8.817	51.074	2.646	2.448	0.70	2517.7	15.594	73.514	1.467	1.066	1.05
26	1498.7	9.043	35.411	2.868	2.930	2.95	2380.6	14.444	54.776	1.189	0.752	0.70

Table D.11: Table of VS/NV features across participants.

P#	G_{mean}	ϕ_{mean}	ϕ_{peak}	$C_{VS,mean}$	$C_{NV,mean}$
2	1.068	68.118	154.840	0.994	0.385
3	0.515	23.376	71.830	0.961	0.951
4	0.596	30.436	145.209	0.882	0.813
5	1.153	46.065	125.846	0.978	0.455
6	0.378	9.428	18.217	0.983	0.890
7	0.700	16.440	60.587	0.993	0.888
8	-0.076	14.922	54.817	0.959	0.845
9	0.438	9.980	45.123	0.987	0.963
10	0.446	10.919	40.031	0.991	0.855
11	1.602	71.951	130.796	0.978	0.352
12	0.625	17.687	45.695	0.991	0.954
13	0.230	5.586	17.395	0.995	0.969
14	1.123	61.114	113.621	0.954	0.407
15	1.090	33.414	100.170	0.980	0.661
16	0.142	1.895	4.198	0.997	0.980
17	0.115	5.115	14.423	0.988	0.961
18	0.314	16.129	54.652	0.961	0.976
19	0.503	8.595	29.938	0.992	0.819
20	0.469	18.315	36.486	0.984	0.783
21	1.494	40.116	110.228	0.977	0.336
22	0.277	8.758	10.675	0.968	0.945
23	0.119	8.353	34.846	0.939	0.967
24	0.288	14.241	25.244	0.830	0.755
25	1.002	15.870	40.370	0.895	0.713
26	1.116	69.642	161.411	0.948	0.471

Table D.12: Table of motion-related features of head motions under the stand-EC condition before forest tests across participants.

Standing, Eyes-Closed Condition before Forest Tests											
P#	AP						ML				
	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]
2	67.447	1.036	6.044	2.07	1.86	2.8	37.595	0.552	1.836	2.803	2.659
3	60.2	0.921	4.085	1.892	1.259	1.05	40.155	0.593	2.215	2.644	2.192
4	53.946	0.813	3.29	1.959	1.658	1.1	30.465	0.451	1.6	2.452	1.704
5	44.268	0.665	3.436	2.459	1.881	1.9	37.846	0.575	2.614	4.287	3.735
6	105.759	1.669	9.727	2.17	2.223	2.4	72.049	1.135	6.328	2.225	1.764
7	69.122	1.123	11.185	2.065	1.498	0.65	66.614	1.402	23.973	1.984	1.398
8	67.173	0.998	4.069	2.059	1.433	0.9	47.178	0.703	3.403	2.242	1.161
9	74.569	1.163	7.696	2.138	1.838	1.25	66.701	1.021	4.665	2.511	2.382
10	80.62	1.268	6.553	2.065	1.805	1.45	59.719	0.944	5.329	2.23	1.819
11	62.76	0.931	3.437	2.291	2.104	3.15	39.842	0.614	3.82	3.601	2.79
12	39.183	0.584	2.073	2.664	2.302	2.4	25.692	0.385	1.838	2.329	1.095
13	75.497	1.157	6.556	1.504	1.241	0.25	50.042	0.79	5.145	2.148	1.26
14	60.748	0.976	8.458	2.118	1.661	1.55	30.67	0.473	2.774	2.203	1.27
15	58.581	0.872	3.131	1.748	1.471	0.95	30.08	0.449	1.867	2.676	1.775
16	55.488	0.83	3.335	2.134	1.589	0.2	53.954	0.843	7.094	2.529	2.358
17	78.798	1.193	6.061	2.203	1.587	1.5	55.538	0.817	3.024	2.586	1.968
18	59.679	0.893	3.558	2.494	2.452	3.1	42.686	0.626	2.345	2.881	1.938
19	61.542	0.963	4.341	2.454	1.854	1.15	45.481	0.692	3.212	2.645	1.993
20	63.758	0.943	4.139	2.318	2.151	1.3	34.418	0.517	2.229	2.03	1.068
21	115.443	1.994	19.388	1.438	1.083	0.6	83.303	1.411	13.121	1.821	1.139
22	75.81	1.107	3.716	2.383	2.547	2.85	35.81	0.529	2.282	3.082	2.643
23	44.447	0.66	2.425	2.447	1.78	1.35	23.526	0.354	1.582	3.979	3.097
24	98.379	1.492	6.387	2.004	1.737	2.05	61.647	0.981	8.615	2.811	2.133
25	86.207	1.302	5.871	2.019	1.689	0.9	63.536	0.985	6.721	2.001	1.633
26	47.909	0.713	3.406	2.344	1.831	0.65	32.793	0.504	3.048	2.649	1.426

Table D.13: Table of motion-related features of head motions under the stand-EO condition before forest tests across participants.

Standing, Eyes-Open Condition before Forest Tests												
	AP						ML					
P#	AVI [$^{\circ}$]	RMS [$^{\circ}$ /s]	ω_{peak} [$^{\circ}$ /s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [$^{\circ}$]	RMS [$^{\circ}$ /s]	ω_{peak} [$^{\circ}$ /s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	60.546	0.893	3.222	1.990	1.520	1.15	33.909	0.501	1.966	3.257	2.787	2.85
3	53.863	0.819	4.186	1.861	1.257	0.55	36.924	0.551	2.139	2.596	1.829	0.6
4	53.221	0.783	2.783	1.901	1.506	2.35	33.439	0.492	1.910	2.768	2.303	2.3
5	38.999	0.586	2.084	2.525	1.887	1.9	39.873	0.619	3.001	4.338	3.778	5.65
6	103.974	1.973	16.746	2.198	1.896	2.4	79.242	1.320	8.588	2.242	1.664	0.75
7	85.436	1.607	16.883	1.332	0.949	0.6	86.696	1.890	17.208	1.170	0.809	0.55
8	56.977	0.943	8.493	2.374	1.716	2.85	50.813	0.858	6.962	2.243	1.063	0.7
9	60.081	0.907	3.784	2.194	1.560	1.15	58.247	0.881	3.909	2.858	2.496	2.6
10	78.635	1.273	8.455	2.162	1.833	0.85	57.813	0.913	5.052	2.221	1.722	1.25
11	52.845	0.796	3.544	2.295	1.843	2.8	34.864	0.524	2.215	3.609	2.581	2.8
12	38.147	0.573	2.337	2.694	2.236	2.35	28.524	0.424	1.637	2.166	1.061	1.05
13	74.235	1.302	19.101	2.692	1.755	1.55	66.382	1.207	12.571	1.890	1.331	0.55
14	49.135	0.762	4.242	2.210	1.729	0.25	28.448	0.439	2.928	2.137	1.083	0.55
15	53.183	0.805	3.444	1.810	1.317	1.15	32.707	0.495	1.680	2.257	1.190	0.95
16	51.574	0.809	4.165	2.558	1.871	1.15	47.509	0.715	3.312	2.886	2.343	2.4
17	76.907	1.222	12.164	2.146	1.502	1.45	52.597	0.822	5.603	2.536	1.941	2.55
18	51.149	0.792	4.931	2.680	2.413	3.05	38.766	0.590	2.568	3.305	2.810	1.15
19	57.172	0.965	11.020	3.033	2.334	0.8	44.486	0.672	3.364	3.079	2.899	3.15
20	61.484	0.916	3.448	2.085	1.631	1.3	40.125	0.624	4.737	1.842	1.008	0.45
21	82.657	1.364	10.300	1.790	1.242	1.15	60.714	0.961	5.334	2.230	1.373	0.55
22	59.171	0.881	3.220	2.498	2.223	2.7	37.282	0.568	3.643	3.222	2.624	2.75
23	35.351	0.524	2.157	2.526	1.414	1.35	21.385	0.321	1.336	4.519	3.831	1.2
24	98.681	1.507	7.153	1.757	1.508	1.15	61.722	0.977	6.363	2.668	1.868	1.7
25	68.354	1.025	5.472	2.203	1.792	1.2	56.311	0.857	3.676	2.226	2.375	2.4
26	45.898	0.686	3.074	2.404	1.839	0.8	34.184	0.529	2.637	2.779	1.679	0.7

Table D.14: Table of motion-related features of head motions under the sit-EC condition before forest tests across participants.

