Phase Synchronization of Electroencephalograph Indicators for Visually Induced Motion Sickness Susceptibility Validated with Habituation Training

by

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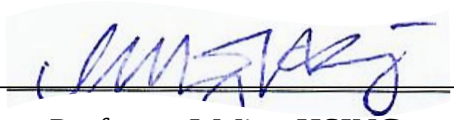

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Phase Synchronization of Electroencephalograph Indicators for Visually Induced Motion Sickness Susceptibility Validated with Habituation Training

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Abstract

Susceptibility to visually induced motion sickness (VIMSS) can prevent people from enjoying 3D films, VR games, and many other entertainments involving self-motion illusion (vection). The mechanism of VIMSS has not been completely understood. In particular, little is known on how the brains of susceptible and resistant individuals differ in responding to VIMS-provoking stimulations. Furthermore, objective and reliable indicators of VIMSS is lack. This research investigates the mechanism and objective indicators for VIMSS from the electroencephalographs (EEG) during a short exposure to VIMS-provoking stimulations. To verify the reliability of the indicators, the VIMSS of each individual was manipulated by a habituation training and the change in VIMSS was validated with two objective measuremens, visual dependency and postural instability. In the current study, rotating random dots around roll and pitch axes were utilized to provoke VIMS and to elicit EEG activities in short exposures. Thirty-four participants were classified into resistant and susceptible groups. To investigate the effect of habituation on VIMSS, participants went through a 7-to-10-day training. Before training, when watching rotating dots in both axes, EEG phase synchronization between the signal from the right parietal region (P4) and signals from central, parietal and occipital regions was significantly higher among the resistant group, while that between signals from two central sites (C3-C4) was significantly higher among the susceptible group. Besides, the synchronization to P4 negatively correlated with VIMS and could be related to neural coordination to relieve VIMS. Positive correlations were found between VIMS and the interhemispheric synchronization (C3-C4), which could indicate a direct response to sensory conflict or VIMS severity. After the training, there was a significant increment in the parietal synchronization (P4-P7) among individuals trained to be resistant from the susceptible group.

The interhemispheric synchronization (C3-C4) was also lower after training. For the first time, we have discovered EEG synchronization indictors that associated the influence of habituation with both reductions in sickness and increases in resistance to VIMS. The two opposite EEG indicators suggest that VIMS could be the consequence of two antagonistic neural activities, and habituation training could reduce the VIMS response by affecting both. Furthermore, less visual dependence and a narrower postural sway range along the x-axis (left to right) were found among the susceptible group after training. The changes in behavioral performance could also be evidence of the effect of habituation on visual-vestibular interaction. The newly discovered EEG phase synchronization indicators offer a new method to predict VIMS susceptibility.

Chapter 1. INTRODUCTION

1.1 Background and Motivations

With the development of visual technology, visually induced motion sickness (VIMS) is more common than before, especially for those people who feel dizzy, nausea and sweating when watching a dazzling IMAX 3D film or playing VR games with self-motion cues. VIMS is a variant of motion sickness, which often occurs to some individuals in a variety of transport (such as buses, cars or ships etc); symptoms include a white pallor, sudden sweat, accompanying nausea and even vomit. There have been a few explanations for those who are unfortunate to suffer from these symptoms, which may be brought on by simply watching certain visual stimulations. These include sensory conflict theory (SCT, Reason & Brand, 1975) and postural instability theory (PIT, Stoffregen & Riccio, 1991). It has been argued that the mismatch between visual and vestibular sensory could be the cause of VIMS (SCT); and people who have not been able to maintain posture stability when watching certain visual stimulations will get VIMS (PIT). However, what the exact representation of sensory conflict was and how to quantify the ability to maintain posture stability in neurophysiology has not yet reached a consensus.

As an unpleasant experience, the severity of VIMS varies among those who suffer from it. Someone who may experience motion sickness in a moving bus could be resistant when taking part in a first-person-shooting game, which makes another person experience symptom of VIMS. The individual differences in VIMS susceptibility make it possible to investigate the mechanism of VIMS. Some past research has tried to measure and explain it, like the inhibitory on visual motion (Brandt et al., 1998) and more theta-band synchronized activity (Y. Wei et al., 2019) could be related with less VIMS. Nevertheless, the change of VIMS susceptibility in a one person has not been well studied. Usually, the change in VIMS susceptibility is uncontrollable. Habituation training with repeated exposures is one method that has been tested to reduce participants' VIMS (Howarth & Hodder, 2008) at-least temporarily. This research intends to utilize habituation training to test hypotheses from two VIMS theories and search for validated VIMS susceptibility indicators.

VIMS symptoms not only vary among population but depends on the type of visual stimulation. It can be dangerous to expose individuals to a potential VIMS-inducing stimulation for a long

period of time. An accurate VIMS predictive approach is required. A few self-report biographical questionnaires on motion sickness and VIMS have been developed (Golding, 2006; Griffin & Howarth, 2000; Keshavarz et al., 2019). Due to the subjectivity of questionnaire and large variance among visual stimulations, the prediction is not always accurate. Given the existing theories on VIMS, several physiological indicators are potential predictors for VIMS. In addition, current research in this area aims to propose an accurate and practical method to predict VIMS susceptibility to a range of predictable visual stimulations.

1.2 Terminology and Explanation

Before the introduction of the current research on VIMS and the outline of this thesis, there are some terms and abbreviations to be specified and explained.

1.2.1 VIMS and VIMS susceptibility

Similar to terms defined under various stimulations like carsickness, airsickness, seasickness, and space-sickness and so on, VIMS is a variant of motion sickness, which is used to specifically describe various discomforts experienced during the exposure to visual stimuli of stationary observers (Hettinger & Riccio, 1992). These include a wide range of symptoms like pallor, dizziness, eyestrain, disorientation, sweating, and most severe but representative, nausea and vomiting, as well as variances in physiological changing.

Susceptibility to sickness has been measured with questionnaires since the middle of the last century. Early studies aimed to measure the sickness susceptibility of people mainly conducted for the pilot training and Navy, whereas those studies also provided valuable reference points to investigate the overall susceptibility of visually induced motion sickness. Derived from Motion Sickness Susceptibility Questionnaire (MSSQ, Golding, 2006), the VIMS Susceptibility Questionnaire (VIMSSQ) was developed and indicated a strong correlation with the VIMS reported by participants in a virtual driving experiment (Keshavarz et al., 2019).

1.2.2 Vection

When there is a exposure to a large FOV of visual stimulations with global motion cues, such as a river surface or a sky full of moving clouds, a self-motion illusion may occur as a physical movement. The investigation of the self-motion illusion can date back to 1875 by Mach, who firstly repeated the illusion under the laboratory conditions, and the term “vection” was firstly used by Tschermak in 1931 (Dichgans & Brandt, 1978). There is a time interval between the

onset of visual motion pattern and the onset of vection, which is referred to as vection latency. As it was documented by Dichgans and Brandt (1978), the latencies contaminating with the circular vection inducing system varied from 1 to 10 s. Vection gradually reached a peak after approximately 5 to 15 s after the stimulus onset.

Vection can be induced by various visual motion stimulations. The current research involved two types of visual motion stimulations, **Roll Stimulation** and **Pitch Stimulation**, to induced vection. Roll stimulation consisted of random dots rotating anti-clockwise with a same and constant angular speed and for pitch stimulation, the random dots rotated upward. After watching either stimulation for several seconds, participants were able to feel self-motion around roll axis and pitch axis which was relative to them. Furthermore, if the exposure was prolonged to about 20 minutes, some participants would experience a range of discomfort and even nausea. Two stimulations are not only vection-provoking but also VIMS-provoking.

1.2.3 Posture Stability and Center of Pressure (CoP)

Postural stability was measured from various data sources, such as the position of the head, the coordination of certain points on the torso, and the center of gravity. The most common and low-cost approach is to record the center of pressure of the feet in a stance position. It was found that the time and frequency domain variation of CoP related to VIMS level (Chardonnet et al., 2017) and postural difference before onset of VIMS appeared to be different between participants who suffered from VIMS and those did not in subsequent experiment (Bonnet et al., 2006; Smart et al., 2002). The quantitative definition for posture stability and instability is still an open question.

1.2.4 Habituation training

Repeated exposures to a range of certain visual stimulations which could induce VIMS was seen to reduce the severity of a following VIMS response; this was referred to as “habituation” by Howarth and Hill (Hill & Howarth, 2000). Previous studies noted that increasing exposure time and repeated times, and shortening intervals between exposures could contribute to reduce VIMS after exposures (Kennedy et al., 2000). Training that incorporated seven repeated exposures was shown to effectively reduce VIMS to the same visual stimulation (Zhao, 2017). It was also found that the effect of habituation training could be effective with a one-day to seven-day interval (Howarth & Hodder, 2008). This research introduces a habituation training

with a roll vection-inducing stimulation which has been applied for at least 7 exposures over a at most two-day interval.

Table 1. Meaning of Terms and abbreviations

ABBREVIATIONS	MEANING
VIMS	Visually induced motion sickness
FOV	Field of view
ROLL/PITCH STIMULATION	Visual Stimulation which can induce circular vection along roll/pitch axis
SCT	Sensory conflict theory
PIT	Postural instability theory
MSSQ	Motion sickness susceptibility questionnaire
RESISTANT/SUSCEPTIBLE GROUP	Group of participants who are relatively easier/harder to suffer from visually induced motion sickness
PRE-SSQ/POST-SSQ SCORES	Simulator Sickness Questionnaire scores before/after exposing to a potiental VIMS-provoking condition
ART-ANOVA	Analysis of variance with aligned rank transformed data
RND TEST	Rod and disk test
PLV	Phase locking value
ROLLPLV / PITCHPLV	The PLV indicator measured with roll / pitch stimulation
VIMS-RESISTANCE / VIMS-SUSCPEPTIBILITY INDICATOR	The indicator which is negatively / positively correlated with VIMS scores

COP	Center of pressure
ROT	The condition in which the random-dot pattern rotated coherently along roll axis or pitch axis, experiment condition in EEG recording
RAN	The control condition in which the random-dot pattern rotated randomly, control condition in EEG recording
EO/EC	Condition with eyes open/eyes closed

1.3 Overview of the current research

1.3.1 Objectives and research gaps

(O1) To source more accurate predictors for VIMS susceptibility

This research requires a portable indicator for VIMS susceptibility in order to measure it before VIMS appears. Suitable indicators would be a VIMSS-biographical-questionnaire indicator, EEG indicators, posture indicators, or an RND test indicator.

(O2) To investigate the effect of habituation training on VIMS susceptibility

A further aim is to understand the changes after the habituation training in both neurological activity and behavioral response, and if these changes are transferable for other visual stimulation.

(O3) To explore the neurophysiological foundation of VIMS susceptibility

Although there were a few studies on neural mechanism of VIMS susceptibly, there has been little investigation into validating the findings with different VIMS-provoking visual stimulations and with the change of VIMS susceptibility with habituation training.

1.3.2 Sub-studies and hypotheses

For the first part, ***Study One***, hypotheses related to the fundamental framework of this research will be initially tested.

(H1.1) Two **visual stimulations** used in current research **are VIMS-provoking**, that is, participants will experience a range of VIMS symptoms after watching them for approximately 20 minutes.

(H1.2) **VIMS susceptibility exists.** When watching VIMS-provoking stimulations, participants may demonstrate various VIMS severity levels. Those people with little discomfort may have resistance to VIMS, and they are referred to as the resistant group. Participants who suffer from more severe symptoms after exposure are referred to as the susceptible group. VIMS susceptibility is a consistent construct within an individual; this can be supported that the VIMS subjective ratings to both visual stimulations are correlated with each other (H1.2a). Other evidence includes that VIMS to two stimulations can be predicted with questionnaire like MSSQ and VIMSSQ-short (H1.2b).

(H1.3) **Habituation training can reduce VIMS susceptibility**. The susceptible group may be less sensitive to VIMS stimulations, which means VIMS to the roll stimulation should be lower after training (H1.3a). For those who were successfully trained to be resistant, the VIMS severity to pitch stimulation should also be lower after the training with roll stimulation, which showed there is an **inter-stimulation effect of habituation** (H1.3b).

Study Two focused on testing hypotheses on the mechanism of VIMS susceptibility explained by Sensory Conflict Theory and reciprocal inhibition in visual-vestibular interaction with EEG activity collected during processing visual motion stimulations.

(H2.1) With regards to **sensory conflict**, **susceptible** individuals should display a **stronger** neural response to sensory conflict; **resistant** individuals should display a **lower** neural response to sensory conflict (H2.1a). The indicators for neural response to sensory conflict are supposed to be positively correlated with their VIMS severity (H2.1b).

(H2.2) With regards to **neural coordination** to relieve the sensory conflict, **resistant** individuals should display **stronger** neural coordination between vestibular and visual regions to process the visual information inducing sensory conflict; the neural coordination of **susceptible** individuals should be **lower** (H2.2a)**.** The indicators for neural coordination are supposed to be negatively correlated with their VIMS severity (H2.2b).

(H2.3) **VIMS severity** could be predicted using the difference between the sensory conflict induced by visual stimulations and the neural coordination to relieve the sensory conflict.

Study Three focused on testing hypotheses on the mechanism of VIMS susceptibility explained by the Postural instability Theory with the center of pressure data collected with stance gesture, in behavioral tests with two stimulations, before, during and after habituation training with roll visual stimulations.

(H3.1) Two groups of participants could demonstrate different posture stability development both during and after watching various stimulations. The susceptible group could be more unstable compared to those in the resistant group.

(H3.2) With training sessions progressing, there would be an improvement in posture instability after the completion.

(H3.3) Among all the participants, the improvement of posture stability might be correlated with the reduced VIMS susceptibility, so that it could be larger in susceptible group than resistant group.

Study four focused on those hypotheses explaining how habituation training affected VIMS susceptibility by comparing pre-training and post-training EEG activity collected during the process of visual motion stimulations.

(H4.1) **After the training** with roll stimulation, participants could have **less response to sensory conflict**, especially for those who were susceptible before, measured with roll stimulation (H4.1a) and pitch stimulation (H4.1b).

(H4.2) **After the training** with roll stimulation, participants, especially those in the susceptible group, could display **more neural coordination** to relieve sensory conflict between vestibular and visual regions to both **roll** stimulation (H4.2a) and **pitch** stimulation (H4.2b) **than before**.

(H4.3) Post-training VIMS severity should be able to be predicted with the difference between the sensory conflict induced by visual stimulations and the neural coordination, in order to relieve the sensory conflict.

Study five focused on hypotheses comparing sensory conflict difference between roll and pitch stimulation.

(H5.1) Two stimulations may provoke different VIMS response on the same individual prior to habituation training. This can be explained with EEG indicators that the visual stimulation

inducing more VIMS symptoms which might provoke **stronger sensory conflict** (H5.1a) compared to the one inducing less VIMS, although one individual should have consistent **neural coordination** independent with visual stimulations (H5.1b).

(H5.2) Prior to the habituation training, two stimulations both result in VIMS-related posture instability between resistant and susceptible groups; however, the degree could be not the same. The one inducing more VIMS symptoms may lead to more posture instability, indicating that the post posture instability is related to the sensory conflict from the visual stimulation.

(H5.3) After the habituation training, the two stimulations may induce similar sensory conflict and VIMS response. Therefore, the EEG indicators (H5.3a) and the posture indicators (H5.3b) of VIMS susceptibility could also not be significantly different.

1.4 Thesis outline

Chapter 1 introduces the background, objectives and hypotheses of this research. To make the terms mentioned in hypotheses comprehensive, a section on terminology explanation is provided as well.

Chapter 2 reviews the literature on the related topics of this research, including the theories on VIMS, previous studies on VIMS susceptibility with various measures, and the habituation to VIMS.

Chapter 3 outlines the experimentation with a sequential order. The details of visual stimulations, methods, and apparatuses in pre-training/post-training behavioral tests, pre-training/post-training EEG recording, and the habituation training were also presented.

Chapter 4 reports Study One, which concerns a subjective VIMS response to two stimulations before training, how the VIMS changed during, and VIMS response after training. The grouping of participants into two groups (resistant group and susceptible group) and the rationality is also explained.

Chapter 5 presents Study Two, which investigates the neurological explanation on VIMS susceptibility with EEG activity processing sensory conflict information induced by vection-inducing stimulations.

Chapter 6 documents Study Three, a study on how posture changed along with habituation training. The posture stability of resistant group and susceptible group is compared before and after training to verify the postural instability theory.

Chapter 7 reports Study Four, where the EEG activity processing sensory conflict from vection-inducing stimulations is compared before and after training to investigate effects of habituation. The EEG indicators for VIMS susceptibility found in Chapter 5 are also validated with the post-training results.

Chapter 8 summaries the findings, together with the discussion on limitations and future work Contribution and conclusion of the research work were also summarized.

Chapter 2. Literature Review

2.1 Theories on VIMS

2.1.1 Sensory conflict theory

As a variant of motion sickness, theories on VIMS were affected by those of motion sickness. The most widely accepted hypothesis for motion sickness was the sensory conflict theory or sensory rearrangement theory (Reason, 1968). It proposed that the confliction between motion information from vestibular system, visual system and proprioceptive system; and the confliction between the physically perceived sensory inputs expected and expectation from previous experience can provoke motion sickness. Symptoms like nausea and vomiting can be attributed to the activation of central nervous system.

From an evolutional perspective of Poison Theory, the emetic response is a reflex to protect the organism from toxic substances, with motion sickness as a byproduct (Stratton, 1897). It has been further proposed that sensory conflict or unexpected sensory inputs could trigger neural activation at the reticular formation in the brainstem (Oman, 2012), Therefore, the symptoms of motion sickness could be the consequence of the activation of central nervous system when the brainstem detected sensory conflict.

Due to the emetic response in motion sickness symptoms, a possible function of vestibular system to detect “toxin” was postulated, where the derangement of expected patterns of vestibular and visual information was recognized as the “toxin” (Golding, 2006). The toxin hypothesis can be an extension of sensory conflict theory.

2.1.2 Posture instability theory

Another hypothesis that concentrated on adaption and evolution regarded the motion sickness as a negative reinforcement model to terminate motion involving sensory conflict or postural instability. Here a range of violent symptoms motivated the individual to either terminate the motion or get away from the scenario (Bowins, 2010).

Other hypotheses attempt to to explain motion sickness from the view of performance and reaction during an exposure to stimulations; these include postural instability theory and eye movement hypothesis. Eye movement hypothesis proposed that optokinetic nystagmus (OKN) induced motion sickness (Ebenholtz et al., 1994). Ebenholtz suggested that it was the

extraocular muscle traction during OKN that evoked motion sickness by activating the vagus nerve in the vestibular system, which resulted in motion sickness symptoms.

Research then focused from questioning the explanatory ability of sensory conflict theory to proposing a "postural instability theory" for motion sickness (Riccio & Stoffregen, 1991). This suggested that motion sickness was from ineffective in controlling the posture stability of the body or body segments. From the theory, it can be implied that when lacking the strategies to maintain postural stability, organisms would become sick, which also supports the statement that provocative situations may be always concomitant with the novel demands on the control of action. As an example of provocative situation, it had been tested that the vibration or oscillation in a frequency similar to intrinsic body sway frequency (0.08 to 0.40 Hz) is more harmful to postural stability than those in other frequencies, leading to more uncontrolled movements (Thomas A. Stoffregen & Smart, 1998). After a period of the prolonged instability, motion sickness is supposed to arise. The instability was regarded as a consequence from a particular strategy in a given situation, where there might be other strategies leading to a stable posture. The detection of instability and its correction to minimal uncontrolled movement was regarded vital for animals to adapt to the environment.

The **sensory mismatch theory** and related studies highlighted that the neural activity during the vection process could be linked to VIMS and the connectivity between vestibular and visual regions could be related to the VIMSS. It is possible to find EEG indicator of VIMS and VIMSS from the neural activity during vection. The **posture instability theory** and related studies hinted that the posture instability before watching VIMS-inducing stimulation could be an indicator of VIMS.

2.2 Assessment of VIMS susceptibility

Although VIMS studies have been carried out for some time, most treated individuals as a whole group or classified them with MSSQ, which may not be a suitable benchmark for VIMS susceptibility. The individual difference of susceptibility of VIMS may be related to the susceptibility of motion sickness, which can be estimated by MSSQ (Golding, 2006). However, it was proven that the correlation coefficient between VIMS susceptibility and MS susceptibility was not high enough to avoid exception (Zhao, 2017). Therefore, an area of further research would be to focus on establishing a measure of VIMS susceptibility.

An early requirement to assess the susceptibility to visually induced motion sickness came from the usage of simulators in the US military. Empirically-derived simulator sickness key from Motion Sickness History Questionnaire was used to be a self-testing tool to predict an individual's risk to simulator sickness (Kennedy et al., 1992). However, it was critiqued that the validity to predict a less provocative condition with lower base rate of sickness, such as simulator sickness, was not large enough (.02 or less) (Smith et al., 2001). It was tested on a relatively large population but appeared low and variant correlations (averaged around r = 0.45) with the objective measures of motion sickness tolerance in previous works (Golding, 1998; 2006). That showed the MSSQ cannot always accurately predict the susceptibility of motion sickness. The bias might be more unpredictable when it was applied to VIMS. From a study with a reference from the subjective report survey, Motion Sickness Susceptibility Survey (MSSS, So et al., 1999), the coefficient of determination between MSSQ score and VIMS susceptibility was about 0.65 and the nausea rating was linearly correlated with MSSQ ($R^2 = 0.32$, p = 0.014) (Zhao, 2017). A more accurate measure to evaluate the VIMS susceptibility is required.

2.3 VIMS and neural activity

2.3.1 Sensory conflict of vection and related neural studies

A visual stimulus with motion cues with an adequate display condition, such as a moving optic flow pattern displayed in a large field of view, will elicit an illusion of self-motion, which is termed as Vection firstly by Tschermak (1931) (Dichgans & Brandt, 1978). As usual, when moving visual information flows in, neurons in visual cortex sensitive to direction and speed will response to recognize the object motion cues, finally forming a visual sensation to the object motion. However, with the same visual stimulus, individuals sometimes can report a definite sensation of self-motion. Brain responses to a visual stimulation with motion cues mainly include the activation in primary visual cortex and MT+/V5 area (Napadow et al., 2013). This vection illusion is supposed to be a consequence of multiple sensory integration including the visual system, medial superior temporal (MST), cingulate sulcus visual area (CSv) (Kirollos et al., 2017) and many other multisensory areas involved. A number of studies on brain activities have been conducted with various visual stimulations.

A great deal of previous research on vection compared the brain activity during moving visual condition and that during stable or partial moving visual condition as the control condition

(Kovács et al., 2008; Palmisano et al., 2016). During the experiment phase, the participants could report different vection experience from a rage of visual stimulations, and it was noted that significant differences in brain activity between vection status and non-vection status could be observed. However, the brain activity would also be different due to the difference in visual stimulations, where the confounding effect may pollute the previous results. A solution to this problem could be to use the same visual stimulation during the experiment and compare the brain signal during vection with that in the period without vection, in which the classification of vection period and non-vection period is required. As the visual stimulus in vection and that in non-vection states are completely the same, the different activity from vection sensation seems not as obvious as that between control conditions.

It has been found that a subset of motion-sensitive brain areas, including V1, V3/V3a, V4 and MT/V5 areas, had significantly lower activity in vection compared with object-motion sensation, and parieto-insular vestibular cortex (PIVC) had significant larger deactivation in vection with a rotational windmill-pattern disk as the visual stimulus. In addition, a region close to the cerebellar nodulus was more active in vection which may correspond to the gain increase of torsional optokinetic nystagmus during vection (Kleinschmidt et al., 2002).

2.3.1.1 EEG components and characteristic related to sensory conflict

EEG studies on vection combined with visual or cognitive task have indicated some components of VEP and characteristics in frequency domain may play vital role in the specific neural activities. P300 of visual stimuli in the passive task, where an intentional discrimination between the two kinds of stimuli is not required, is smaller than that in active task (Bennington & Polich, 1999). An experiment with moving altered black-and-white vertical stripes found a stationary pattern in the center with a moving peripheral would lead to a higher vection rating, where the occipital N2 was largest among the conditions (Keshavarz & Berti, 2014). Note that this current research is more focused on the neural activities in pure vection. One most related work was Thilo's experiment, which asked the subjects to report the spontaneous alternations between self-motion and object-motion under a consistent visual stimulus with a flipping checkerboard surrounded by a rotating background. A reduced N70 amplitude was observed when participants perceived self-motion (in contrast with perceiving object motion), which was explained as that early visual cortex deactivates during the self-motion illusion elicited by visual flow (Thilo et al., 2003). With a checkboard stimulus, the dipole locations of N75 and P100 were revealed to be respectively correlated with a positive

BOLD activation and a negative BOLD activation in primary visual cortex (Whittingstall, 2005). Nevertheless, they only applied three occipital electrodes channels to acquire the signal for processing, which may fail to do pre-processing involving ICA with signal from the whole brain to reduce artifacts. Furthermore, the frequency and the synchronization properties distinctively in vection sensation have not been revealed. Although there was a study on the event-related spectral perturbation (ERSP) data in vection stimulus and scrambled control condition suggesting greater event-related desynchronization in beta and gamma bands for vection. Because of the different visual stimuli in comparison, the inconsistency cannot be clearly decided to be from vection.

2.3.2 VIMS susceptibility individual difference and related neural studies

Coherent brain activities among different regions have been proven to mediate the individual difference in sensation and cognition (Miyazaki et al., 2015; Napadow et al., 2013; Y. Wei et al., 2019; Wolff et al., 2019). Under the exposure of a motion visual stimulation, some people may suffer from severe motion sickness symptoms, like dizziness, nystagmus and even nausea. Based on nausea symptom, the microstructural difference, lower mean diffusivity on IFOF (inferior fronto-occipital fasciculus), was found in susceptible individuals compared to those resistant with diffusion tensor imaging (Napadow et al., 2013). Furthermore, the functional experiment revealed that the connectivity between MT+/V5 area to anterior insula and mid-cingulate was increased from the baseline to peak nausea status in susceptible individuals (Toschi et al., 2017). Besides, the connectivity decreasing between left and right visual cortex (MT area and primary visual cortex) was also detected in susceptible people under VIMS-provoking stimulus (Miyazaki et al., 2015; Toschi et al., 2017). Nevertheless, those measurements focused on the brain activity difference with and without significant nausea in those susceptive individuals, leaving a gap from visual information processing to the nausea provocation unconsidered. As nausea was induced in these studies, the different activities in early stage between two groups of participants were confounded with the brain activities related to nausea.

By including a stage of nausea, there would also be many extraordinary cortical areas involved that respond to brain-gut interaction involved. Therefore, this proposed experiment is design to focus on the early stage in motion visual stimulation processing, and examining whether there are different activities in the early stage among individuals with different VIMS

susceptibility. Due to the subtlety of brain activity within a supposed extremely short period, EEG is adopted as the measurement tool.

2.3.2.1 EEG studies on individual difference in VIMS susceptibility

There were few EEG studies on the individual difference in sickness susceptibility, much less with phase coherence of EEG signals. One exception was Wei's work published in 2019, which focused on the individual difference motion sickness susceptibility. By recording EEG signals when participants being exposed to short periods of roll rotating dots pattern, they analyzed phase locking values between EEG signals from different channels to quantify the connectivity between cortical regions during respective visual information processing. Higher global connectivity with right central region (C4) were found in resistant group than susceptible group before vection. The result supported that the cortical coordination indicated by PLV could be a valid indicator of VIMS susceptibility during vection perception.

Inspired by Wei's work, PLV is adopted in the current research. Nevertheless, there are four major differences between the current research and Wei's work: (1) the definition and measurement of susceptibility; (2) the creation of different levels of the susceptibility (IV); (3) the design of experiment (DV); (4) another type of visual stimulation was introduced in current research to validate the finding. First, as for the definition and measurement of susceptibility, Wei's work used MSSQ scores to measure the susceptibility motion sickness as an estimation of participants' VIMS susceptibilities; while the VIMS susceptibilities of all participants were measured with 20-minute exposures to two types of VIMS-provoking stimulation in current research. Second, there were two levels of susceptibilities (high and low) from different participants in Wei's work; in current research, besides the intrinsic different susceptibilities among participants, a habituation training was also utilized to manipulate the VIMS susceptibility. As a result, for some susceptible participants, there were two levels of VIMS susceptibility: susceptible level and trained-resistant level. Third, in Wei's experiment design, EEG signals collected with coherence rotation stimulation (experiment condition) and those collected with random rotation stimulation (control condition) were compared separately for resistant group and susceptible group; while in current research, direct comparisons between different groups have been adopted to explore the possibility of prediction among individuals. Furthermore, only roll rotation dots pattern was used as the experiment condition in Wei's work; in current research, another pitch rotation dots pattern has been adopted in parallel to validate the findings from roll stimulation.

2.4 VIMS susceptibility and postural stability

2.4.1.1 Qualification of Postural Stability

Postural stability had been measured in various methods, among which the most common approach is recording the center of pressure of feet when standing upright. One study with stereoscope 3D display (45 min exposure) recorded a measurement on postural stability to indicate VIMS, with a Wii balance board. The COP in 1 minute standing still condition with eyes closed and feet together was recorded. The area, spatial variability and velocity variability of CoP were analyzed to present the postural stability, but in later analysis only marginally significant main effects (before/after stimuli exposure) were found in eclipse area and spatial variability of CoP and the difference due to conditions was not significant (Hwang et al., 2017). The failure indicated the postural stability may be related to VIMS, but not every parameter from CoP can reflect the subtle difference in VIMS from different display conditions.

Another metrics except CoP was acquiring X and Y coordinates by attaching a Velcro strap on the center of the subjects' backs with the sensor of Polhemus Fastrak. To reflect the postural sway, sample entropy and normalized path length was calculated, and the elliptical area and path length were used to indicate the magnitude of postural sway (Kinsella et al., 2017).

2.4.1.2 Postural instability to predict VIMS

It was found that individuals with higher susceptibility appeared to have significant postural instability from a roll visual stimuli (0.1-0.4 Hz) displayed by a FMD (Yokota et al., 2005b). The real-time postural instability was found to be able to predict the VIMS (Smart et al., 2002). After 10-min exposure to a VR rollercoaster, pre-post balance ability was assessed using the surface area (in cm^2) of the mass center's movements. The surface area indicating postural instability appeared increased after exposure in static standing condition with eyes closed (51.2 s). In a dynamic roll condition (25.6 s), the mean surface area decreased after exposure with eyes opened (Hartnagel et al., 2017). Another experiment involved a walking on the floor task with participants' eyes closed showed no significant difference. In an experiment where participants were exposed to video clips with first person shooter game motion. Although the VIMS scores during and after exposure were significantly higher compared with still snapshots at the baseline, the postural instability components increased in both still images condition and motion condition (Lubeck et al., 2015). It suggested those components were not sensitive enough to classify VIMS intensity in their different two visual conditions.

2.5 VIMS susceptibility and visual dependency

Visual dependency refers to the reliance on visual input in determining spatial orientation. The judgement of spatial orientation depends on the integration of visual, vestibular and somatosensory inputs. Higher visual dependency has been found in vestibular impaired patients (Hafstrom et al., 2007) and related with persistent vestibular symptoms (poor recovery) after acute vestibular neuritis (Cousins et al., 2014). Those who had chemotherapy in childhood could also have elevated visual dependency when being adult (Einarsson et al., 2018). The measurement of visual dependency can be conducted with Rod and Frame test and Rod and Disk test, with or without physical body tilt. In a Rod and Fame test, a participant in dark is instructed to position a lit rod to the perceived horizontal or vertical orientation with or without a tilted frame. Those who judge the orientation depending more on visual information would have more bias in the rod position. For the Rod and Disk test, the frame in peripheral field of view is replaced with a rotating disk with dots. As a measurement of visual dependency to investigate the effect of habituation on participants' visual-vestibular interaction, a Rod and Disk test (RND test) was used in the research.

Chapter 3. Introduction to Experiment: VIMS susceptibility and habituation training

3.1 Procedure of Experiment

This research work includes two major linked parts: (i) investigating physiological indicators for the susceptibility to VIMS; (ii) studying the effects of habituation training with one kind VIMS-provoking stimulation. As indicated by the previous literature, this research focused on the brain activity during the processing of sensory confliction cues and behavioral modality like posture stability and visual dependence.

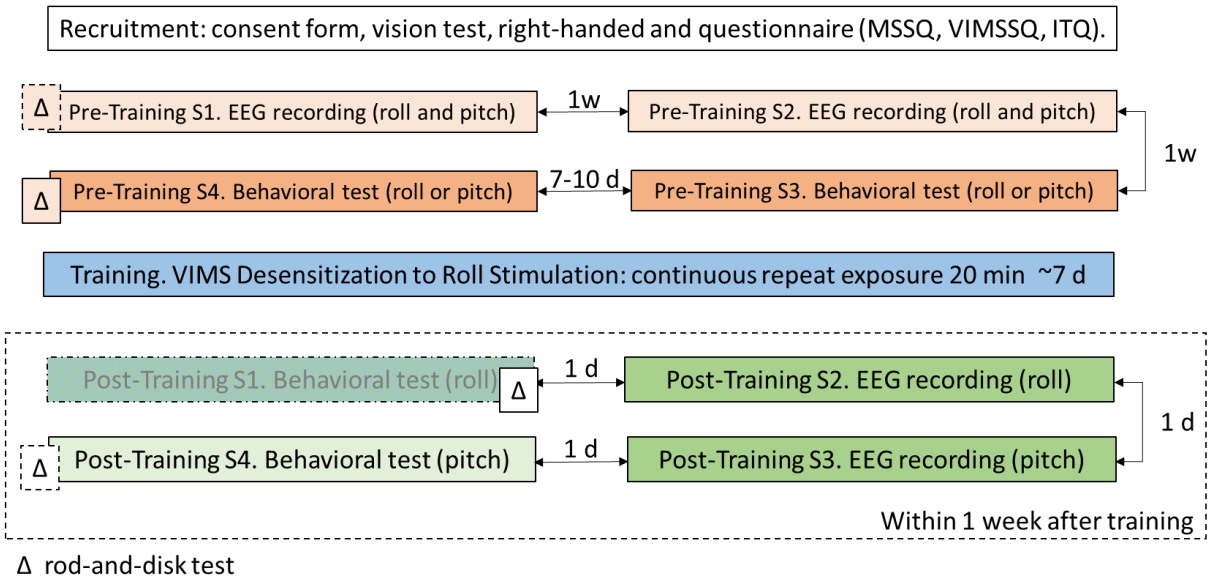


Figure 1. The Flowchart of Experiment Procedure

The research is based on a wholistic experiment (as illustrated in Figure *1*). Chapter 4 to Chapter 7 concentrate on different aspects of the experiment and report corresponding parts of the experimental data. In addition, there are repeated experiment modules before and after the training, in which the procedures and methods were the same. To keep the coherence and to avoid redundant description as possible, this chapter starts with the procedure of experiment and then introduces detailed information of the experiment, like the participants involved in the present research and methods of each experiment module. There are three stages of experiments: (1) baseline VIMS susceptibility measurement (pre-training stage), (2) habituation training (training stage) and (3) re-measurement of VIMS susceptibility (post-training stage). In both pre-training stage and post-training stage, besides that the actual VIMS severity was measured,

the EEG signals during vection processing, posture stability and rod-and-disk test were recorded as well to explore VIMS susceptibility indicators.