Sitting, Eyes-Closed Condition before Forest Tests												
	AP						ML					
P#	AVI [$^{\circ}$]	RMS [$^{\circ}$ /s]	ω_{peak} [$^{\circ}$ /s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [$^{\circ}$]	RMS [$^{\circ}$ /s]	ω_{peak} [$^{\circ}$ /s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	20.829	0.546	4.905	2.457	1.691	0.55	14.862	0.353	1.662	4.348	2.544	4.50
3	15.173	0.356	1.573	2.925	1.697	1.05	14.637	0.341	1.369	4.097	2.214	0.35
4	11.973	0.354	5.050	2.717	2.180	1.95	13.576	0.342	1.736	2.213	1.146	0.25
5	12.897	0.289	0.991	3.171	1.694	0.40	20.409	0.470	1.655	6.122	5.138	5.10
6	13.265	0.305	1.132	4.182	2.794	2.70	16.407	0.397	2.486	4.464	2.270	1.35
7	33.004	0.859	4.672	3.166	2.701	3.80	31.828	1.025	8.318	2.677	2.022	1.10
8	25.382	0.584	2.851	3.999	3.736	6.35	21.402	0.511	2.180	4.956	4.911	5.05
9	21.110	0.507	2.453	2.612	1.424	0.35	19.642	0.514	2.550	5.047	4.978	1.05
10	37.493	0.948	5.466	2.171	1.884	2.05	26.472	0.650	3.992	2.547	2.506	2.80
11	17.063	0.406	1.843	3.352	2.572	0.65	16.183	0.394	1.776	6.026	6.351	7.25
12	14.666	0.342	1.606	2.682	1.525	0.90	10.993	0.252	0.793	4.280	3.404	1.15
13	18.965	0.451	1.861	2.315	1.311	1.30	20.792	0.491	2.477	4.339	2.650	0.35
14	20.295	0.500	2.612	3.302	2.253	1.50	11.741	0.293	1.270	4.813	3.726	1.60
15	20.612	0.457	1.372	1.620	1.211	1.25	12.775	0.298	1.150	4.851	4.848	2.50
16	18.344	0.428	1.881	2.936	1.529	1.05	21.617	0.535	2.297	5.030	4.388	4.15
17	32.495	0.744	3.151	2.490	1.354	1.30	29.627	0.696	3.269	5.294	5.116	4.95
18	19.493	0.447	1.673	3.425	2.422	1.95	19.457	0.472	1.754	5.735	6.386	2.80
19	16.734	0.400	2.580	4.402	4.306	2.60	18.173	0.434	1.827	5.197	4.901	2.65
20	16.257	0.371	1.292	3.878	3.033	2.00	8.820	0.212	0.988	5.684	4.277	3.90
21	15.223	0.358	1.574	2.717	1.215	1.20	16.295	0.371	1.441	4.178	2.409	2.40
22	32.430	1.063	8.165	1.651	1.103	0.25	22.924	0.551	2.636	4.028	1.882	1.30
23	11.875	0.274	1.138	3.017	1.593	0.35	12.867	0.300	1.205	5.531	5.526	4.50
24	22.955	0.544	2.422	3.401	1.743	1.10	24.546	0.623	2.975	5.848	5.785	1.60
25	26.728	0.753	7.737	2.259	1.629	1.30	22.755	0.542	2.662	2.874	2.115	4.00
26	17.536	0.420	2.051	3.465	2.178	0.55	15.051	0.356	1.449	4.037	3.122	4.55

Table D.15: Table of motion-related features of head motions under the sit-EO condition before forest tests across participants.

D

Sitting, Eyes-Open Condition before Forest Tests												
	AP						ML					
P#	AVI [$^{\circ}$]	RMS [$^{\circ}/s$]	ω_{peak} [$^{\circ}/s$]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [$^{\circ}$]	RMS [$^{\circ}/s$]	ω_{peak} [$^{\circ}/s$]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	18.760	0.448	1.882	3.335	2.435	0.25	15.666	0.373	1.632	4.807	4.446	4.60
3	18.074	0.419	1.724	2.370	1.240	1.20	18.407	0.420	1.767	3.600	1.609	0.75
4	12.293	0.290	1.293	3.401	2.137	2.10	13.016	0.302	1.175	3.080	1.573	1.25
5	13.222	0.299	0.997	3.959	2.311	6.95	22.098	0.535	2.477	5.764	5.211	5.20
6	13.677	0.329	2.405	3.713	2.714	6.80	17.360	0.409	2.101	4.626	2.727	1.35
7	38.174	1.192	15.985	2.349	1.404	1.15	30.169	0.945	10.244	1.818	1.082	0.70
8	24.459	0.567	2.208	4.004	3.737	1.05	20.892	0.490	2.201	4.988	4.809	0.60
9	22.391	0.588	5.685	2.568	1.601	0.40	20.241	0.524	2.403	5.542	5.414	1.15
10	33.959	0.809	3.986	2.511	2.143	1.55	26.307	0.634	3.222	3.103	2.855	3.00
11	18.345	0.432	2.024	3.196	2.645	1.50	17.169	0.406	2.027	4.302	2.461	1.25
12	15.996	0.376	1.533	2.938	1.914	2.20	11.847	0.278	1.189	4.205	3.243	1.10
13	21.035	0.499	2.999	2.414	1.399	1.25	22.579	0.534	2.821	4.401	3.187	0.25
14	21.222	0.504	2.129	3.125	2.051	0.35	13.513	0.350	2.081	4.692	4.129	1.30
15	20.580	0.484	2.022	1.640	1.166	1.20	15.093	0.359	2.149	4.269	3.104	1.30
16	22.863	0.624	4.739	2.549	1.537	1.05	25.047	0.662	5.310	4.253	4.121	4.20
17	35.548	0.822	4.552	2.165	1.236	1.20	30.160	0.723	3.280	5.146	4.907	1.20
18	19.029	0.453	2.311	3.171	2.183	1.70	21.360	0.514	2.686	4.873	2.988	2.75
19	17.318	0.410	1.851	4.345	4.068	5.35	19.374	0.457	2.542	4.733	3.867	2.70
20	19.614	0.482	2.761	3.144	2.443	1.60	13.215	0.323	1.515	3.887	2.240	1.45
21	20.600	0.475	1.719	1.687	0.745	0.25	19.418	0.438	1.588	3.412	2.402	2.45
22	24.715	0.599	3.278	2.601	1.492	1.15	25.654	0.629	2.709	3.469	1.603	0.75
23	16.209	0.367	1.602	3.064	1.390	0.35	16.284	0.383	1.607	5.266	4.866	4.75
24	25.647	0.606	2.733	2.687	1.312	1.10	28.192	0.699	3.579	4.640	3.351	0.55
25	22.031	0.532	2.289	2.570	1.645	1.35	23.321	0.549	2.692	2.815	2.846	2.90
26	17.098	0.396	1.570	3.336	2.010	0.30	15.710	0.366	1.555	3.915	2.312	4.60

Table D.16: Table of motion-related features of head motions under the stand-EC condition before spinning tests across participants.