As it illustrated in Figure 1, the recruitment of participants was conducted together with a questionnaire survey on their susceptibility to motion sickness, VIMS, and immersion. Then the participants were invited to laboratory where a vision test and baseline rod-and-disk test were conducted.

In pre-training stage, to avoid the habituation effect of the exposure to visual stimulation, the first two experiment sessions were EEG recording with roll stimulation and pitch stimulation. To collect EEG signals with two types of vection-inducing stimulations, it was estimated that this would take approximately six hours with an entire experiment session, which might lead to large variation of the connection between EEG electrodes and the human scalp and fatigue of participants. Therefore, the EEG signal recording was separated into two days with a one-week interval, which was to keep the second session away from the potential habituation effect of the first session.

Then, two behavioral tests were conducted to measure the VIMS susceptibility to roll-rotation and pitch-rotation visual stimulation. The VIMS after a 20-minute observation was measured with Simulator Sickness Questionnaire (Kennedy et al., 1993), and the vection and nausea intensity were rated every five minutes with a vection score rated from 0 to 100 and a 7-point nausea rating scale (adapted from Golding & Kerguelen, 1992). Furthermore, each behavioral test included posture stability measurements before, during and after participants watching the visual stimulation. The presentation order of roll-rotation stimulation and pitch-rotation stimulation were balanced in participants group. Two behavioral tests were separated with at least seven days to avoid the effect of exposure to the previous visual stimulation.

On the first day of training, participants did a second rod-and-disk test as a record for their visual dependency at that time. In the training stage, participants watched a roll-rotation visual stimulation for a continuous 20 minutes over a period of seven or more days until the maximal nausea scores during watching reduced to 2 or below for two adjacent days. In the last day, they did a third rod-and-disk test as a record for their visual dependency after habituation training.

On the completion of training, the post-training stage experiment started and finished within a week. A 20-minute re-test with roll-rotation stimulation was needed to measure their VIMS and posture stability after training, which was conducted on the last day of habituation training.

Right after those days in which they continuously exposure to roll-rotation stimulation, the post-training EEG signal collection was conducted for roll and pitch stimulation. At the final session, participants finished a post-training pitch stimulation re-test with the same procedure as pre-training pitch behavioral test. The experiment ended with a last rod-and-disk test.

3.2 Participants and Questionnaire Survey

Participants were students in Hong Kong University of Science and Technology. Thirty-four participants (aged at 23.6±3.3, 17 female) took part in the pre-training stage experiment, including pre-training VIMS measurement and postural tests, EEG recording experiment and rod-and-disk test. Thirty (aged at 23.8±3.3, 16 female) of them participated the training, in whom one participant terminated the training before the completion. Twenty-nine (aged at 23.8 ±3.4, 15 female) participants finished the post-training stage experiment after a complete training session which lasted for at least 7 days. The detailed data source of each experiment module will be described in corresponding chapter.

After being informed about the experiment procedure and risk of being sick, all participants provided written consent. They were advised that they could leave the experiment at any time without giving reason. Their participation was compensated with 50 HKD/hour. The experiment conformed to the requirement of the University Research Ethic Committee and had been approved by the Human Participants Research Panel of the Hong Kong University of Science and Technology.

Participants in the research are right-handed and had been verified to possess at least 20/20 visual acuity (Stereo Optical CO. Inc. Vision Tester) with glasses or naked eyes. None of them had heart disease or neurological diseases including vestibular injury. They finished an online survey (APPENDIX-1) including a Motion Sickness Susceptibility Questionnaire (MSSQ, Golding, 1998), a 17-item version of 19-item Immersive Tendency Questionnaire with two improper items excluded (ITQ, Witmer & Singer, 1998), and the Visually Induced Motion Sickness Susceptibility Questionnaire – Short Version (VIMSSQ-short, Golding, 2019) before the experiment.

Compared with the original sample of 257 university students in (Golding, 2006b), nearly 2/3 of current participants had an MSSQ score higher than 70% people and nearly 1/3 of them had an MSSQ score lower than 50% people. As suggested by Prof. Golding, the options “never”, “rarely”, “sometimes”, “often” of each VIMSSQ-short item were assigned with scores 0, 1, 2,

3 and the VIMSSQ-short scores were the sum of five symptom items and one avoidance item. There was a high positive correlation between VIMSSQ-short scores and MSSQ scores (r=.875, p<0.001). The 17-item ITQ scores were calculated by summing up the ratings from all 7-point items as Witmer and Singer did. A higher 17-item ITQ score indicated that the respondent had a higher tendency to be involved or immersed.

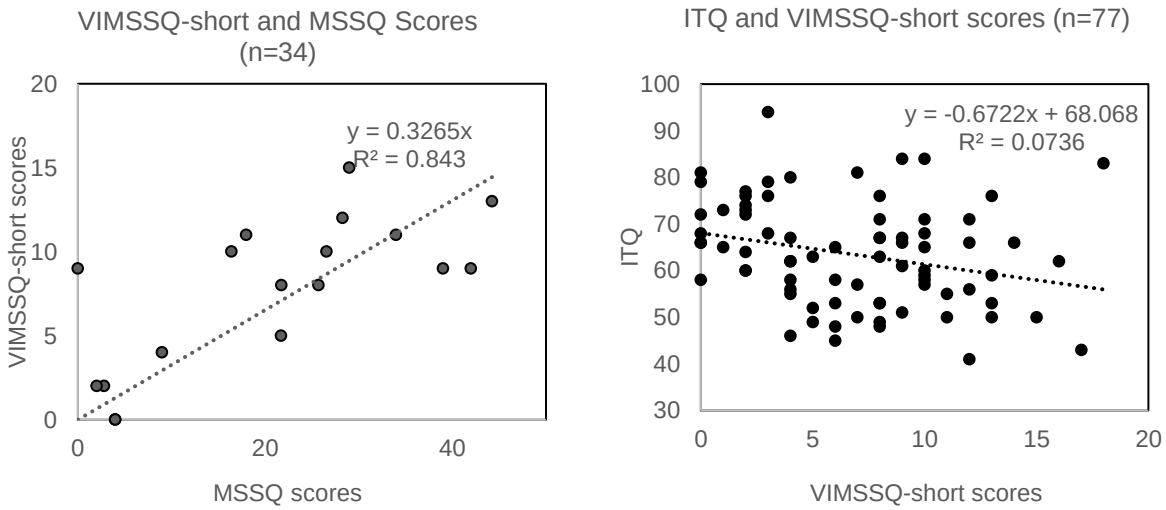


Figure 2. Correlation between VIMSSQ-short scores, VIMSSQ and ITQ scores

Except for three questionnaires mentioned above, the online survey also asked participants for information about gender, age, preference to extreme sports and experience of migraines. At the end of this research, approximately one hundred responses were received with 76 completed. With this larger sample came improved understanding on the relationship among VIMSSQ score, MSSQ scores and ITQ. With the 34 survey respondents who participated the following experiment, there seemed no correlation between ITQ scores with VIMS or motion sickness susceptibility. As for all 77 respondents who completed ITQ when filling in the survey, revised-ITQ scores had weak and negative correlation with VIMSSQ-short scores (r=.271, p=0.017) and MSSQ scores (r=.251, p=0.027). With all 82 respondents who completed VIMSSQ-short and MSSQ in the survey, the two scores were still positively correlated (r=.885, p<0.001). The genders difference was also analyzed on the results of the survey. With 76 respondents who responded their genders, it was found that the occurrence of migraine experience was higher in females than males (chi-squared test, p=0.004): 19/43 in females and 10/33 in males had or might have experienced migraine. The preference of extreme sports was also more frequently reported in female (16/43) than male (4/33) (chi-squared test, p=0.007). None of the respondents had experience of migraines, the preference for extremes sports or the gender

separated respondents into two groups different in VIMS susceptibility or motion sickness susceptibility. However, interestingly, male participants had higher ITQ scores than female participants (two sample t-test, p=0.002).

3.3 Behavioral test: VIMS, vection and posture measurement

In pre-training and post-training behavioral tests, all participants were asked to report their VIMS severity and vection when watching the visual motion stimulation. A complete behavioral test session contained a 20-minutes display of one type of stimulation. Though the planned duration of visual stimulation was 20 minutes, participants were informed that they could terminate the exposure by reporting to the stand-by experimenter whenever they felt moderate nausea and could not continue to watch. At that time, the visual stimulation would stop, and that one behavioral test would finish.

3.3.1 Visual stimulation and apparatus

The random-dot pattern was the same for two stimulations, generated with Psychophysics Toolbox (Psychtoolbox-3) in Matlab (R2015b, academic license). There were about 1472 gray dots (luminance = 4.10 cd/m^2) in the black background (luminance = 0.01 cd/m^2), every frame, with diameter ranging from 5 to 14 pixels (3.87-10.84 mm). Two types of visual motion stimulations, a roll-rotation random-dot pattern and a pitch-rotation random-dot, pattern were displayed on a 65-inch OLED screen (1448 mm × 836 mm, FOV: 114.17° × 79.79°, Sony BRAVIA OLED TV) in behavioral tests. Participants adopted a stance observation gesture at 50 cm in front of the screen. In the center of the screen, there was a red fixation point (luminance = 6.24 cd/m^2, d = 5.42mm, FOV = 0.62°), and a black round disk area (luminance = 0.01 cd/m^2, d = 10.84 cm, FOV = 12.42°) without any other dots on it to maintain a stable fixation. The height of the screen was controlled with a height-adjustable table to be at the same level of the participant's eyes.

The difference between two stimulations was the pattern's motion. In behavioral tests with the roll stimulation, the random-dot pattern on the screen rotated about the axis going through the fixation point along the straight-ahead direction of participants. All dots had a same anti-clockwise angular speed of 15 deg/second around the central fixation point. In behavioral tests with the pitch stimulation, the random-dot pattern on the screen rotated about the axis parallel with the horizontal long edge of the screen at the eye fixation level of participants. The rotation speed of a dot on the screen decreased with its vertical distance from the eye fixation level to

simulate a drum interior pattern rotating around pitch-axis. The linear speed on eye fixation level was about 10.6 deg/second upward.

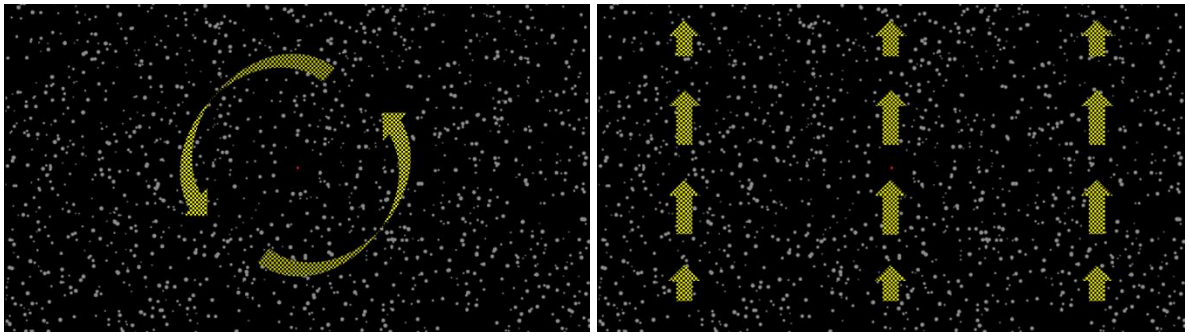


Figure 3. Visual stimulations: roll stimulation and pitch stimulation

3.3.2 Questionnaire and Scales

To measure the VIMS response of participants to visual stimulations, before and after the 20-minute exposure, Simulator Sickness Questionnaires were twice completed (Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness, 1993). The SSQ scores before watching (pre-SSQ scores) and the SSQ scores after watching (post-SSQ scores) were calculated with the same method suggested by the Kennedy (1993).

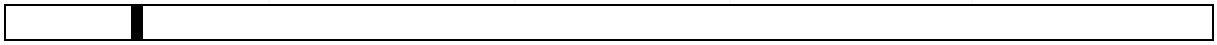
During the observation, at every 5 minutes, participants were asked to report their nausea scores with a 7-point Nausea scale (Golding & Kerguelen, 1992) and to rate their vection intensity with a number from 0 to 100%. After watching, they would be asked to check their reports again to confirm, when they would see two scales in the following formats. The vection scale is a visual scale with which participant could translate the bar in the bottom to the number they wanted to report and saw the number.

Table 2. Definition of 7-point nausea rating (Adapted from Golding and Kerguelen, 1992)

Nausea Score	**Definition**
1	No symptoms
2	Any unpleasant symptoms, however slight
3	Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea
4	Mild nausea
5	Mild to moderate nausea
6	Moderate nausea but can continue
7	Moderate nausea, want to stop

Table 3. Visual scale of Perception of motion

You feel like you are stationary, and it is the image which appears to be moving only.	You feel like you are moving a bit, but the image is moving more.	You feel like you are moving at the same speed as the image.	You feel like you are moving a lot and the image is moving a bit.	You feel like you are moving, and the image appears stationary.
0	25	50	75	100



3.3.3 Posture stability measurement

In behavioral tests, posture stability was measured. Spontaneous posture sway with eyes open and eyes closed was measured before and after the 20-minute observation. During the observation period, the posture sway was continuously recording as participants kept a stationary stance gesture until the end or they experienced an imbalance in their posture.

As a low-cost and portable tool to measure the posture data, a Nintendo Wii Balance Board was used to record the center of pressure (COP) when participants standing on it. There were four sensors in its four corners, from which the COP coordinators on x and y axis could be calculated and collected. The COP coordinator signal of Wii Balance Board was sent to a Raspberry Pi (module 3) via Bluetooth connection. The COP data were calculated and recorded with a python script on the Raspberry Pi. The raw COP data was not collected at a regular sampling rate. Thus, a resampling method verified to produce similar results to laboratory-grade force plate (Audiffren & Contal, 2016), Sliding Window Average with Relevance Interval Interpolation (SWARII), was adopted to resample the COP data to a frequency of 25 Hz.

3.4 EEG signal recording

To search for the neurological indicators, EEG signal was recorded during the display of vection-inducing visual stimulations. The roll and pitch stimulations in behavioral tests (subsection 3.3.1) were embedded in the visual stimulations used in the EEG recording to induce roll and pitch circular vection for a short time (3s). The vection duration was controlled to be short at each trial to avoid the VIMS which could be provoked by a longer exposure.

3.4.1 Visual stimulation

The two types of visual stimulations in EEG experiment both started with a 3-second black condition (c, Figure *4*), followed by a coherently rotating random-dot pattern (ROT) condition

(d, Figure *4*), the experiment condition to induce self-motion illusion (vection) and sensory conflict. Participants were instructed to press button when they felt the self-motion illusion. There was a training to familiarize them to report vection by pressing button with three to five trials (one trial: the presented parts a. to e. in Figure *4*). After the button was pressed, the coherently rotating stimulation condition would be displayed for another 3 seconds (VEC condition, e, Figure *4*), during which the participants were still in vection. Then, a 3-second black condition appeared again (a, Figure *4*), followed by a 3-second randomly moving random-dot pattern (RAN condition, b, Figure *4*). The duration of each trial depended on the vection latency of each participant. There were about 150-180 trials collected for each participant, which were separated into several experiment blocks. Between every two blocks, there was sufficient time for participants to rest to minimize any nausea.

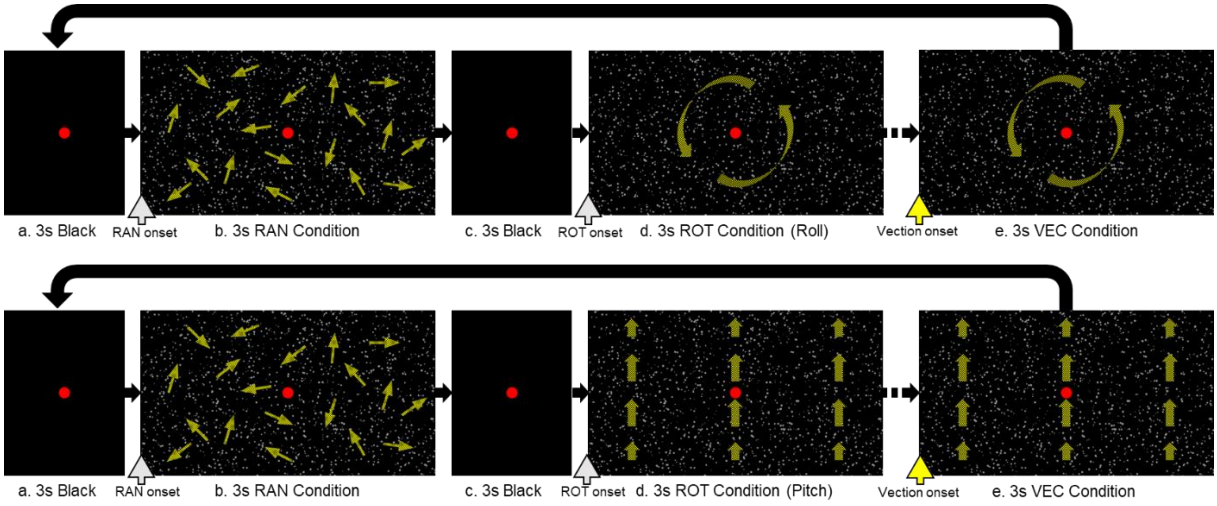


Figure 4. Visual stimulations used in EEG signal recording

3.4.2 Apparatus

The visual stimulations were displayed with the same 65-inch OLED screen (size: 1448 mm×836 mm, FOV: 114.17°×79.79°, Sony BRAVIA OLED TV) in behavioral tests. The screen was connected to a Windows 7 desktop on which the Matlab with Psychophysics Toolbox (Psychtoolbox-3) was running to synchronize visual stimulation and the trigger sent to EEG signal. The EEG signal was recorded with a NuAmps amplifier (DC-coupled, 22 bits, monpolar) connected to 32-channel Ag/AgCl sintered electrodes (Quick-Cap, Compumedics Neuroscan) placed according to the international 10-10 system referenced to linked mastoid electrodes. Impedances between all channels and the ground channel were reduced below 10 kΩ. Raw data were digitized at a sampling rate of 1000 Hz and a bandwidth of DC-260 Hz. The

experiment was conducted in an acoustic booth (Industrial Acoustic Company Limited), of which a wireframe could provide electromagnetic shielding.

3.4.3 Preprocessing of EEG data

Preprocessing was done with EEGLAB plugin (EEGLAB v2021.0) in MATLAB. The raw EEG signal was filtered with a 1.6-47 Hz bandpass finite impulse response filter and a 50 Hz notch filter to eliminate the interference of power line frequency. Then, EEG signal epochs were extracted from ROT, RAN and VEC conditions, starting from 2 seconds before the onsets to 3 seconds after the onsets. Epochs with artifacts were excluded with ERPLAB plugin in EEGLAB: the moving-window peak-to-peak method (window size: 200 ms, step: 50 ms, threshold: ±100 μV; and window size: 20 ms, step: 50 ms, threshold: ±50 μV) and the extreme amplitudes of epoch method (threshold: ±150 μV). Independent components analysis was applied to these epochs and components with artifacts like blinking and eye movements were removed with ADJUST plugin in EEGLAB (Mognon et al., 2011). To reduce the volume conduction effect, current source density analyses was conducted with the order of spline of 4 (Kayser & Tenke, 2006). Limited to the condition of EEG Caps, there was a few electrodes broken during the signal collection and interpolated with the EEGLAB plugin in the offline preprocessing. With those electrodes excluded, the electrodes F3, F4, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, P7, P3, Pz, P4, P8, O1, Oz, and O2 were involved in following analyses.

3.4.4 Phase synchronization calculation

The instantaneous phase ϕ for each time point in the epoch and each frequency from 2 to 46 Hz was extracted with wavelet analyses ($f/\sigma_f=6$, $\sigma_f = 1/2\pi\sigma_t$, σ_t is the standard deviation of the Gaussian window) (Kawasaki et al., 2014; Lachaux et al., 2000; Y. Wei et al., 2019). Then, the phase synchronization between each pair of electrodes at each time point in the epoch was evaluated with a phase locking value (PLV) (Lachaux et al., 2000; Totah et al., 2013). For a condition with N epochs, the PLV between electrode j and k, at time point t and frequency f can be calculated with their phase $\phi(t)$ as:

$$PLV_{j,k}(f, t) = N^{-1}|\sum e^{i[\phi\_j(t)- \phi\_k(t)]}|$$

The phase synchronization at theta band were calculated by averaging PLV at theta band (4 - 7 Hz). Correspondingly, the phase synchronization at alpha and beta band were calculated by averaging PLV at alpha band (8-12 Hz) and beta band (13-29 Hz). To correct for the bias of

the epoch number N, the phase synchronization indicator was transformed according to Rayleigh's Z value (Totah et al., 2013):

$$PLV_z = N \times PLV^2.$$

3.4.5 Node strength analysis to determine time of interest

With 30 electrodes on the scalp, a synchronization network was made up of these 30 nodes. The node strength of each electrode was defined as the averaged PLV linked to the electrode at certain frequency band. Three networks corresponding to three frequency bands were analyzed in the research. The aim of node strength analysis for each network was to determine the time of interest when the brain activity were the specific response to process the vection-provoking stimulation.

To determine the time of interest, the node strengths during the early display (1.5s) of ROT and RAN conditions were compared. The cluster based permutation test was adopted to cope with the multiple comparison problem via Fieldtrip toolbox (Oostenveld et al., 2010). A cluster was defined with at least two nodes neighbour in the triangulation method. The within-subjects effect was quantified by t-values of each node-time pair. The cluster-level statistics were calculated by taking the sum of the t-values within every cluster and the maximum of the cluster-level statistics significance was chosen. The significance probability of the test was computed with the Monte Carlo method and 2000 times random draws. If the p-value of a cluster is smaller than the critical alpha-level (0.05), the nodes in the time window demonstrated significant different phase synchronization between two conditions.

3.4.6 EEG PLV indicator calculation

With the time window revealed by the cluster based permutation tests, the time of interest was determined for the frequency band. For example, from the analysis on the theta band, the time of interest was found around 200 to 400 ms from the onset of stimulaitn. The PLV indicator of each electrode pair at theta band was calculated by averaging the PLVz (transformed PLV) at theta band at the time window.

The phase synchronization in this research would be represented with the transformed PLV in theta band. There were 30 electrodes and 435 combinations of electrode pairs in total. According to the number of each electrode in 10-20 system, the transformed theta-band phase synchronization would be labelled as PLV001 to PLV435 for short, depending on the

electrode pair. For example, the numbers of FCz and Pz are 10 and 25, and the combination of them is the 240th one, so that the theta-band phase synchronization between FCz and Pz represented by PLV transformed by the number of its epoch would be “PLV240”. For the following abbreviations, the two electrodes which the phase synchronization was calculated from would be explained. The larger a PLV indicator is, the more synchronized activities are between two recording sites.

3.5 Rod and disk test

The rod-and-disk test (RND test) is a measure for visual dependence. The visual stimulation in RND test is a roll rotating random-dot pattern like the Roll stimulation used in current research but displayed on a smaller monitor. The FOV in RND test is restricted with a viewing cone subtending a viewing angle of 39° with an observation distance of 15 cm. There is a white rod in the center on the black background. The rod can be rotated around the center point by participants using the wheel of mouse. In the RND test, the background white dots in peripheral visual field will rotate clockwise or anti-clockwise at an angular speed of 30 ˚/s.

In the RND test of current research, participants were instructed to align the orientation of the rod with their subjective vertical direction when the background dots were rotating. For each rotation direction, the participants would rotate and confirm the rod orientation for five times. Before each time, the initial orientation of the rod was alternatively set at 40˚ and -40˚. Participants were instructed to rotate the orientation of the rod with the wheel of mouse and confirm the final orientation of their subjective vertical with space button. Five final angles between rod and physical vertical were recorded for each rotation direction. The later four rod tilt angles with each of two rotation directions were averaged to get the RND test result.

Figure 5. Rod and Disk Test

The RND tests were conducted four times in total before and after the training. The first RND test was done right after vision test, to record the visual dependency before any exposures to

visual stimulations of the research. The second and third RND tests were conducted right before the first session of training and after the last session of training. The fourth RND tests were conducted after the post-training experiment. The present order of two rotation directions were balance within two RND tests before training and two RND test after training.

3.6 Habituation Study

Repeated exposures to a VIMS-provoking stimulation could reduce the following VIMS response to the stimulation. In the research, the Roll stimulation was used as the repeated stimulation to train participants. The procedure was similar to a behavioral test with Roll stimulation. The training started after the pre-training behavioral tests, EEG recording and RND tests. The training consisted of at least 7 sessions. In each session there was an at most 20-minute exposure to roll stimulation. Participants were free to ask for stop before the ending, no matter when they feel moderate nausea. Before and after the exposure, the pre-SSQ and post-SSQ would be completed based on their feeling at that time, as the procedure in behavioral tests (Subsection 3.3.2). During the exposure, the posture data were recorded with the same apparatus with posture measurement in behavioral tests (Subsection 3.3.3). After every 5 minutes, participants were asked to report vection and nausea scores with same scales in behavioral tests (Subsection 3.3.2). The intervals between every two sessions were controlled to be shorter than two days. Most participants finished the training continuously day by day.

Chapter 4. Study One – Habituation to VIMS Susceptibility induced by Roll-rotation and Pitch-rotation Visual Stimulations

4.1 Introduction

Vection-inducing visual stimulations have been known to induce motion sickness symptoms, which have wildly used to induced motion sickness or nausea safely in research (Brandt et al., 1998; Senqi Hu et al., 1997). Repeated exposures to such a VIMS-inducing stimulation would lead to a reduction of the severity of VIMS to that stimulation (Howarth & Hodder, 2008; Regan, 1995). The phenomenon has been referred to as "habituation" (Hill & Howarth, 2000). Along with the habituation, the hand-eye coordination could be improved, compared with the level impaired by a sensory confliction condition (Biocca & Rolland, 1998). With the popularization of virtual reality technology, the habituation to VIMS induced by a certain visual stimulation can be common in the scenario like VR training. There were some unanswered questions like (i) if the habituation method is efficient to everyone, (ii) how the efficacy of habituation can be, and (iii) if the habituation effect is inter-stimulation transferable. To answer these questions and to form two groups of participants with difference VIMS susceptibility, the following experiment was planned, designed, and conducted.

4.2 Hypotheses

(H1.1) Two **visual stimulations** used in current research **are VIMS-provoking**, that is, participants will experience a range of VIMS symptoms after watching them for approximately 20 minutes.

(H1.2) **VIMS susceptibility exists.** When watching VIMS-provoking stimulations, participants may demonstrate various VIMS severity levels. Those people with little discomfort may have resistance to VIMS, and they are referred to as the resistant group. Participants who suffer from more severe symptoms after exposure are referred to as the susceptible group. VIMS susceptibility is a consistent construct within an individual; this can be supported that the VIMS subjective ratings to both visual stimulations are correlated with each other (H1.2a). Other evidence includes that VIMS to two stimulations can be predicted with questionnaire like MSSQ or VIMSSQ-short (H1.2b).

(H1.3) **Habituation training can reduce VIMS susceptibility**. The susceptible group may be less sensitive to VIMS stimulations after training, which means VIMS to the roll stimulation

should be lower (H1.3a). For those who were successfully trained to be resistant, the VIMS severity to pitch stimulation should also be lower after the training with roll stimulation, which showed there is an **inter-stimulation effect of habituation** (H1.3b).

4.3 Design of Experiment

4.3.1 To verity that two stimulations were VIMS-provoking

Dependent variables: SSQ scores; nausea scores
Factor A-exposure to visual stimulation: before/after; time: 5/10/15/20 min
Factor B- type of visual stimulation: roll stimulation, pitch stimulation

4.3.2 To classify VIMS susceptibility

Dependent variables: SSQ scores; nausea scores
Factor A-exposure to visual stimulation: before/after; time: 5/10/15/20 min
Factor B- VIMS susceptibility: susceptible group, resistant group

4.3.3 To test the effect of habituation training on VIMS susceptibility

Dependent variables: post-SSQ scores, nausea scores; RND test result
Factor A-VIMS susceptibility: susceptible group; resistant group
Factor B- habituation training: pre-training, post-training

4.4 Procedure

The study one consists of behavioral tests in three stages: pre-training, during-training and post-training. Before and after the habituation training, there was two behavioral tests (Subsection 3.3.1 and 3.3.2) with roll stimulation and pitch stimulation respectively, as well as two RND tests (Section 3.5) at the beginning and ending.

During the behavioral tests, pre-SSQ scores, post-SSQ scores and nausea scores were recorded as the metrics for VIMS severity. Vection scores were also recorded together with nausea scores.

4.5 Result

4.5.1 Visual stimulations are sufficient to induce VIMS (H1.1)

Both stimulations induced VIMS after the 20-minute watching in behavioral test before habituation training. During the exposure, the nausea scores increased with time. Roll stimulation induced more severe VIMS than pitch stimulation.

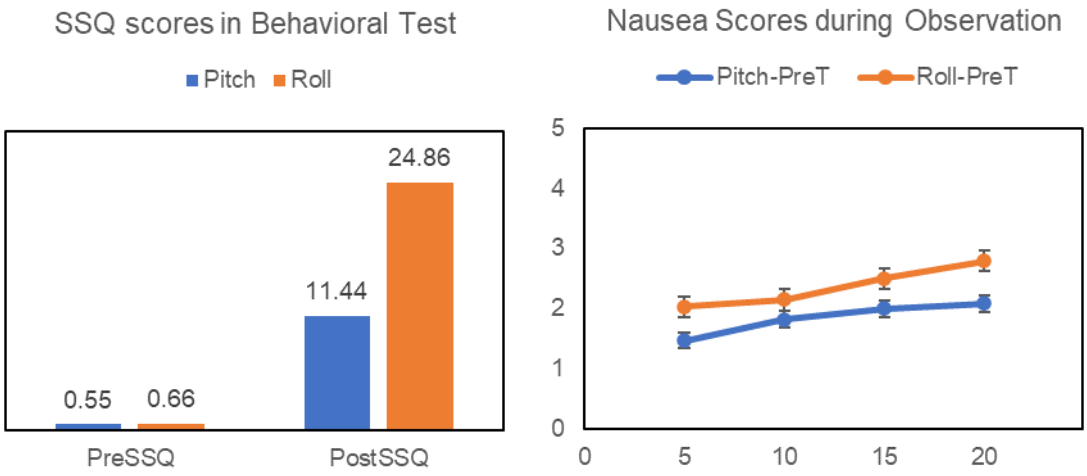


Figure 6. Higher SSQ scores were reported (left) and nausea scores increased along the observation (right) after the 20-minute watching in the pre-training behavioral test

The averaged SSQ scores under roll condition increased to 24.86 (Wilcoxon signed rank test, $p < 0.001$) and that of pitch condition increased to 11.44 (Wilcoxon signed rank test, $p < 0.001$). By non-parametric repeated measures two-way ANOVA with Aligned Rank Transform (ART-ANOVA), the effects of Exposure (pre/post) and Stimulation Type (Roll/Pitch) were both significant on SSQ scores [Stimulation Type: $F(1, 33) = 13.192$, $p < 0.001$; Exposure: $F(1, 33) = 52.322$, $p < 0.001$]. The interaction between Stimulation Type and Exposure was also significant [$F(1, 33) = 13.043$, $p < 0.001$]. Post hoc analysis with Holm adjustment showed that SSQ scores before watching were not found to be different between two stimulations, while SSQ scores after watching increased for both stimulation and higher in Roll stimulation ($p = 0.045$).

Besides, the nauseas scores reported under roll condition were higher than those reported under pitch condition and increased with time. With the two-way ART-ANOVA on Nausea scores (Time: 5min/10min/15min/20min; Stimulation Type: Roll/Pitch), both were significant factors without interaction on nausea scores [Stimulation Type: $F(1, 33) = 15.409$, $p < 0.001$; Time: $F(3, 99) = 5.518$, $p = 0.001$]. Post hoc comparison with Holm adjustment indicated that nausea scores increased significantly after 20 minutes compared with those reported at 5^{th} minute ($p = 0.002$) or at 10^{th} minute ($p = 0.005$).

4.5.2 Evidence for VIMS susceptibility (H1.2)

4.5.2.1 VIMS to both visual stimulations are correlated (H1.2a)

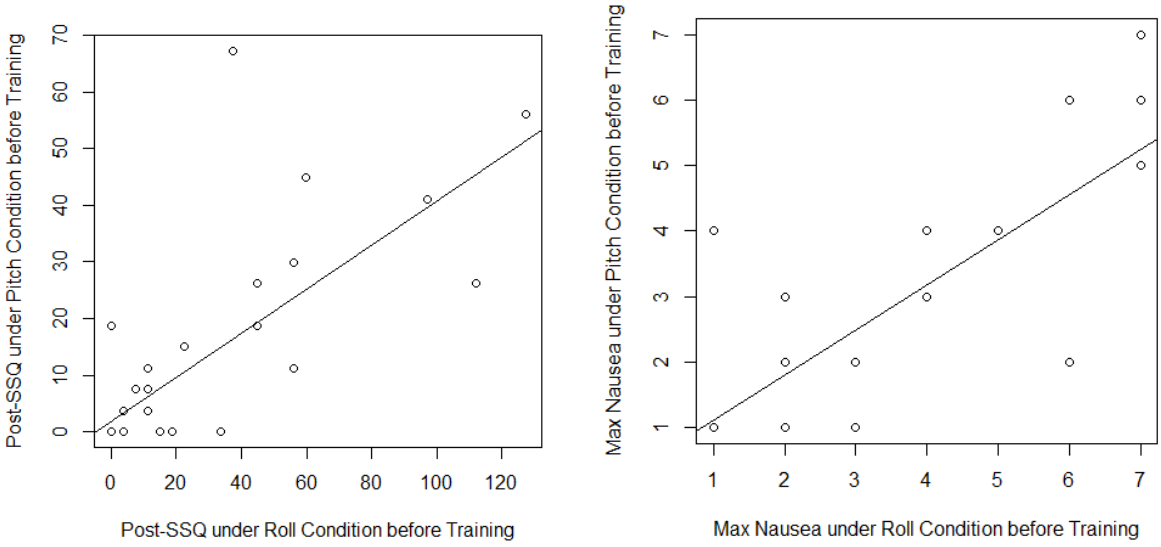


Figure 7. Correlation of VIMS subjective ratings between two stimulation conditions

Spearman's correlation coefficient between Post-SSQ scores under two stimulation conditions was 0.721 ($p < 0.001$) and it was 0.744 between maximal nausea scores under two conditions ($p<0.001$).