Standing, Eyes-Closed Condition before Spinning Tests												
	AP						ML					
P#	AVI [$^{\circ}$]	RMS [$^{\circ}$ /s]	ω_{peak} [$^{\circ}$ /s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [$^{\circ}$]	RMS [$^{\circ}$ /s]	ω_{peak} [$^{\circ}$ /s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	53.132	0.789	3.109	2.708	2.715	2.90	31.555	0.471	1.893	3.439	2.973	3.05
3	65.239	0.974	4.013	1.930	1.568	0.45	39.147	0.587	2.521	2.854	2.409	2.45
4	60.666	0.909	3.509	1.898	1.633	0.20	32.103	0.477	1.654	2.610	2.148	1.10
5	40.227	0.591	1.954	2.293	1.829	1.85	35.490	0.529	1.868	4.376	3.966	5.55
6	89.758	1.407	7.141	1.945	1.747	2.20	52.730	0.787	3.883	3.102	1.801	3.50
7	73.299	1.224	9.499	1.894	1.391	0.35	67.259	1.264	13.491	1.698	1.224	0.70
8	65.983	1.066	7.272	2.188	1.584	0.40	48.603	0.759	4.366	2.114	1.040	0.60
9	74.761	1.215	9.323	2.249	2.297	2.45	53.433	0.812	3.568	2.603	2.383	2.45
10	76.312	1.157	4.891	2.106	1.859	1.55	58.110	0.889	3.962	2.496	1.993	0.80
11	62.092	0.953	5.514	2.385	2.275	3.15	45.507	0.701	3.589	3.311	2.555	1.10
12	42.137	0.638	3.236	2.571	1.783	1.35	27.885	0.413	1.808	2.663	1.115	0.85
13	143.202	2.413	16.881	1.202	1.067	0.80	72.642	1.140	5.881	1.478	0.838	0.55
14	57.036	0.887	5.188	2.135	1.762	1.75	33.748	0.519	2.565	1.825	1.046	0.85
15	58.937	0.895	4.590	1.711	1.386	1.55	30.550	0.468	3.040	2.544	1.620	0.85
16	70.771	1.054	3.812	2.057	1.704	2.60	60.144	0.900	3.710	2.632	2.559	2.60
17	113.229	1.731	8.109	2.435	2.132	2.15	66.081	1.029	6.924	2.345	1.791	1.25
18	61.440	0.910	3.297	2.647	2.506	3.15	37.107	0.563	2.999	3.903	3.155	3.15
19	67.521	1.086	5.993	2.469	2.001	1.25	50.015	0.777	4.306	2.256	1.637	0.30
20	63.909	0.980	5.849	2.209	1.775	1.45	34.750	0.530	2.731	1.770	0.910	0.60
21	113.113	1.850	14.063	1.764	1.301	1.75	90.140	1.492	7.919	1.487	0.810	0.30
22	82.794	1.262	5.901	2.506	2.611	2.95	41.132	0.604	2.378	2.986	2.693	2.95
23	41.873	0.618	2.009	2.510	2.163	1.30	23.295	0.355	1.746	4.122	3.835	3.90
24	75.848	1.163	6.080	2.301	1.919	1.65	59.141	0.927	4.555	3.150	2.305	2.30
25	93.644	1.429	6.549	1.975	1.733	1.05	57.680	0.866	3.717	2.133	1.822	0.85
26	49.182	0.766	4.691	2.227	1.421	0.85	39.049	0.629	4.322	2.289	1.666	0.80

Table D.17: Table of motion-related features of head motions under the stand-EO condition before spinning tests across participants.

Standing, Eyes-Open Condition before Spinning Tests												
P#	AP						ML					
	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	44.287	0.668	3.123	2.550	2.350	2.70	29.443	0.440	1.944	3.046	2.634	2.70
3	53.169	0.811	4.516	1.932	1.319	2.50	38.576	0.576	2.600	2.884	2.410	2.50
4	53.858	0.799	3.818	1.947	1.844	2.40	33.094	0.504	2.456	2.655	2.288	2.40
5	41.448	0.626	4.016	2.582	1.904	1.90	40.113	0.609	2.429	4.246	3.822	1.90
6	81.661	1.410	15.437	2.631	2.349	2.35	59.294	0.942	7.174	2.839	2.117	1.70
7	99.610	2.086	23.856	2.491	1.583	0.30	76.570	1.342	13.793	2.289	1.590	0.35
8	67.256	1.017	4.813	2.083	1.196	0.95	49.754	0.829	8.425	1.886	0.966	0.65
9	57.529	0.861	4.756	2.748	2.336	2.35	48.733	0.737	3.198	3.092	2.397	2.45
10	71.700	1.086	4.190	2.337	2.025	1.75	55.056	0.833	3.425	2.439	1.772	0.90
11	48.898	0.733	3.292	2.583	2.572	3.00	35.165	0.529	2.528	3.630	2.682	3.00
12	35.722	0.543	2.370	3.089	2.537	2.60	25.182	0.371	1.485	3.211	1.573	0.90
13	206.732	3.771	28.029	1.947	1.502	0.75	151.218	3.133	32.810	1.529	0.787	0.70
14	46.513	0.703	3.199	2.588	2.143	2.00	32.728	0.505	2.353	2.046	1.155	1.05
15	57.706	0.939	9.128	2.660	1.554	1.45	30.385	0.464	2.649	3.067	1.693	0.85
16	60.385	0.941	5.030	2.243	2.024	2.55	54.853	0.842	4.391	2.459	2.278	2.55
17	82.024	1.301	10.590	2.473	1.928	1.10	54.935	0.869	7.550	2.567	2.119	0.80
18	59.770	0.906	4.474	2.681	2.367	3.00	45.752	0.704	4.975	3.237	2.782	0.95
19	61.384	1.122	11.532	2.722	1.854	1.45	51.007	0.849	6.372	2.568	2.018	0.70
20	56.757	0.856	3.930	2.168	2.178	2.35	32.398	0.477	2.106	1.713	0.772	0.55
21	103.587	2.020	30.857	1.562	1.191	0.30	70.244	1.194	12.225	2.110	1.590	0.75
22	78.996	1.168	5.243	2.403	2.458	2.90	40.067	0.603	2.410	3.069	2.376	2.90
23	36.123	0.527	2.355	2.475	1.849	1.25	22.229	0.335	1.693	4.254	3.807	1.25
24	70.544	1.079	6.383	2.013	1.674	1.25	50.266	0.775	3.329	3.402	2.102	1.25
25	66.479	0.997	4.072	2.102	1.736	1.10	47.920	0.765	5.460	2.164	1.874	0.50
26	45.609	0.682	3.525	2.446	1.747	1.35	37.624	0.603	3.128	2.459	1.690	2.75

Table D.18: Table of motion-related features of head motions under the sit-EC condition before spinning tests across participants.