4.5.2.2 Predicting VIMS susceptibility with questionnaire (H1.2b)

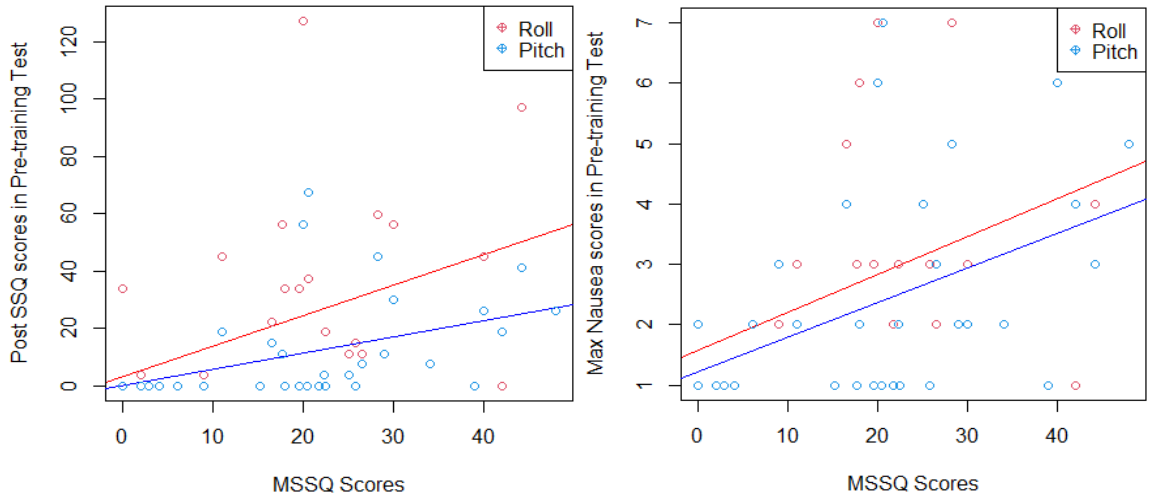


Figure 8. Fit VIMS severity in pre-training behavioral test with MSSQ scores

MSSQ score was a predictor for the post-SSQ scores after the behavioral test with two visual stimulations, although only about 18% of the total variation in post-SSQ scores can be explained (Roll: R-square=0.178, p=0.013; Pitch: R-square=0.177, p=0.013). The VIMSSQ-short score was not a statistically significant predictor for the SSQ scores.

When the VIMS severity was represented by the maximal nausea scores during participants watching stimulations, MSSQ also could explained the variance in nausea scores, while VIMSSQ-short scores could not. For roll stimulation, the linear regression model showed 16.2% variance of maximal nausea scores can be explained with MSSQ scores (R-squared=0.162, p=0.018); for pitch stimulation, it was 19.3% (R-squared=0.193, p=0.009).

4.5.3 VIMS reduced after habituation training (H1.3)

The habituation training was determined to be completed when (1) the maximal nausea scores reported by one participant in two adjacent sessions were both lower than 2, which means "slight discomfort" in the nausea rating scale; and (2) the participants had watched the roll visual stimulation for at least 7 sessions. Most participants met the criteria after a 7-session training after watching the roll stimulation for 8 times, including the one in pre-training behavioral test (n = 19, 10 were Resistant, 9 were Susceptible). Three participants finished a 6-session training after watching the roll stimulation for 7 time with a nausea score of 0 (no discomfort) in the last five sessions (n = 3, 2 were Resistant, 1 was Susceptible). Besides, two participants after a 10-session training and one participant with a 9-session training satisfy the completion criteria, who were all susceptible participants (n = 3). The averaged nauseas scores of resistant group and susceptible group were plotted in Figure *9*. To plot the mean curves, the 6-session/9-session participants were made up to be 7-session/10-session participants, which is reasonable as they did not feel any discomfort during the last five/three sessions, and if they were asked to do one more session, it was very likely to feel no discomfort as before.

With the habituation training, afore-mentioned 25 participants' maximal nausea scores all reduced below to 2 - "slight discomfort". Another 2 participants who suffered from severe VIMS reduced to 3 - "moderate discomfort" or below for two adjective training sessions (s12 and s40). There were 2 participants still felt nausea at the end of training (s2 and s19). These four unsuccessfully trained participants were also demonstrated in Figure *9* with dashed lines. They were very susceptible people, suffered from nausea and even considered stopping in early sessions (a nausea score of 6 or 7 – "moderate nausea can or cannot continue"). Although at

last they did not meet the completion criteria of the habituation training, it could be found their nausea scores at the end of training were relatively lower than they used to be.

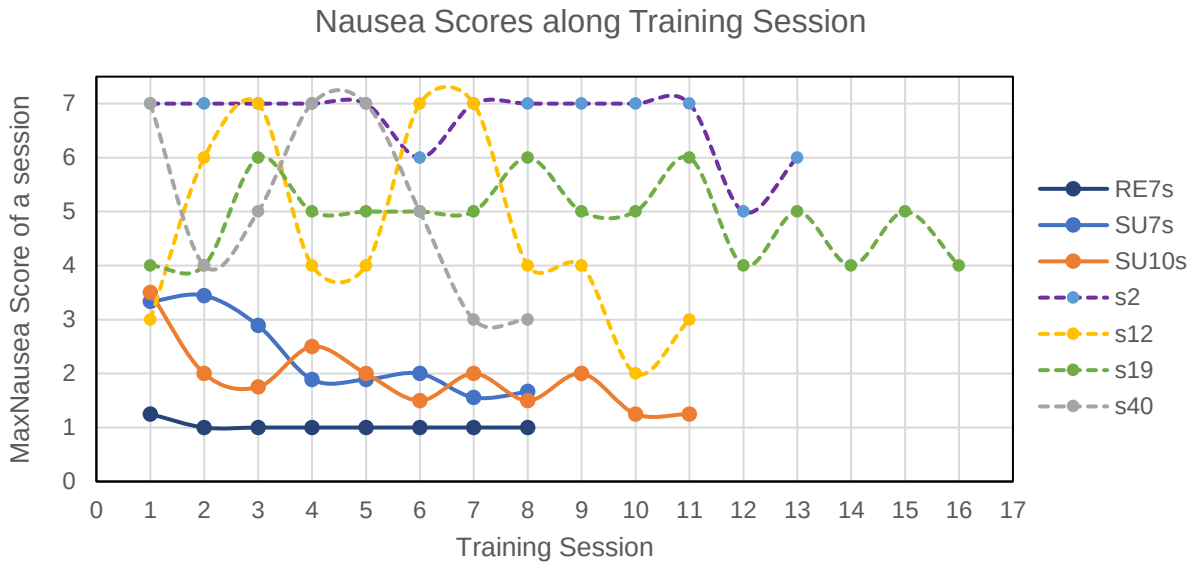


Figure 9. Characteristics of habituation training with roll stimulation

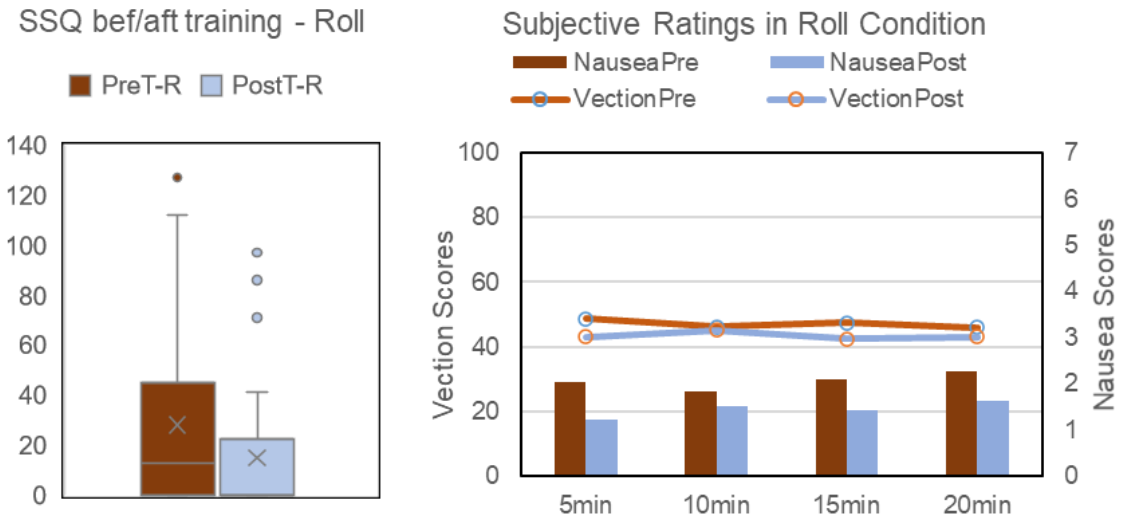


Figure 10. Comparison of SSQ and nausea scores in behavioral tests before and after habituation training under roll condition

As for roll stimulaition, the post-SSQ scores after training reduced significantly after training (Wilcoxon signed rank test, $p < 0.008$). The maximal nausea scores after training were also significantly lower than those before (Wilcoxon signed rank test, $p < 0.001$) (H1.3a).

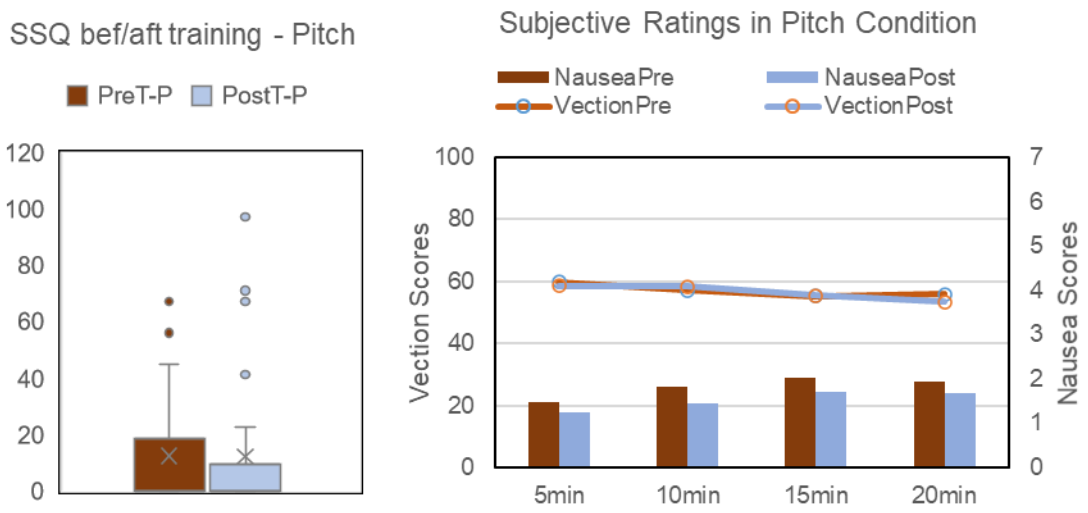


Figure 11. Comparison of SSQ and nausea scores in behavioral tests before and after habituation training under pitch condition

As for pitch stimulaition, there was no significant difference in post-SSQ scores and marginally significant difference in maximal nausea scores (Wilcoxon signed rank test, p = 0.054) reported in the re-test after training and those reported in pre-training behavorial test (H1.3b).

4.5.4 Classification participants into resistant group and susceptible group

It worth noticing that, there were some participants reported very low SSQ scores after their first time watching the roll stimulation. And in the following repeated exposure, most of them still did not suffer from discomfort. Those participants who had never had a nausea score over 3, which meant that no “moderate discomfort” ever occurred during these exposures to roll or pitch stimulation, were grouped as **resistant** people (n=15). The rest participants were classified into susceptible group (n=19).

Table 4. Grouping of Participants

Method 1	**Susceptible (>=3)**			**Resistant (<3)**
Pre-training	19			15
Training	17 (+1)			12
Post-training	Unfinished	Trained-R (<3)	Trained-S (>=3)	Trained (<3)
	1	13	4	12

In pre-training stage, resistant group reported similar SSQ scores before and after watching roll or pitch stimulation; while susceptible group did report higher SSQ scores after the exposure to roll stimulation (Wilcoxon signed rank test, $p < 0.001$) and pitch stimulation (Wilcoxon signed rank test, $p = 0.001$). For both two stimulations, susceptible group reported larger post SSQ scores (Wilcoxon signed rank test, $p < 0.001$) and higher nausea scores (Wilcoxon signed rank test, $p < 0.001$) than resistant group.

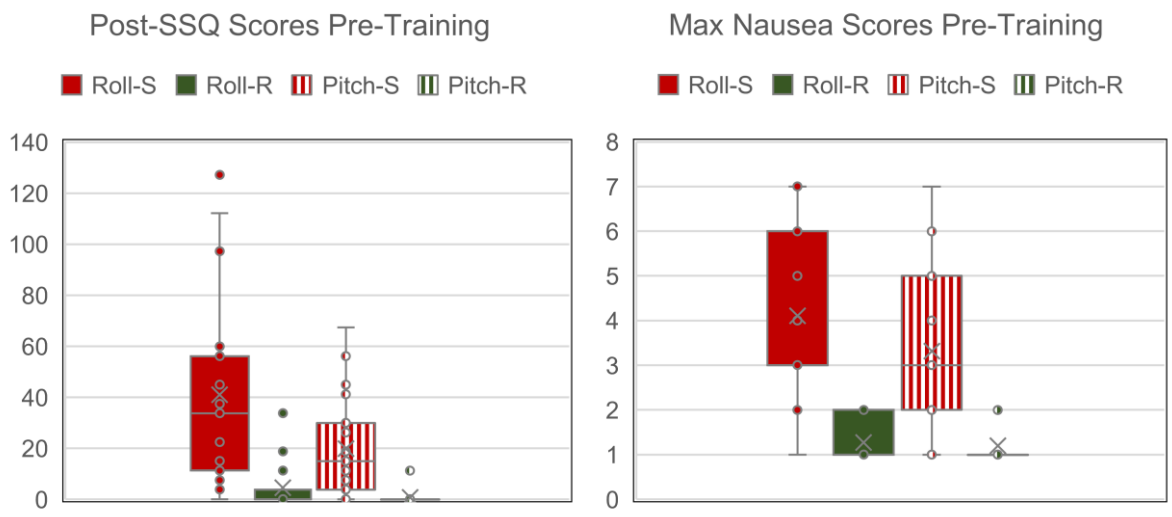


Figure 12. Different VIMS response between two participant groups

With two-way ART-ANOVA on SSQ scores under roll condition and under pitch condition (Exposure: Pre/Post; Group: Resistant/Susceptible), the interaction between two factors was significant [Roll: $F = 23.982$, $p < 0.001$; Pitch: $F = 24.112$, $p < 0.001$]. Post hoc analysis with Holm adjustment revealed that before exposure to both visual stimulations, pre-SSQ scores of two groups were similar and not different from post-SSQ scores of resistant group, while susceptible group had larger post-SSQ scores than pre-SSQ scores ($p < 0.001$), and also larger than post-SSQ scores of resistant group ($p < 0.001$).

Two-way ART-ANOVA on nauseas scores under roll condition indicated that the interaction effects between Group (Resistant/Susceptible) and Time (5/10/15/20minute) during observation was significant [$F (3, 99) = 18.950$, $p < 0.001$]. Post hoc analysis with Holm adjustment showed that in susceptible group, nausea score did not change until the end of watching, only the nausea scores rated at the 20 minute was significantly higher than at 5 minute ($p < 0.001$) or 10 minute ($p < 0.001$). In resistant group, nausea scores reported at four time points were not found different. At all four time points, the susceptible group reported

higher nausea scores than resistant group ($p < 0.001$). The ART-ANOVA on nausea score under pitch condition also showed the interaction between Time and Group was significant [$F(3, 99) = 5.650$, $p = 0.001$]. Nauseas scores of resistant group under pitch did not increase with time and those of susceptible group increased significantly after 15 minutes (5 min-15 min: $p = 0.010$, 5 min-20 min: $p < 0.001$). After the 5th minute, the nausea scores of susceptible group and resistant group were starting to be different (10 min: $p = 0.012$; 15 min: $p = 0.002$; 20 min: $p < 0.001$).

4.5.5 RND test results of resistant group and susceptible group

Two RND test results before training were highly correlated (Pearson $r = 0.878$, $p < 0.001$) and not significantly different (pairted t test, $p > 0.05$), and it was the same for two RND test results after training (Pearson $r = 0.891$, $p < 0.001$; pairted t test, $p > 0.05$). The RND test showed reliablility to measure the visual dependencey. The visual dependency before and after training were represented by the means of two RND test results before and after training.

There was a significant difference in susceptible group in RND test results after training than before ($n = 18$, $p = 0.032$). For resistant group, there was no such a difference ($n = 12$, $p > 0.05$). The result support the classification of resistant group and susceptible group.