Sitting, Eyes-Closed Condition before Spinning Tests												
	AP						ML					
P#	AVI [$^{\circ}$]	RMS [$^{\circ}$ /s]	ω_{peak} [$^{\circ}$ /s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [$^{\circ}$]	RMS [$^{\circ}$ /s]	ω_{peak} [$^{\circ}$ /s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	20.082	0.493	2.729	2.826	1.375	1.30	12.981	0.303	1.416	5.243	4.117	2.30
3	14.246	0.331	1.135	3.461	2.077	1.05	15.675	0.361	1.329	4.215	4.114	0.30
4	7.987	0.188	0.799	4.224	2.800	1.95	10.951	0.259	1.135	3.613	1.747	1.45
5	12.269	0.278	0.850	3.519	1.718	1.65	20.265	0.483	2.069	5.781	5.051	5.00
6	13.277	0.320	1.451	3.682	2.186	1.35	19.416	0.460	2.392	4.929	5.191	1.35
7	27.206	0.651	3.092	3.752	3.426	1.75	19.533	0.467	2.538	3.976	2.147	1.70
8	19.255	0.452	2.288	4.138	2.721	6.40	20.032	0.469	2.095	4.184	2.620	0.30
9	22.459	0.577	3.427	2.088	1.065	0.65	19.723	0.524	2.968	4.599	4.219	1.15
10	21.945	0.523	2.823	2.628	2.068	2.95	19.554	0.454	2.032	3.744	2.952	2.95
11	16.931	0.400	1.846	3.562	2.756	1.35	17.143	0.427	2.758	5.719	6.082	6.65
12	15.849	0.362	1.767	3.506	2.328	2.35	11.875	0.275	0.968	4.040	1.919	1.20
13	27.779	0.628	2.454	1.748	1.386	1.50	23.393	0.570	3.292	2.843	1.141	0.50
14	25.713	0.670	4.660	2.900	1.743	0.65	12.070	0.296	1.246	4.782	3.792	1.20
15	20.293	0.456	1.485	1.770	1.202	1.15	12.388	0.291	1.233	5.043	4.700	1.85
16	17.740	0.411	2.209	2.301	1.104	1.05	18.519	0.469	2.385	5.614	5.311	5.15
17	62.987	1.454	5.496	2.690	1.685	1.20	40.154	0.954	4.800	3.393	2.380	1.35
18	19.315	0.449	1.747	4.183	2.902	2.90	21.533	0.518	2.108	5.651	5.530	2.90
19	16.358	0.384	1.459	4.044	3.703	2.45	17.405	0.402	1.435	4.590	3.617	2.45
20	16.656	0.390	1.466	3.241	2.257	2.00	9.136	0.221	1.250	4.652	3.696	2.95
21	13.997	0.346	2.613	3.493	2.532	1.10	17.119	0.405	2.066	3.425	2.236	0.30
22	24.962	0.578	2.169	2.267	1.338	1.35	20.981	0.477	1.930	3.854	1.776	1.70
23	15.085	0.343	1.425	2.854	1.514	0.35	13.769	0.323	1.574	5.305	4.800	4.15
24	33.292	0.783	3.275	1.981	1.029	1.10	28.728	0.716	5.228	4.761	2.810	1.60
25	20.429	0.476	1.978	2.593	1.605	1.60	17.759	0.419	2.028	3.109	2.546	1.70
26	15.572	0.388	2.679	3.256	1.678	0.80	14.405	0.343	1.635	4.573	4.549	4.70

Table D.19: Table of motion-related features of head motions under the sit-EO condition before spinning tests across participants.

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Sitting, Eyes-Open Condition before Spinning Tests												
P#	AP						ML					
	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	AVI [°]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	24.645	0.630	5.415	2.604	1.221	0.50	14.891	0.346	1.574	4.872	4.123	1.95
3	15.866	0.372	1.537	2.795	1.513	1.15	15.069	0.353	1.441	4.240	4.162	1.00
4	11.846	0.296	1.927	3.060	1.979	2.00	13.830	0.328	1.295	3.154	1.476	1.30
5	14.775	0.362	1.985	3.599	1.772	1.65	22.864	0.560	2.728	5.607	5.011	5.00
6	18.810	0.500	3.627	2.010	1.265	1.30	22.684	0.542	2.724	4.570	2.652	1.40
7	30.029	0.762	4.152	3.185	2.333	1.50	20.730	0.532	3.287	3.288	1.701	1.55
8	18.163	0.421	1.652	3.824	2.645	1.70	20.465	0.472	2.213	4.032	2.627	0.55
9	25.568	0.605	2.144	2.089	0.877	0.80	23.469	0.598	2.658	4.645	4.428	1.10
10	33.856	0.836	6.287	2.410	1.824	1.55	30.277	0.755	5.847	2.863	2.506	3.10
11	19.576	0.467	2.755	3.360	2.816	0.80	19.041	0.457	1.980	4.828	4.406	1.75
12	16.325	0.383	1.589	3.133	2.184	0.30	13.731	0.320	1.278	3.719	1.596	1.15
13	31.329	0.791	5.473	1.799	1.231	1.45	26.744	0.716	5.886	3.108	1.466	0.90
14	26.028	0.643	5.951	2.991	1.679	0.30	14.551	0.344	1.670	3.943	2.474	0.65
15	20.827	0.478	1.866	1.535	1.161	1.20	14.102	0.335	1.784	4.922	4.739	4.75
16	18.174	0.444	2.212	2.140	1.318	1.00	19.798	0.515	2.631	5.013	4.952	1.35
17	60.842	1.572	11.600	2.683	1.789	1.10	39.140	0.940	4.718	3.783	3.032	0.95
18	27.177	0.759	6.495	3.308	2.264	2.30	22.989	0.545	2.576	4.973	3.144	2.80
19	15.946	0.374	1.442	4.226	3.724	2.45	18.740	0.428	1.757	4.377	3.561	2.45
20	22.204	0.581	5.113	2.255	1.576	0.75	10.195	0.241	1.557	4.664	3.279	3.20
21	15.022	0.357	1.421	2.807	1.165	1.15	17.796	0.416	1.742	3.619	2.319	2.25
22	27.061	0.644	3.439	2.022	1.215	1.15	19.651	0.468	2.104	4.823	2.800	1.50
23	16.513	0.386	1.904	3.158	2.014	0.35	14.552	0.339	1.454	5.392	4.674	4.65
24	33.524	0.804	2.936	2.009	1.204	1.25	29.477	0.729	3.761	4.826	3.579	1.45
25	23.055	0.594	4.361	2.690	1.568	1.60	20.793	0.506	2.330	2.749	1.892	1.45
26	19.392	0.457	1.830	2.365	1.076	0.55	18.837	0.449	2.337	3.009	1.412	0.30

Table D.20: Table of VIMS- and vection-related features in forest tests across participants. The $MISC_{mean}$ of P21 was not applicable because of a misunderstanding of the experimental protocol.