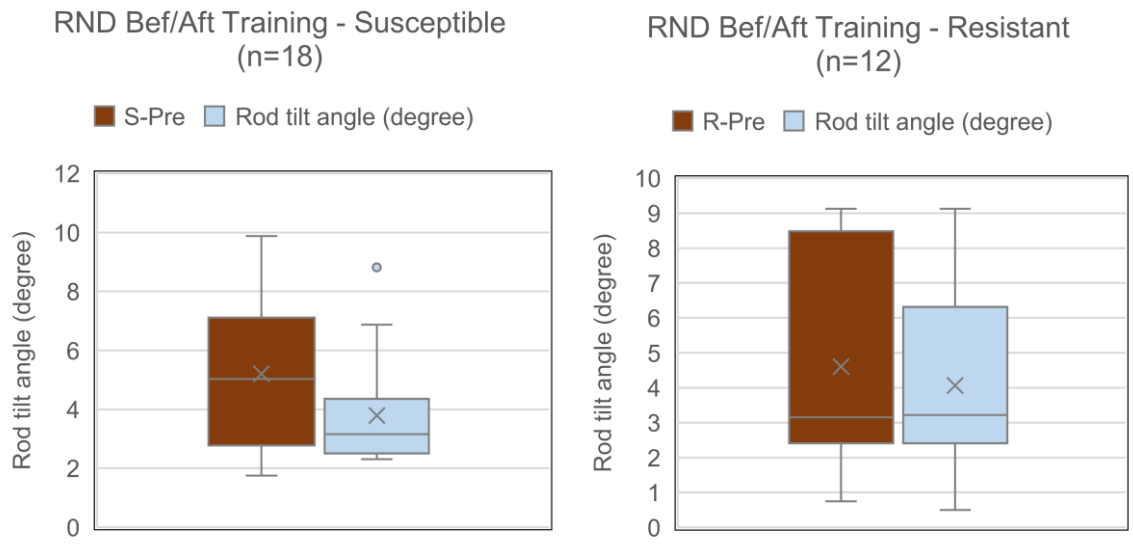


Figure 13. Different habituation effects on susceptible group and resistant group

4.6 Discussion

This study verified that two visual stimulations could make participants got motion sickness symptoms after a 20-minute exposure. The SSQ scores corresponding to both roll and pitch

stimulations increased significantly after watching. Besides, the nausea scores rated at the 20th minute were also larger compared with those rated at the 5th minute for both two visual stimulations. In addtion, it was revealed that the Roll stimulation is more VIMS-provoking than Pitch stimulaiton, the difference were consistantly significant in both post-SSQ scores and maximal nausea scores. From the perspective of sensory conflict theory, the difference in the VIMS response to two conditions, which were equal except the visual stimulation, suggested the difference in "sensory conflict" that could be induced by two visual stimulations. Furthermore, a two-way ART ANOVA on Vection (Time × Stimulation Type) indicated that during the 20-minute watching, the vection intensity was roughly constant along the observation. Stimulaiton Type [$F(1, 33) = 17.341$, $p < 0.001$] was a significant factor of Vection subjective rating, which showed that Vection under Pitch condition was higher than that of Roll condition. More exploration is needed to understand the higher vection instensity but lower VIMS induced by pitch stimulation compared with that of roll stimulation.

In the study, subjectively rated post-SSQ scores and nausea scores were adopted to represent the VIMS response. There were a high correlation between each VIMS response to two visual stimulations. This result implied that there could be an intrinsic property of participant, which determined the severity of discomfort, such as nausea and other motion sickness symptoms, one might suffer from when they were exposured to such environments. The questionnaire MSSQ which had been tested and used as a reference in many previous study also support the existance of VIMS susceptibility. MSSQ scores could explain about 16.2% to 19.3% of the variation in VIMS nausea scores after the exposure to the two visual stimulations used in this research. There is space for better prediction on VIMS susceptibility.

Repeated exposures to a VIMS-provoking stimulation would result in a reduction in the VIMS response to it after these exposure, which was utilized in this research as the habituation training. Over all VIMS response to Roll sitmulation reduced after training as indicated by SSQ scores and nausea scores.

Based on all the VIMS responses from beginning to ending, those who had never had a feeling, which was more unpleasant than "slight discomfort", were classified into resistant group. Rest participants who had experienced moderate discomfort or nausea composed of susceptible group. The grouping had been justified with their response in pre-training behavioral tests to both stimulations, and the comparison between pre-training and post-training behavioral tests. Susceptible group did show higher VIMS severity than resistant group.

As shown in Figure 9, most participants who had severe VIMS response gradually turned to be less discomfort when watching the roll stimulation. The orange curve (SU10s) and the blue curve (SU7s) illustrated the mean maximal nausea scores averaged among all participants with a 10-day training (n = 3) or a 7-day training (n = 9). Some of them started with a nausea score up to 7, which meaned the most severe VIMS status in which they had moderate nausea and could not continous. However, the habituation training was not effective on four participants in our 34 participants sample. The four dashed lines were for these individuals. In the first training, the nausea scores of S12 were not extremely high, but afterward S12 became more sensitive to the Roll stimulation. S2, S19 and S40 all reported nausea at the first time when they were exposured to the Roll stimulation.

In adddition, a cross-stimulation relief effect was possible from the habituation training. The nausea level reduced after training with a marginally significant difference. Although in the training, only Roll stimulation were repeated displayed, the VIMS response to Pitch sitmulaiton was also lower after the training for those who got the trained-resistance (n = 13, paired t-test, p = 0.012).

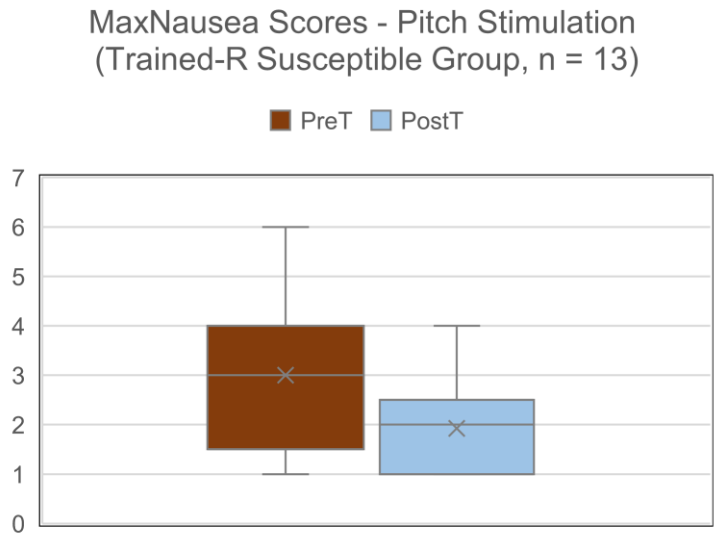


Figure 14. Maximal nausea scores under Pitch condition reduced after training with roll stimulation for those who trained to be resistant

The grouping was also supported by the changes in RND test performance. The averaged bias angle between two groups were not different before training. However, susceptible group showed significant reduction in angle of RND test after the training, suggesting that there was

a visual dependence reduction after the repeated exposures. The resistant group did not change significantly in RND test performance after training.

Chapter 5. Study Two – VIMS Susceptibility-related Phase Synchronization in response to Vection-inducing Stimulation

5.1 Introduction

The reason of VIMS has been explained with the sensory conflict or sensory rearrangement when visual sensory is not matched with vestibular sensory. However, it could need another hypothesis to explain why some individuals did not have any unpleasant feelings when they were physically stationary and exposed to a VIMS-provoking visual stimulation to other individuals. Most VIMS-resistant individuals can feel vection as susceptible individual, that is, there was also a mismatch between visual sensory (self-motion) and vestibular sensory (no self-motion).

Brandt et al. (1998) has found there was a reciprocal inhibitory visual-vestibular interaction in processing self-motion sensory induced by a visual motion stimulation. The visual motion stimulation brought up circular vection to the participants and deactivates the parieto-insular vestibular cortex. It was proposed that the reciprocal inhibitory visual-vestibular interaction could be a mechanism to prevent sensory conflict during vection. Vection and OKN were regarded as the trigger of VIMS as they were often prior to the occurrence of VIMS. The right lateralized activation in MT+ during vection and OKN could be the reason and the desynchronization between left and right visual areas under VIMS-provoking condition was found compared to VIMS-free control condition (Miyazaki et al., 2015). The inter-hemispheric desynchronization could be related to the processing of VIMS-provoking stimulation. An EEG study was more directly investigated on the susceptibility of motion sickness with EEG phase synchronization (Y. Wei et al., 2019). The susceptible participants were found to demonstrate an impaired theta-band phase synchronization, compared with participants resistant to motion sickness.

In 1999, Tokumaru et al., found significant change in EEG topography while subjects felt vection. Theta band was known to be related with processing memory formation in rodent animal hippocampal (Stanton & Sejnowski, 1989) and memory load (Gevins et al., 1997); however, increased theta power in frontal midline region were also found during concentrate mental activity, arithmetic calculation, sensory imagery and attention (Ishii et al., 1999).

In Study Two, phase synchronization at theta band of the EEG signals with self-motion and object motion distinguished would be analyzed to find reliable indicators for VIMS susceptibility.

5.2 Hypotheses

Study Two focused on testing hypotheses on the mechanism of VIMS susceptibility explained by Sensory Conflict Theory and Reciprocal Inhibition Theory with EEG activity collected during processing visual motion stimulations.

(H2.1) With regards to **sensory conflict**, **susceptible** individuals should display a **stronger** neural response to sensory conflict; **resistant** individuals should display a **lower** neural response to sensory conflict (H2.1a). The indicators for neural response to sensory conflict are supposed to be positively correlated with their VIMS severity (H2.1b).

(H2.2) With regards to **neural coordination** to relieve the sensory conflict, **resistant** individuals should display **stronger** neural coordination between vestibular and visual regions to process the visual information inducing sensory conflict; the neural coordination of **susceptible** individuals should be **lower** (H2.2a)**.** The indicators for neural coordination are supposed to be negatively correlated with their VIMS severity (H2.2b).

(H2.3) **VIMS severity** could be predicted using the difference between the sensory conflict induced by visual stimulations and the neural coordination to relieve the sensory conflict.

5.3 Design of Experiment

In this Study Two, a randomly moving random-dot patten which would induce object motion was used as the control condition; a coherently moving random-dot pattern (roll stimulation or pitch stimulation), which would induce self-motion after a latency, was used as the experiment condition. In previous study (Y. Wei et al., 2019), individuals resistant to motion sickness showed higher global synchronization when comparing the difference between two conditions. The design of the sequential segments in visual stimulations was adopted same as Wei's study. This study aimed to source some more specific indicators for VIMS susceptibility during the development and the processing of vection. This study would collect and EEG signals with the visual stimulations shown in Figure *4*. The procedure, task and data processing method can be referred to Section 3.4.

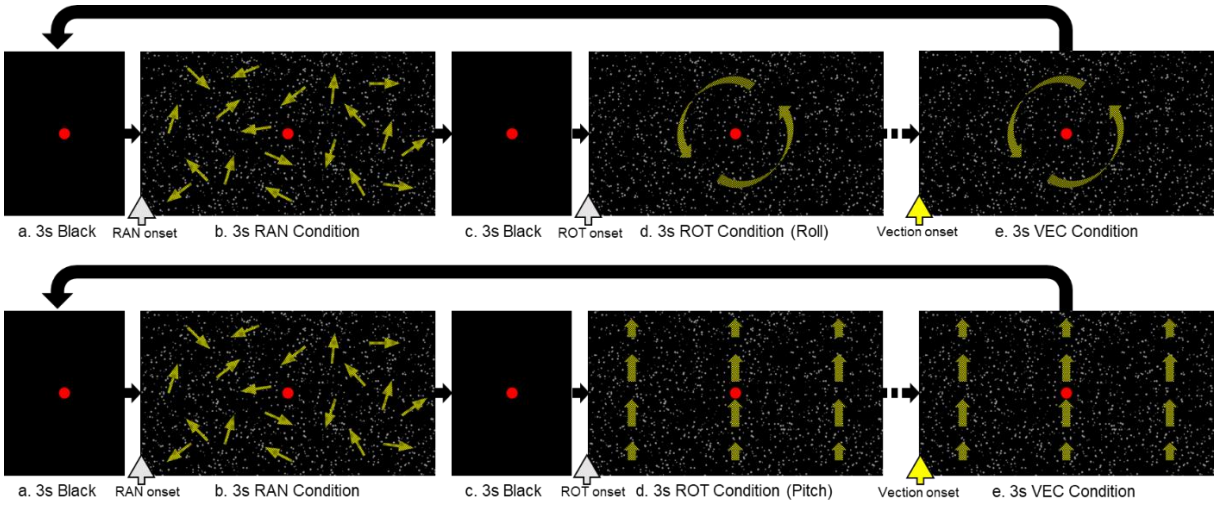


Figure 4. Visual stimulations used in EEG signal recording

Dependent Variable	Roll Stimulation	Pitch Stimulation
	Phase synchronization indicators	
Independent Variable	VIMS Susceptibility: susceptible group, resistant group	

5.4 Result

In this section, the node strength analyses results were shown first to acquire the time of interest (Section 5.4.1), and then the PLV indicators were calculated on the time of interest for each electrode pair. The inter-subject variability on PLV indicators were analyzed for two groups of participants (Section 5.4.2). At last, the VIMS severity prediction with PLV indicators was conducted (Section 5.4.3).

5.4.1 Node strength analyses in theta, alpha, and beta bands

The phase of EEG signal from each electrode was extracted with wavelet analysis and the node strength of electrode was calculated as described in Section 3.4. By comparing the phase synchronization under ROT and RAN conditions at certain frequency bands, the time of interest along with the display of stimulation could be revealed, in which the brain activity were most related to the vection-provoking information processing. Cluster based permutation test was applied on the node strength on theta (4-7 Hz), alpha (8-12 Hz) and beta (13-29 Hz) bands.

As for the theta band (4-7 Hz), the node strength analyses showed there was a significant positive cluster with both roll stimulation ($clusterstat > 2.656e + 4$, $p < 0.001$) and pitch stimulation ($clusterstat > 2.656e + 4$, $p < 0.001$). From the EEG signals measured with roll stimulation, the positive cluster ranged from 127 to 484 miliseconds at all channels except FP1.

From the EEG signals measured with pitch stimulation, the positive cluster ranged from 152 to 435 miliseconds at the channels FT8, Cz, C4, T8, TP7, CP3, CPz, TP8, P7, P3, Pz, P4, P8, O1, and O2. No significant negative cluster was found.

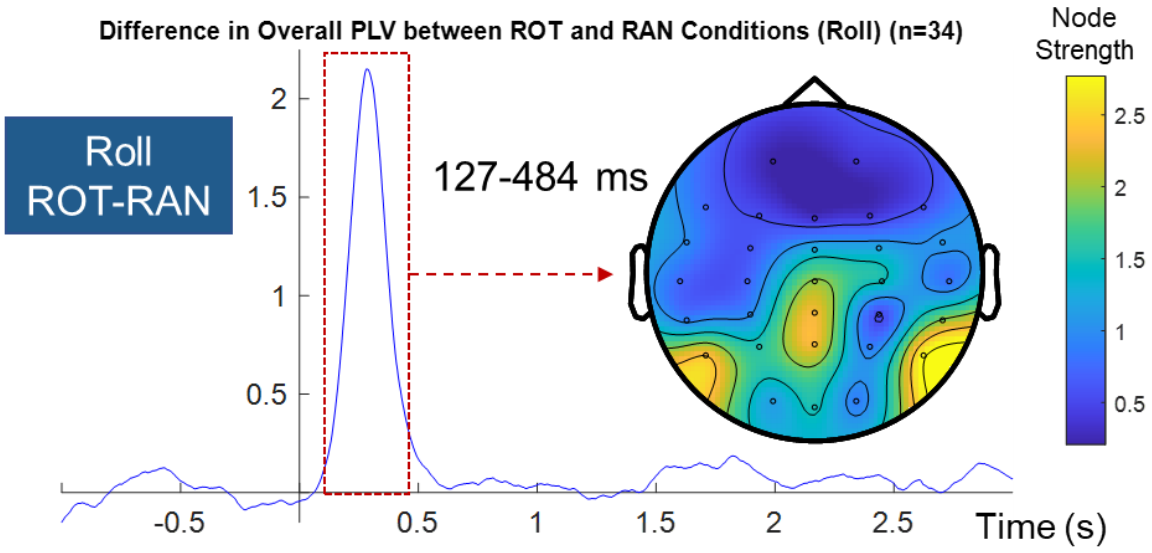


Figure 15. Positive cluster found in the comparison between ROT and RAN condition of EEG signal collected with Roll Stimulation

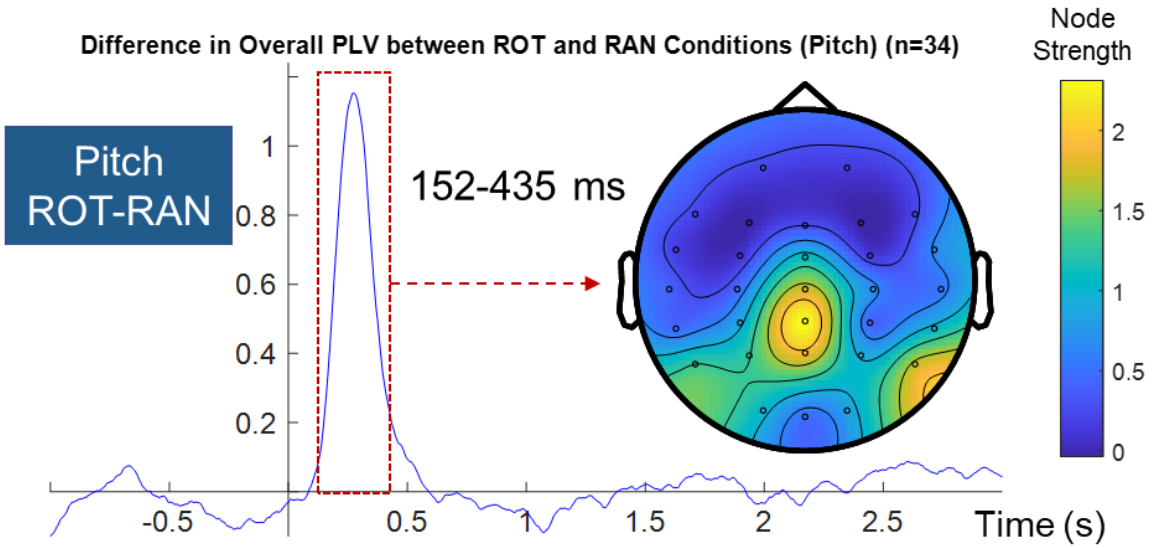


Figure 16. Positive cluster found in the comparison between ROT and RAN condition of EEG signal collected with Pitch Stimulation

As for the alpha band (8-12 Hz), there were no significantly different node-time cluster between ROT condition and RAN condition for EEG signals collected with the roll sitmulation. For the pitch stimulation, there was one marginally significant positive cluster (clusterstat = 514.903, p = 0.047) found at 948 to 1001 ms at Fz, FCz, FC4, Cz, C4. (The criteria alpha level was 0.050 for two-side so that a cluster is significant only if the p-value is smaller than 0.025).