P#	SSQ _N	SSQ _O	SSQ _D	SSQ _{TS}	$MISC_{mean}$	$MISC_{max}$	$MISC_{rate}$ [s ⁻¹]	$1/t_{end}$ [s ⁻¹]	$Vection_{mean}$	Dropout
2	76.32	60.64	111.36	45.92	0.892	6	0.041	0.007	0.962	True
3	9.54	7.58	0	2	0.000	0	0.000	0.002	0.005	False
4	85.86	22.74	41.76	23.22	3.491	6	0.029	0.005	0.000	True
5	47.7	75.8	83.52	37.44	1.033	3	0.006	0.002	0.000	False
6	104.94	68.22	153.12	61.14	1.387	6	0.011	0.002	0.017	True
7	19.08	30.32	13.92	9.74	1.013	6	0.027	0.005	0.000	True
8	66.78	22.74	69.6	28.7	3.222	6	0.013	0.002	0.015	True
9	85.86	60.64	125.28	50.66	2.507	6	0.036	0.006	0.385	True
10	104.94	60.64	167.04	63.88	3.062	6	0.053	0.009	0.000	True
11	76.32	37.9	83.52	35.44	2.900	6	0.017	0.003	0.879	True
12	66.78	15.16	27.84	16.48	2.105	6	0.054	0.009	0.000	True
13	57.24	30.32	83.52	32.44	1.596	6	0.010	0.002	0.981	True
14	-9.54	0	-27.84	-8.48	0.000	0	0.000	0.002	0.000	False
15	19.08	15.16	55.68	18.96	2.545	6	0.036	0.006	0.990	True
16	47.7	45.48	180.96	59.62	2.066	6	0.011	0.002	0.002	True
17	9.54	7.58	13.92	5.74	0.893	3	0.005	0.002	0.179	False
18	9.54	7.58	0	2	0.451	1	0.004	0.002	0.000	False
19	-9.54	7.58	0	0	0.000	0	0.000	0.002	0.007	False
20	28.62	0	-13.92	-0.74	1.477	4	0.008	0.002	0.000	False
21	47.7	22.74	0	8	N/A	6	0.011	0.002	0.000	True
22	66.78	45.48	97.44	39.18	2.348	4	0.008	0.002	0.215	False
23	66.78	45.48	83.52	35.44	2.799	6	0.054	0.009	0.104	True
24	-9.54	37.9	13.92	7.74	0.009	2	0.009	0.002	0.048	False
25	38.16	7.58	0	5	0.628	4	0.007	0.002	0.008	False
26	66.78	37.9	139.2	49.4	2.833	6	0.124	0.021	0.000	True

D

Table D.21: Table of VIMS- and vection-related features in spinning tests across participants.

P#	SSQ _N	SSQ _O	SSQ _D	SSQ _{TS}	MISC _{mean}	MISC _{max}	MISC _{rate} [s ⁻¹]	1/ <i>t</i> _{end} [s ⁻¹]	Vection _{mean}	Dropout
2	47.7	37.9	83.52	32.44	0.502	6	0.012	0.002	0.951	True
3	19.08	7.58	0	3	1.009	2	0.008	0.002	0.015	False
4	85.86	53.06	83.52	38.44	3.192	6	0.026	0.004	0.843	True
5	57.24	83.38	69.6	35.7	3.722	6	0.011	0.002	0.000	True
6	57.24	30.32	69.6	28.7	2.821	6	0.027	0.005	0.336	True
7	85.86	45.48	69.6	33.7	1.437	6	0.029	0.005	0.000	True
8	66.78	30.32	69.6	29.7	1.058	6	0.014	0.002	0.000	True
9	95.4	53.06	180.96	65.62	2.566	6	0.059	0.010	0.365	True
10	76.32	45.48	97.44	40.18	3.797	6	0.030	0.005	0.000	True
11	95.4	45.48	97.44	42.18	2.333	6	0.044	0.007	0.345	True
12	19.08	15.16	13.92	7.74	2.185	6	0.018	0.003	0.000	True
13	0	-7.58	27.84	6.48	1.879	2	0.037	0.002	0.992	False
14	9.54	0	-27.84	-6.48	0.919	2	0.004	0.002	0.538	False
15	76.32	53.06	111.36	44.92	3.933	6	0.046	0.008	0.977	True
16	66.78	60.64	180.96	63.62	3.673	6	0.020	0.003	0.470	True
17	47.7	22.74	13.92	11.74	3.300	5	0.018	0.002	0.979	False
18	9.54	7.58	0	2	0.256	1	0.002	0.002	0.557	False
19	-9.54	7.58	0	0	0.244	2	0.004	0.002	0.982	False
20	19.08	-7.58	-13.92	-2.74	0.337	2	0.003	0.002	0.316	False
21	57.24	37.9	0	11	3.403	6	0.047	0.008	0.011	True
22	38.16	37.9	69.6	27.7	0.633	3	0.005	0.002	0.774	False
23	66.78	53.06	83.52	36.44	2.318	6	0.042	0.007	0.139	True
24	9.54	45.48	13.92	10.74	1.499	3	0.007	0.002	0.067	False
25	66.78	22.74	13.92	13.74	2.999	6	0.018	0.003	0.415	True
26	28.62	22.74	111.36	35.92	3.271	6	0.060	0.010	0.884	True

Table D.22: Table of motion-related features in forest tests across participants.

P#	AP					ML				
	RMS [° / s]	ω_{peak} [° / s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	RMS [° / s]	ω_{peak} [° / s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	2.019	18.737	0.924	0.608	0.30	1.954	12.132	1.047	0.580	0.35
3	0.587	6.111	1.668	0.994	0.25	0.625	3.910	1.647	0.674	0.35
4	0.520	8.510	1.564	0.991	0.35	0.723	4.127	1.107	0.643	0.20
5	0.888	11.169	2.068	0.807	0.30	1.167	16.563	1.810	0.844	0.40
6	1.108	15.712	2.047	1.445	0.30	1.174	19.336	1.891	1.258	0.35
7	1.669	33.919	2.010	1.063	0.25	1.376	22.637	1.579	1.212	0.55
8	1.701	31.977	1.362	0.575	0.30	1.215	16.106	1.848	0.610	0.40
9	3.909	31.834	0.950	0.519	0.40	2.170	21.189	1.242	0.581	0.35
10	0.688	5.804	2.081	1.657	1.50	0.844	9.068	2.005	1.226	0.35
11	0.470	4.180	2.738	1.764	0.35	0.393	3.827	3.534	1.595	0.20
12	0.273	1.989	3.484	1.498	1.20	0.270	1.076	3.296	1.258	1.20
13	3.420	33.803	0.894	0.524	0.35	3.280	37.654	0.644	0.431	0.20
14	0.987	17.100	1.645	1.208	0.60	0.498	9.014	2.192	1.096	0.60
15	1.014	11.659	1.670	1.038	1.05	0.788	5.303	2.199	0.985	0.35
16	0.929	31.012	2.258	1.400	1.10	0.783	11.645	2.872	1.877	0.35
17	1.443	19.593	2.216	1.338	1.25	0.885	6.248	3.044	1.537	0.35
18	1.691	28.538	2.130	1.511	0.45	1.673	22.288	2.123	1.466	0.35
19	1.037	18.481	2.024	1.067	0.25	1.248	15.224	1.351	0.613	0.25
20	2.493	38.494	2.077	1.432	0.75	1.973	51.034	1.417	0.911	0.55
21	1.551	30.317	1.338	0.805	0.55	1.281	14.338	1.076	0.653	0.25
22	1.605	41.929	1.306	0.978	0.35	1.254	14.496	1.413	0.465	0.20
23	0.372	1.464	2.493	1.366	0.40	0.366	1.735	4.405	3.888	6.65
24	0.963	11.950	1.793	1.154	0.35	0.712	10.332	3.900	2.265	0.60
25	1.039	25.393	1.244	0.833	0.35	0.706	7.971	1.704	1.045	0.50
26	0.750	4.523	1.931	1.049	0.85	0.508	3.687	2.331	1.259	1.25

Table D.23: Table of motion-related features in spinning tests across participants.

P#	AP					ML				
	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]	RMS [°/s]	ω_{peak} [°/s]	f_{mean} [Hz]	f_{med} [Hz]	f_{peak} [Hz]
2	1.004	15.209	1.453	0.632	0.20	0.880	11.518	1.301	0.509	0.30
3	1.156	29.462	1.516	0.956	0.85	0.686	8.066	1.870	0.958	0.45
4	6.573×10^{25}	6.536×10^{27}	9.017	8.981	4.20	2.714×10^{32}	2.699×10^{34}	9.017	8.981	4.20
5	1.763	45.022	1.214	0.590	0.50	1.504	32.832	1.922	1.146	0.35
6	1.161	16.596	2.258	1.724	1.15	0.962	13.417	2.022	1.170	0.40
7	1.011	13.502	3.088	2.264	2.10	0.880	8.481	2.314	1.310	0.35
8	1.145	23.192	1.828	1.069	0.35	0.710	15.864	2.721	1.336	1.20
9	3.424	27.105	1.296	0.730	0.75	1.885	13.376	1.648	0.828	0.60
10	3.306	48.490	2.579	2.811	0.35	1.815	12.884	2.201	1.558	0.70
11	0.575	3.603	2.198	1.316	0.25	0.532	3.166	2.973	1.404	1.25
12	0.409	2.136	2.870	1.544	1.25	0.312	1.254	3.108	1.298	1.25
13	4.274	63.527	1.178	0.671	0.35	1.548	23.315	1.448	0.814	0.60
14	1.021	13.119	1.524	0.969	0.50	0.693	10.455	1.836	1.113	0.70
15	1.328	8.648	2.102	1.312	1.20	1.607	13.655	1.392	0.900	0.45
16	0.654	9.315	2.260	1.315	1.10	0.630	11.221	3.228	1.810	0.40
17	1.857	13.627	2.394	1.468	1.30	1.045	9.374	3.025	1.789	1.30
18	1.582	17.230	1.831	1.233	0.40	1.565	31.774	1.793	1.037	0.45
19	1.138	19.876	2.363	1.592	0.70	1.081	30.050	2.124	1.058	0.20
20	1.899	40.739	2.112	1.460	0.70	2.310	75.588	1.788	1.492	1.10
21	1.725	15.487	1.226	0.935	0.90	2.373	17.586	0.635	0.468	0.45
22	0.943	22.519	1.863	1.287	1.25	0.791	15.247	2.788	1.463	0.75
23	0.784	5.597	1.422	1.098	1.10	0.439	3.028	2.894	1.642	1.80
24	0.601	7.216	2.770	1.573	1.35	0.659	4.256	4.672	3.398	1.70
25	1.507	35.638	1.302	0.948	0.65	0.765	6.092	1.708	1.098	0.50
26	0.787	3.088	1.845	1.188	1.25	0.595	4.833	1.774	1.087	1.35

E

CORRELATION TABLES

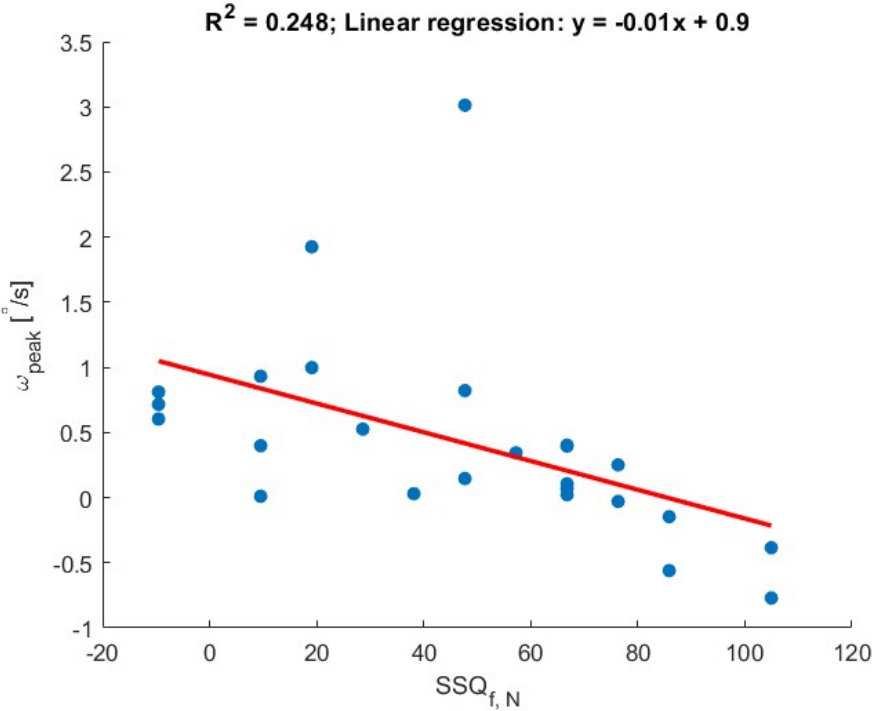


Figure E.1: Linear regression between the peak angular velocity in the ML direction and the SSQ-Nausea sub-score in the forest test.

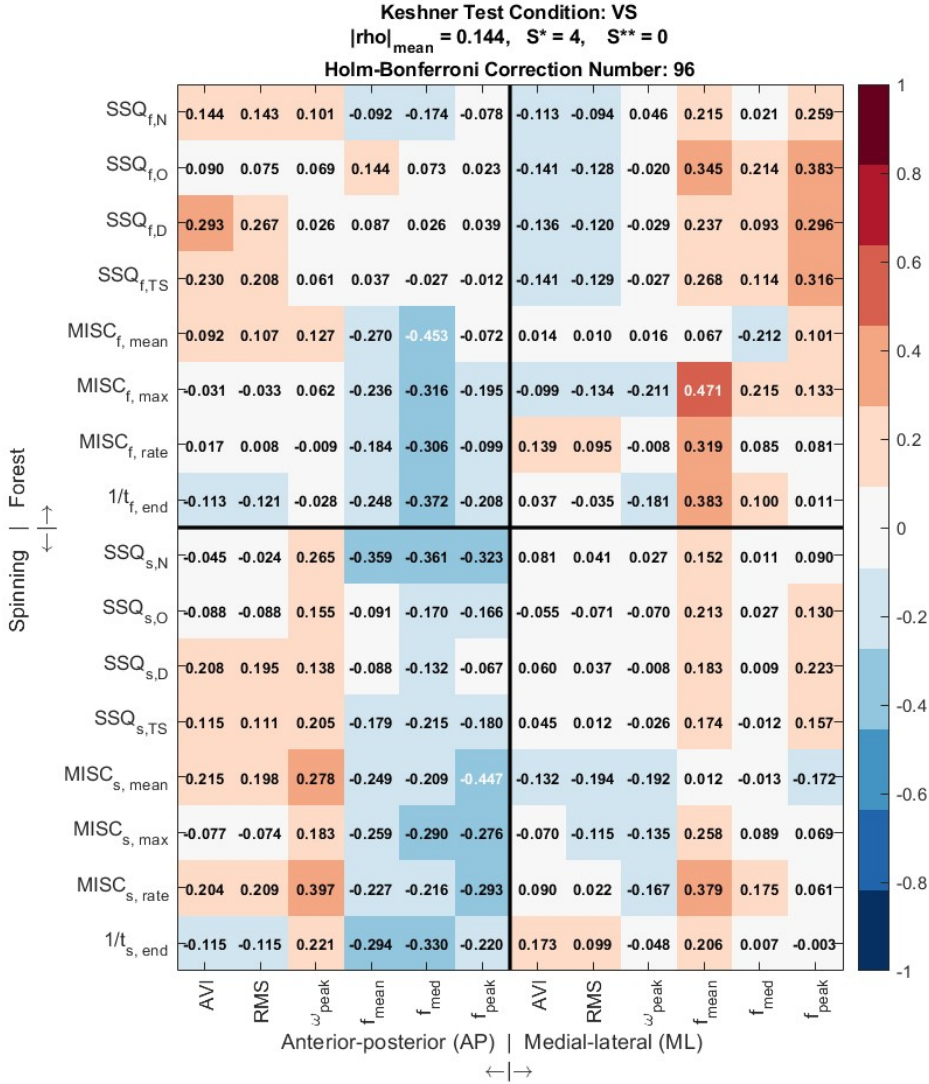


Figure E.2: Correlations of VIMS-related features in the forest (upper half) and the spinning (lower half) tests with the sway motion features during the Keshner test under the VS condition.