As for the beta band (13-29 Hz), there were no significantly different node-time cluster between ROT and RAN conditions for EEG signals collected with either roll or pitch stimulation.

5.4.2 PLV indicator in theta band under ROT condition (H2.1 and H2.2)

With the time window revealed by the cluster-based permutation test on theta band data above, the PLV indicators of all participants were calculated for each condition and stimulation. The results from the comparison between ROT condition and RAN condition, which was inspired by a previous study (Y. Wei et al., 2019), were listed in Appendix. Compared to it, there were a set of VIMS susceptibility indicators directly from the ROT condition, which can be validated with both Roll and Pitch stimulation condition.

Under the roll stimulation condition, the theta band phase synchronization under ROT condition between resistant group and susceptible group were compared with permutation test to solve the multiple comparison problem on the large number of combinations. However, no significant results were found with a 5% chance of mistake for all hypothesis tests. This also happened to pitch stimulation condition. To avoid missing meaningful neural indicators, significant results from two sample t tests were investigated for analysis. The inter-subject variability on PLV indicators is demonstrated with following two subsections respectively focusing on resistance indicators and susceptibility indicators.

5.4.2.1 Theta band PLV indicators correlated with VIMS resistance

Comparing the PLV indicators of resistant group and susceptible group, the following links was found to be significantly higher in resistant group. In Figure 17, the left collumn shows those measured with roll stimulation, middle part showed thosed measure with pitch stimulation and the right one showed the comment connections of two stimulations. The nine VIMS resistance connections (PLV240: FCz-Pz; PLV241: FCz-P4; PLV242: FCz-P8; PLV325: Cz-Pz; PLV326: Cz-P4; PLV386: CPz-P4; PLV410: P7-P4; PLV426: P4-P8; PLV429: P4-O2) were around frontal-central, parietal and occipital areas (H2.2a).

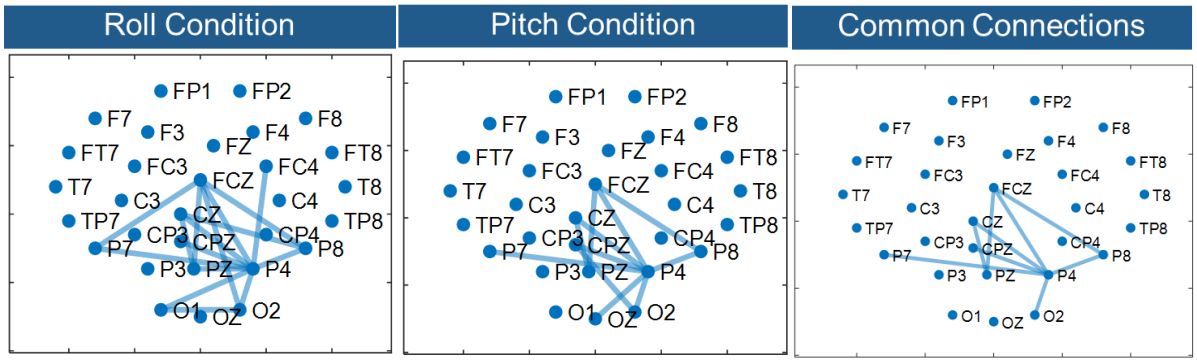


Figure 17. Theta band PLV indicators under ROT condition: resistant>susceptible group

Therefore, the correlation between these PLV indicators and actual VIMS scores were analyzed with Spearman correlation test. The VIMS scores included SSQ scores rated for both roll stimulation (RollSSQ) and pitch stimulation (PitchSSQ) and nausea score rated for two stimulations (RMNausea and PMNausea). Significant correlation coefficients were demonstrated in the following Figure 18 ($p<0.05$). All nine PLV indicators measured by roll stimulation and six PLV indicators measured by pitch stimulation showed significant correlation with VIMS (H2.2b).

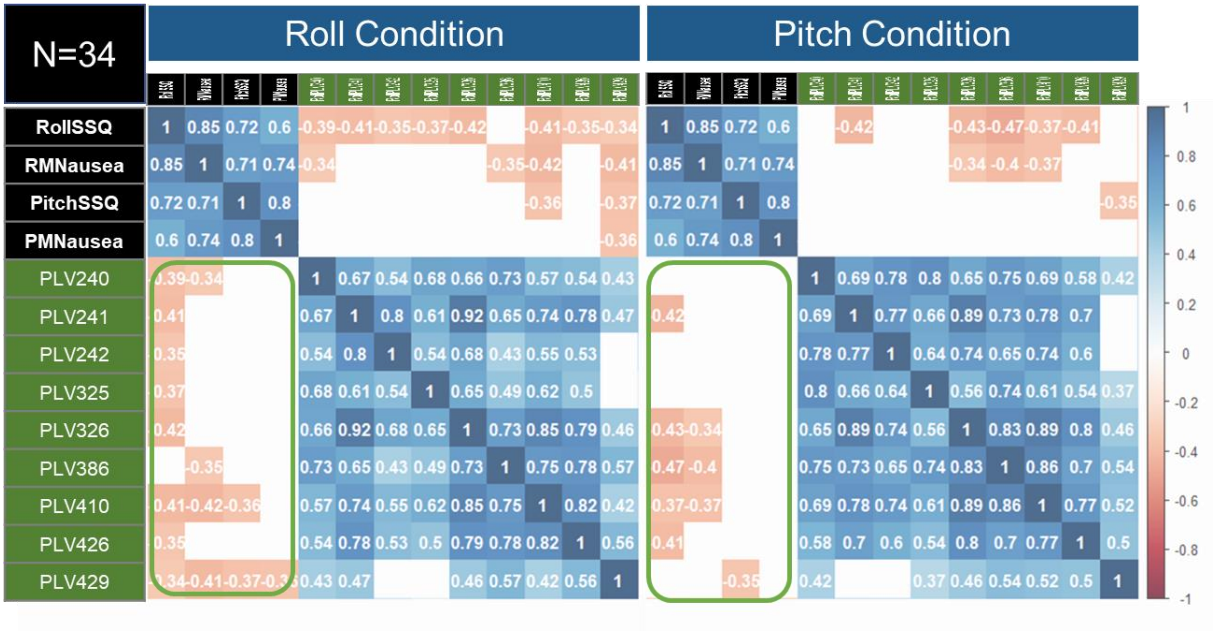


Figure 18. Significant Spearman correlation coefficients between PLV VIMS-resistance indicators (left: roll, right: pitch) and VIMS scores

5.4.2.2 Theta band PLV indicators correlated with VIMS susceptibility

Comparing the PLV indicators of resistant group and susceptible group, the following links was found to be significantly higher in susceptible group. In Figure 19, the left part shows

those measured with roll stimulation, and the right part showed thosed measured with pitch stimulation (H2.1a).

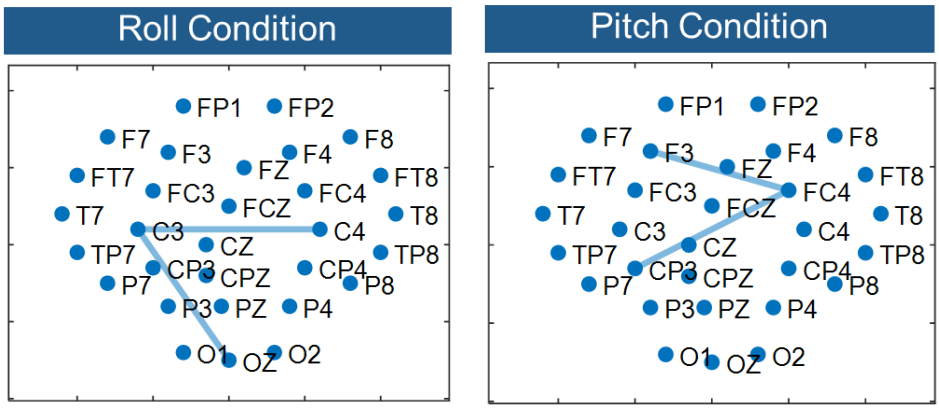


Figure 19. Theta band PLV indicators under ROT condition: resistant<susceptible group

The Spearman correlation analyses showed PLV301 (C3-C4) and PLV 314 (C3-O2) were significantly correlated with VIMS scores, no matter if they were measured with roll stimulation or pitch stimulation (Figure 20); the PLV91 (F3-FC4) and PLV253 (FC4-CP3) measured by pitch stimulation were significantly correlated with VIMS scores rated for both stimulations (H2.1b).

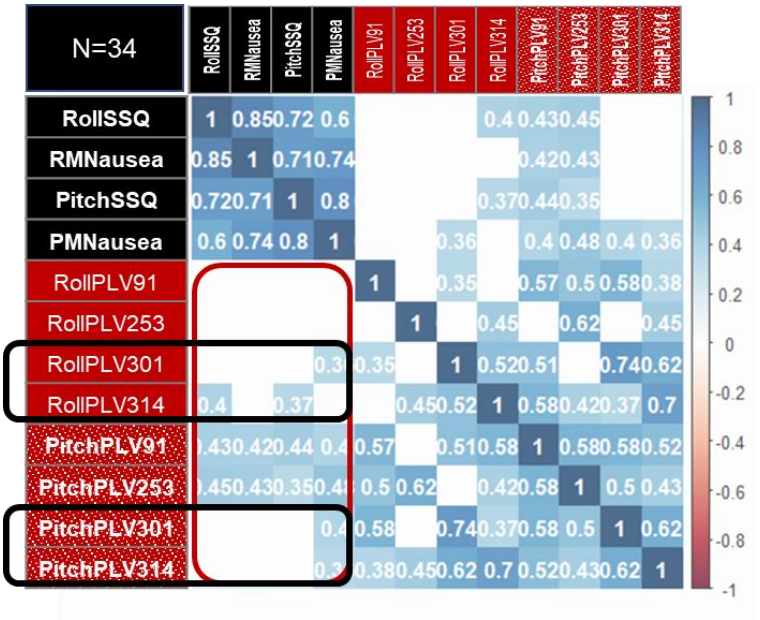


Figure 20. Significant Spearman correlation coefficients between PLV VIMS-susceptibility indicators (left: roll, right: pitch) and VIMS scores

5.4.3 VIMS severity prediction with PLV indicators (H2.3)

EEG signals from two pairs of electrodes measured with roll stimulation (RollPLV301 between C3 and C4, RollPLV314 between C3 and Oz) were found to be correlated with the VIMS severity corresponding to roll stimulation. Another two pairs of electrodes (PitchPLV91 between FC4 and F3, PitchPLV253 between FC4 and CP3) were found to be correlated with VIMS to pitch stimulation. They were labeled as VIMS-susceptibility indicators. A brunch of electrodes around P4 were negatively correlated with the VIMS severity to pitch stimulation. Except for them, linkages between Pz and Cz, Pz and FCz, together with P4 and P7 were negatively correlated with VIMS to roll stimulation. They were labeled as VIMS-resistance indicators.

5.4.3.1 VIMS under roll stimulation condition

As to roll VIMS severity, forward stepwise regression analysis was applied on RollSSQ with as 9 VIMS-resistance indicators and 2 VIMS-susceptibility indicators as predictors. The result was shown in Table *5*. One VIMS-resistance indicator (RollPLV325) and one VIMS-susceptibility indicator (RollPLV301) were left in the final model. They both contributed to the model which could significantly predict 27.9% of the variance in SSQ scores after first watching roll stimulation for 20 minutes.

Forward stepwise regression analysis was also applied on the nausea scores rated for RMNausea with all 11 predictors. The result was in Table *6*. One VIMS-resistance indicator (RollPLV410) and one VIMS-susceptibility indicator (RollPLV301) were left in the final model. They both contributed to the model which could significantly predict 35.8% of the variance in maximal Nausea scores during watching roll stimulation for 20 minutes.

Table 5. Forward step regression model for the prediction of Roll VIMS - FirstSSQ

Variables of RollSSQ	**Coefficient**	**P-value**	**Location**
(Intercept)	17.299	0.145	
RollPLV301	1.872	0.013	Between C3 and C4
RollPLV325	-1.108	0.020	Between Cz and Pz
Multiple R-squared	0.279	**P-value**	0.006

Table 6. Forward step regression model for the prediction of Roll VIMS - FirstNausea

Variables of RMNausea	**Coefficient**	**P-value**	**Location**
(Intercept)	2.017	0.008	

RollPLV301	0.133	0.002	Between C3 and C4
RollPLV410	-0.070	0.026	Between P7 and P4
Multiple R-squared	0.358	**P-value**	0.001

With two types of indictors, the VIMS severity to roll stimulation could be better predicted than with questionnaires only.

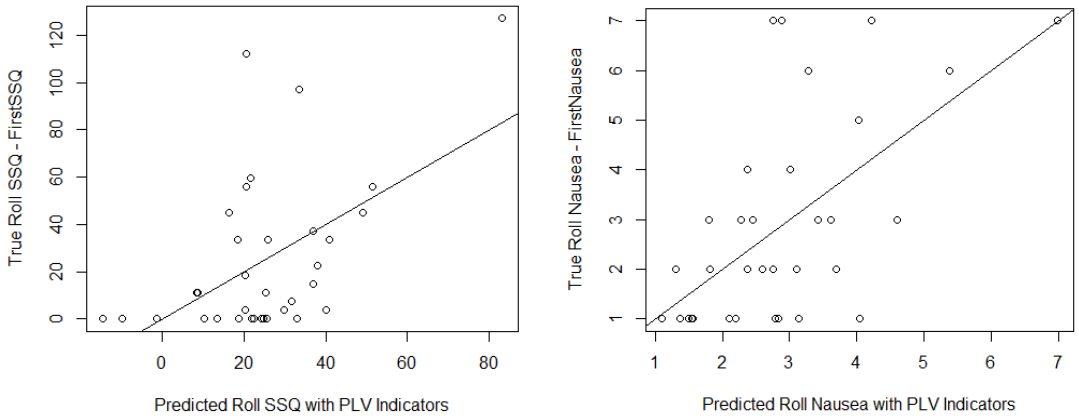


Figure 21. Predicted VIMS Severity under Roll Stimulation Condition
(Left: RollSSQ; right: RollNausea)

5.4.3.2 VIMS under pitch stimulation condition

As to pitch VIMS severity, forward stepwise regression analysis was applied on PitchSSQ with as 6 VIMS-resistance indicators and 2 VIMS-susceptibility indicators as predictors. The predictors left were not significant. Forward stepwise regression analysis was applied on PMNausea with as 6 neural coordination indicator and 2 sensory conflict indicators as predictors. The result was shown in Table *7*. One VIMS-resistance indicator (PitchPLV429) and one VIMS-susceptibility indicator (PitchPLV253) were left in the final model. They both contributed to the model which could significantly predict 27.9% of the variance in maximal Nausea scores during watching roll stimulation for 20 minutes.

Table 7. Forward step regression model to predict PMNausea with PLV429 and PLV253

Variables of PMNausea	Coefficient	P-value	Location
(Intercept)	2.782	<0.001	
PitchPLV429	-0.070	0.013	Between P4 and O2
PitchPLV253	0.220	0.026	Between CP3 and FC4
Multiple R-squared	0.279	**P-value**	0.006

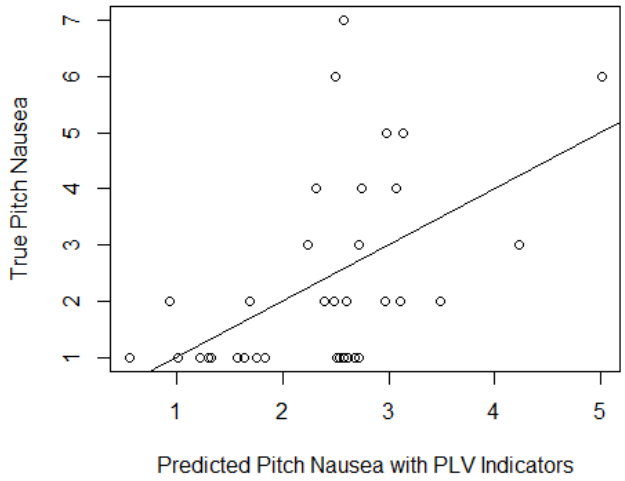


Figure 22. Predicted VIMS Severity under Pitch Stimulation Condition

5.5 Discussion

5.5.1 Theta band PLV indicators for VIMS resistance and VIMS susceptibility

This study two focused on the EEG signals collected with short exposures to two VIMS-provoking stimulations (roll and pitch) and intended to find VIMS susceptibility indicators from the phase synchronization in theta band aroung critical regions like parietal areas (Brandt et al., 1998). With the node strength analyses during short exposures to two stimulations, the theta band (4-7 Hz) signals were found to be more related to sensory conflict during exposures to vection-provoking visual stimulations. However, no significantly cluster was found when the analyses were applied to the EEG signals in alpha or beta bands (see results in Section 5.4.1). In theta band, similar significantly positive time-node clusters were found with both visual stimlations around the first 152 to 435 miliseconds of the exposures at the middle parietal region (electrode Pz).