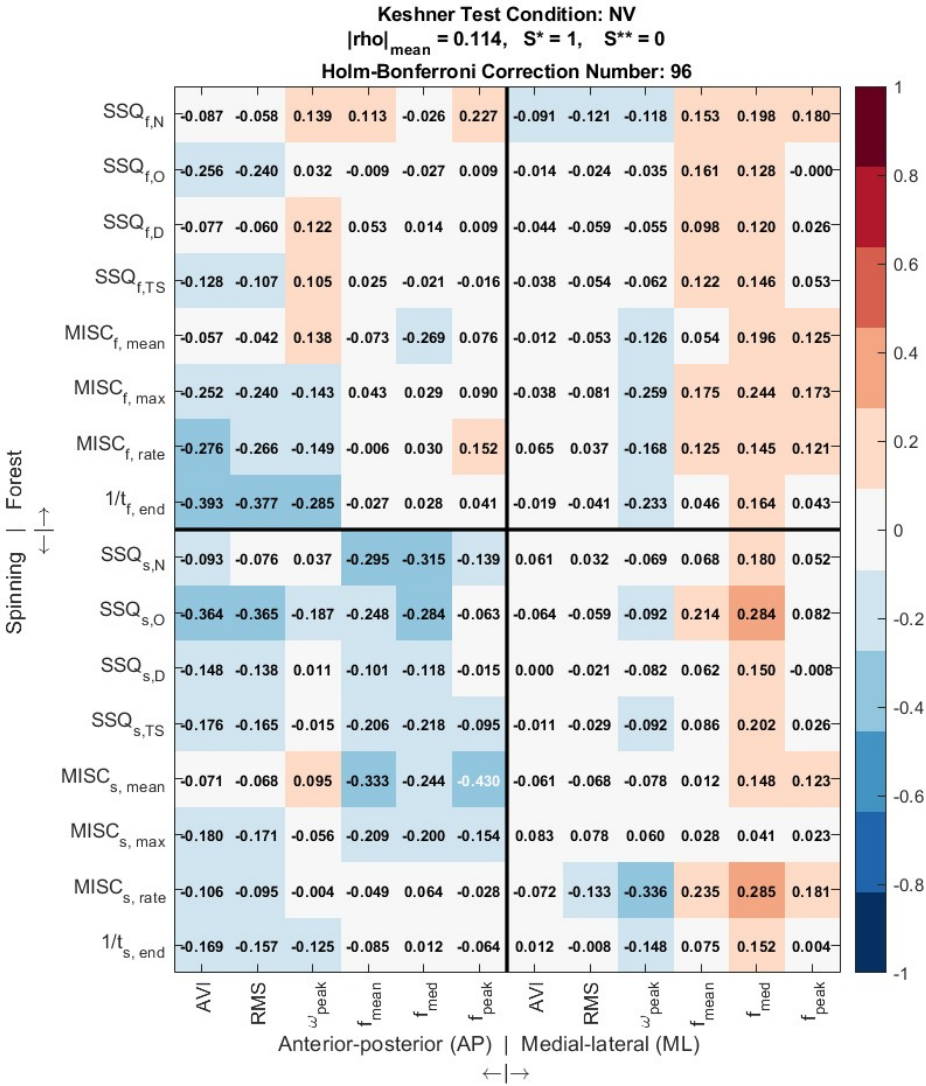


Figure E.3: Correlations of VIMS-related features in the forest (upper half) and the spinning (lower half) tests with the sway motion features during the Keshner test under the NV condition.

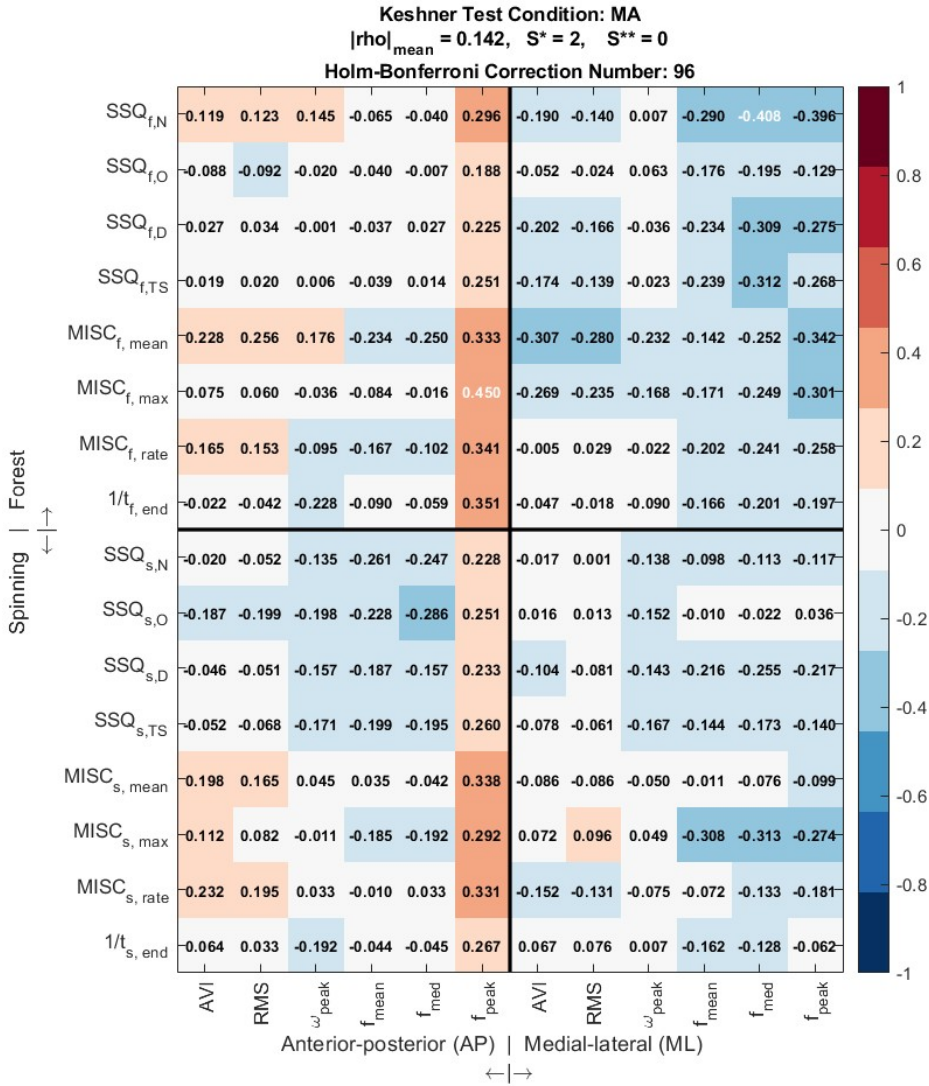


Figure E.4: Correlations of VIMS-related features in the forest (upper half) and the spinning (lower half) tests with the sway motion features during the Keshner test under the MA condition.

E

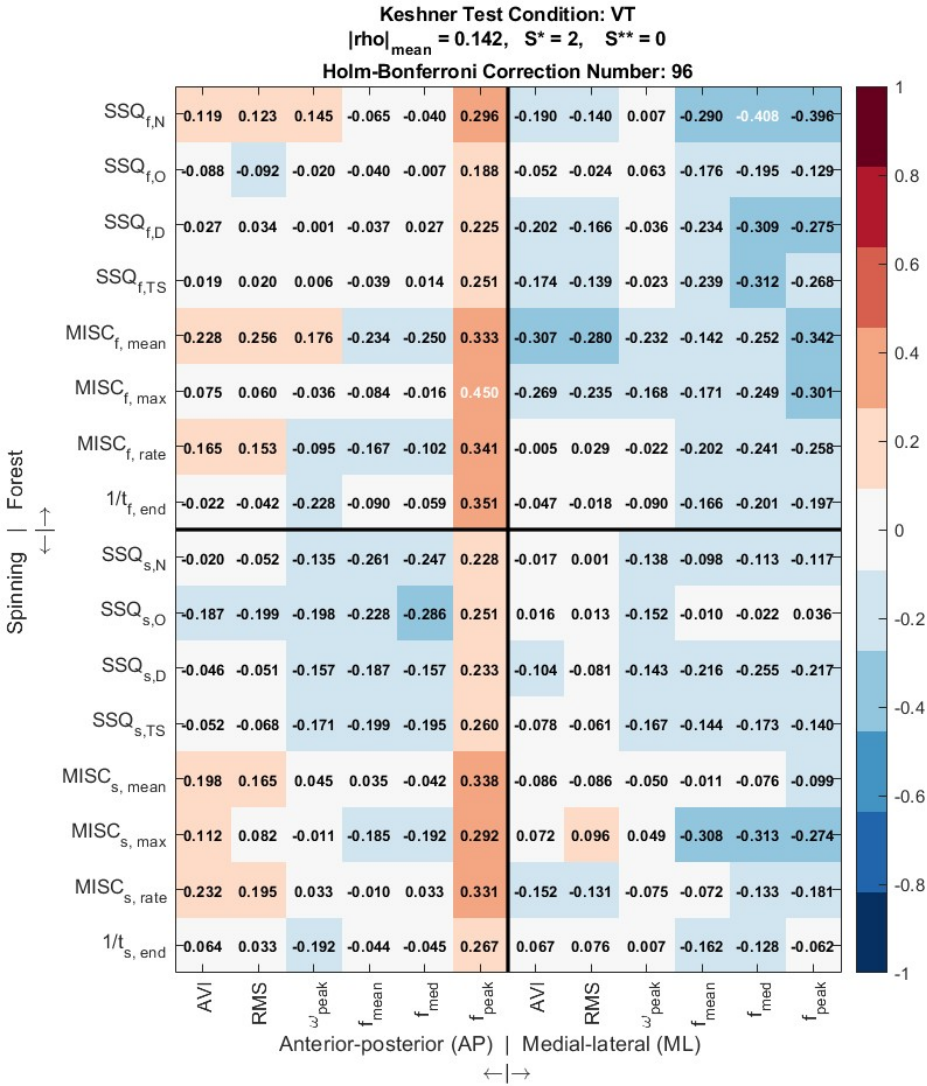


Figure E.5: Correlations of VIMS-related features in the forest (upper half) and the spinning (lower half) tests with the sway motion features during the Keshner test under the VT condition.

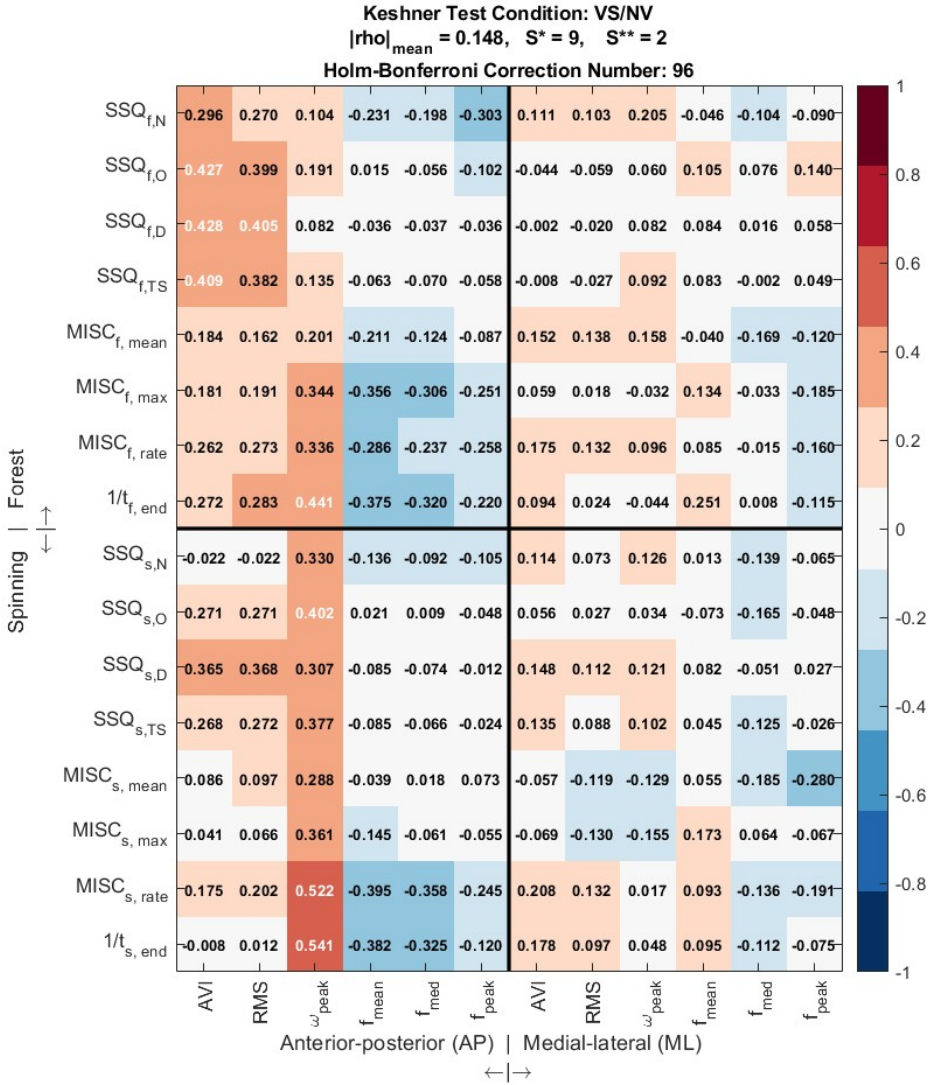


Figure E.6: Correlations of VIMS-related features in the forest (upper half) and the spinning (lower half) tests with the VS/NV relative sway motion features during the Keshner test. For AVI, RMS, and ω_{peak} , the features were calculated as the ratio of features under VS to those under NV, while f_{mean} , f_{med} , and f_{peak} were calculated as features under NV subtracted from those under VS.