Then, VIMS resistance indicators and VIMS susceptibility indicators were explored through the between-group comparisons in Section 5.4.2. Consistantly for both visual stimlations, the phase synchronization around right parietal (P4) and the phase synchronization between central (Cz, FCz) and parietal (Pz) regions were found to be related to individual resistance to VIMS, as shown by the negatively correlations between VIMS scores and VIMS-resistance PLV indicators (see results in Section 5.4.2.1). When it come to VIMS susceptibility indicators, which were positively correlated with VIMS scores, the results were not consistant for two visual stimlations. For roll stimulation, the phase synchronization between right and left central regions (C3 and C4) and that between left central and middle occipital regions (C3 and Oz)

were positively correlated with VIMS; for pitch stimulation, the phase synchronization between left frontal and right frontal-central regions (F3 and FC4) and that between left central-parietal and right frontal-central regions (CP3 and FC4) were positively correlated with VIMS. The results supported that the VIMS resistance could be a consistant property of individuals, while the VIMS susceptibility could be affected by the type of VIMS-provoking stimulations. However, as just two type of visual stimulations were utilized in the study, only limited consistence could be verified.

Furthermore, the stepwise regression analyses on VIMS scores indicated that the difference between VIMS-susceptibility and VIMS-resistance indicators was a better predictor for VIMS scores under both roll and pitch stimulation conditions. From the perspective that the VIMS-susceptibility indicators showed the sensory conflict induced by the stimulation and the VIMS-resistance indicators showed the individual property of neural coordination to reduce the sensory conflict and relief VIMS, the difference between them was a possible metrix of the residual sensory conflict after the alleviation neural coordination.

5.5.2 Cross-stimulation prediction of VIMS

These PLV indicators were correlated between roll stimulaiton condition and pitch stimulation condition, as shown in Figure 18 and Figure 20. They demonstrated the ability of cross-stimulation prediction.

Some PLV indicators measured under roll stimulaiton condition can also predict the VIMS severity to Pitch stimulaition (RollPLV429, RollPLV242, RollPLV 301 and RollPLV314 were significantly correlated with PitchSSQ or PMNausea). Some PLV indicators measured under pitch stimulaiton condition can also predict the VIMS severity to Pitch stimulaition (PitchPLV386, PitchPLV 429, PitchPLV 253 have moderate significant correlations with PitchSSQ or PMNausea).

Interestingly, some PLV indicators measured under pitch condition were not correlated with VIMS to Pitch stimulaiton but they were correlated with the VIMS to Roll stimulation, like PitchPLV326 and PitchPLV426. They were both negatively correlated with VIMS severity and were higher in resistant group, which indicated that they could be related with neural coordination to relief VIMS. One explanation for this interesting phenomenon could be from sensory conflict theory: although PLV indicators measured under Pitch condition should have been correlated with both Pitch VIMS and Roll VIMS, the correlation relationship with Pitch

VIMS might be blurred as the relatively low sensory conflict induced by Pitch stimulaiton. As the Pitch stimulation is not as VIMS-provoking as Roll stimulation , which means it induced a relatively low level sensory conflict. The VIMS is a consequency of the residual sensory conflict minused by neural coordiniation, in which the latter is related to phase synchronization indicators found to be higher of resistant group in current research. As the sensory conflict is high in Roll stimulation, after a part of it has been cancled out by the neural coordination, the residual sensory conflict can still induce VIMS. For Pitch stimulation, the sensory conflict is relatively low and in a similar quantity with the reduction effect of neural coordination, the residual sensory conflict may induce less VIMS. The fluctuation in Pitch VIMS is not sufficient to demonstrate a correlation relationship.

Table 8. Forward step regression model to predict Roll FirstSSQ with PLV indicators measured under pitch condition

Variables of FirstSSQ	Coefficient	P-value	Location
(Intercept)	29.563	0.004	
PitchPLV426	-0.946	0.005	Between P4 and P8
PitchPLV253	5.081	0.008	Between CP3 and FC4
Multiple R-squared	0.324	**P-value**	0.002

Table 9. Forward step regression model to predict Roll FirstNausea with PLV indicators measured under pitch condition

Variables of FirstNausea	Coefficient	P-value	Location
(Intercept)	3.431	<0.001	
PitchPLV429	-0.085	0.013	Between P4 and O2
PitchPLV253	0.236	0.047	Between CP3 and FC4
Multiple R-squared	0.260	**P-value**	0.009

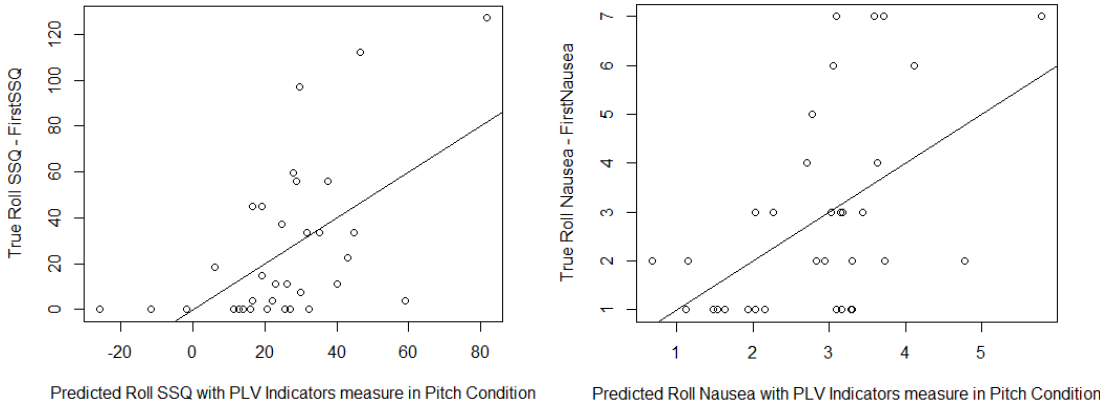


Figure 23. VIMS under Roll condition can be predicted with indicators measured in Pitch condition

Prediction of roll VIMS with PLV indicators measured under pitch stimulation condition (Table *8*) demonstrated feasibility of the approach that the susceptibility to the VIMS induced by a visual stimulation with higher VIMS-provoking tendency could be measured with a visual stimulation with less VIMS-provoking tendency. The coefficients of PitchPLV426 and PitchPLV429 were significantly negative. The result supported that they could be the indicators related to neural coordination to relieve VIMS, and independent with the type of stimulation with which the indicators were measure. The positive coefficient of PitchPLV253 supported it could be related to the VIMS response directly and also transferable between roll and pitch visual stimulations.

Table 10. Forward step regression model to predict PitchNausea with PLV indicators measured under roll stimulation condition

Variables of PitchNausea	Coefficient	P-value	Location
(Intercept)	1.438	0.015	
RollPLV301	0.130	<0.001	Between C3 and C4
RollPLV410	-0.057	0.022	Between P7 and P4
Multiple R-squared	0.432	**P-value**	<0.001

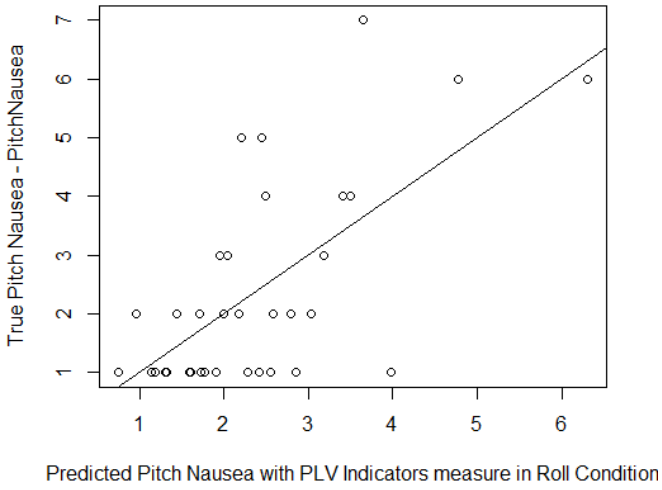


Figure 24. VIMS under Pitch condition can be predicted with indicators measured in Roll condition

On the other side, the indicators measured under roll stimulation were able to predict the nausea level during the exposure to Pitch stimulation. The 43.2% of the variation could be explained with the two predictors. RollPLV301 between C3 and C4 was a positive predictor, which could

be related with the VIMS response to sensory conflict. RollPLV410 between P7 and P4 was a negative predictor, which was likely to related to the neural coordination in parietal areas to relieve VIMS symptoms.

Chapter 6. Study Three – Effect of Habituation Training on VIMS and Postural Indicators

6.1 Introduction

Posture instability is common symptom accompanied with motion sickness, reported in flight simulator and virtual reality exposure (Cobb, 1999; Robert S Kennedy et al., 1996; T. A. Stoffregen et al., 2000). It was thought to be induced by inter-sensory mismatch and its intensity should be a function of the magnitude of the mismatch (Paulus et al., 1984). Postural instability theory of motion sickness (Thomas A Stoffregen & Riccio, 1991) proposed that motion sickness occurred when the animals have not possessed the ability to maintain posture stability and prolonged instability would lead to sickness symptoms.

The theory was supported in many following experiments. In 1998, Stoffregen et al. found that postural instability preceded motion sickness from participants' head position in a moving room experiment, in which significant difference in posture between sick group and well group was found in pre-exposure posture sway (variability, velocity and range). With a seated posture, the prediction that postural instability preceded motion sickness onset has also been confirmed (T. A. Stoffregen et al., 2000). Except the head motion indicators for posture instability (Flanagan et al., 2004; Merhi et al., 2007; Smart et al., 2002; Thomas A. Stoffregen et al., 2004), experiments also showed postural sway (Bonnet et al., 2006; K. Wei et al., 2010; Yokota et al., 2005a) and hip sway (Cobb, 1999) could be indicators for posture.

With the popularity of somatosensory game, devices similar to force platforms become available and low-cost. The validity and reliability of game device like Nintendo Wii balance board (WBB) for assessment of standing centre of pressure (COP) has been discussed (Clark et al., 2010). Majority of qualified studies assessing WBB with adequate processing method reported moderate to excellent reliability and excellent validity as compared to reference force plate (Clark et al., 2018). The major problems of WBB are its inconsistent sampling rate and poor signal to noise ratio. With a linear interpolation method, the data can be resampled uniformly but the results could be inaccurate, especially when differentiating the data. We followed a tested resampling method, sliding window average with relevance interval interpolation (SWARII), which could yield closest data distribution to that recorded by a laboratory-grade force platform than other resampling methods (Audiffren & Contal, 2016).

6.2 Hypotheses

Study Three focused on testing hypotheses on the mechanism of VIMS susceptibility explained by Postural instability Theory with center of pressure data collected with stance gesture, in behavioral tests with two stimulations, before, during and after habituation training with roll visual stimulations.

(H3.1) Two groups of participants could demonstrate different posture stability development both during and after watching various stimulations. The susceptible group could be more unstable compared to those in the resistant group.

(H3.2) With training sessions progressing, there would be an improvement in posture instability after the completion.

(H3.3) Among all the participants, the improvement of posture stability might be correlated with the reduced VIMS susceptibility, so that it could be larger in susceptible group than resistant group.

6.3 Design of Experiment

In pre-training behavioral tests, before watching roll or pitch stimulation, there were three one-minute postural tasks, during which the COP data were recorded. Participants would stand quietly on the Wii balance board with eye open for one minute with bare feet and shoes cover. The first 1-min task was standing with eyes gazing at a center fixation point on a black background (EO: eyes open), followed by a 1-min standing task with eyes closed (EC). The third one was focusing on the central fixation point in a stationary random-dot pattern. When the participants were watching the stimulation, the postural COP data were recorded at the same time. After the exposure to roll or pitch stimulation (scheduled to be 20 minutes at most), the first two postural tasks, one with eyes gazing at center fixation point on black background and the other with eyes closed, were repeated once more. After the training sessions, the postural data were recorded in post-training behavioral tests with the same procedure as that before. Raw data was collected with Nintendo Wii Balance Board and sent to a Raspberry Pi 3 Model B via Bluetooth to record. A resampling method SWARII was applied to resample the irregular sampled COP signal to 25 Hz (see more details in Subsection 3.3.3).

Table 11. Experiment procedure of postural data collection

<table>
<tr><td colspan="8">Pre-training stage</td><td rowspan="2">Training (Roll)</td><td rowspan="2"></td><td colspan="8">Post-training stage</td></tr>
<tr><td colspan="2">Before</td><td colspan="4">During Roll exposure</td><td colspan="2">After</td><td colspan="2">Before</td><td colspan="4">During Roll exposure</td><td colspan="2">After</td></tr>
<tr><td>eyes open (EO)</td><td>eyes closed (EC)</td><td>5</td><td>10</td><td>15</td><td>20</td><td>EO</td><td>EC</td><td>EO</td><td>EC</td><td>5</td><td>10</td><td>…</td><td>20</td><td>EO</td><td>EC</td></tr>
<tr><td colspan="2">Before</td><td colspan="4">During Pitch exposure</td><td colspan="2">After</td><td>Day 1</td><td rowspan="2">…</td><td colspan="2">Before</td><td colspan="4">During Pitch exposure</td><td colspan="2">After</td></tr>
<tr><td>EO</td><td>EC</td><td>5</td><td>10</td><td>…</td><td>20</td><td>EO</td><td>EC</td><td>5 10 15 20</td><td>EO</td><td>EC</td><td>5</td><td>10</td><td>…</td><td>20</td><td>EO</td><td>EC</td></tr>
</table>

As shown in Table *11*, COP for one minute under conditions labeled as EO and EC were collected before and after exposure to two stimulations (Roll and Pitch), in both pre-training and post-training stages, were recorded. The COP data in first 20 seconds were excluded to avoid the noise from gesture adjustment in the beginning. Besides, during the 20-minute exposure to Roll or Pitch stimulation in pre/post-training and training stages, the COP data in four time-windows (2-3 min, 7-8 min, 12-13 min and 17-18 min) were extracted to represent the postural stability at that time.

6.3.1 Two groups differed in posture stability as response to vection-inducing stimulations

Dependent variables: spontaneous sway - EO; spontaneous sway - EC; sway during watching roll stimulation; sway during watching pitch stimulation in pre-training stage
Factor A-exposure to visual stimulation: before/after;
Factor B- VIMS susceptibility: susceptible groups, resistant group

6.3.2 Training improved postural stability

Dependent variable 1: indicators found in 6.3.1
Factor A-training: before training/ after training
Factor B- VIMS susceptibility: susceptible groups, resistant group

The following variables were calculated as the indicators of postural stability.

Table 12. Postural indicators

Postural Indicator	Explanation
RMS-x	Root mean square of x displacement around center
RMS-y	Root mean square of y displacement around center

path-S	Path length of posture sway
displacement	2D distance between the starting point to the ending point
range-X	Posture sway range along x axis (left to right)
range-Y	Posture sway range along y axis (top to bottom)

6.4 Result

6.4.1 Postural stability differs with VIMS susceptibility (H3.1)

Pre-training stage EC: Two-way repeated measures ANOVA was conducted on the postural sway to investigate the effects of Time (before/after exposure) and Group (Susceptible /Resistant). The results showed a significant effect of Time on all indicators, suggesting that postural sway with eyes closed were significantly larger after exposure to both roll stimulation and pitch stimulation. Furthermore, difference in range-x was found between two groups with different VIMS susceptibility. The increased sway lengths were more from susceptible group (paired t-test on range-x, Roll: $p = 0.019$; Pitch: $p = 0.029$) and the differences in resistant group before and after exposure were not significant statistically.

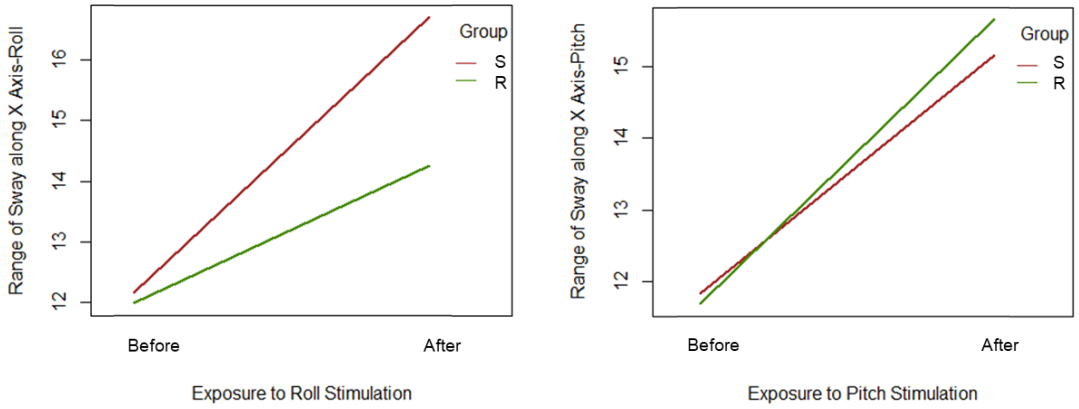


Figure 25. Eyes-closed sway range along x-axis of Susceptible group was particularly wider after exposure to both Roll stimulation (Left) and Pitch stimulation (Right)

Pre-training stage EO: Two-way repeated measures ANOVA indicated the significant interaction effects between Group (Susceptible/Resistant) and Exposure (Before/After) for both indicators (path-S: $F = 4.679$, $p = 0.038$; displacement: $F = 5.850$, $p = 0.021$). Compared to the eyes open sway before exposure, the postural stability of susceptible group was significantly damaged during sway with eyes open (path-S: $p=0.014$, displacement: $p = 0.010$), while the

resistant group did not change significantly. The pitch stimulation did not lead to significant increment of postural instability to both groups.

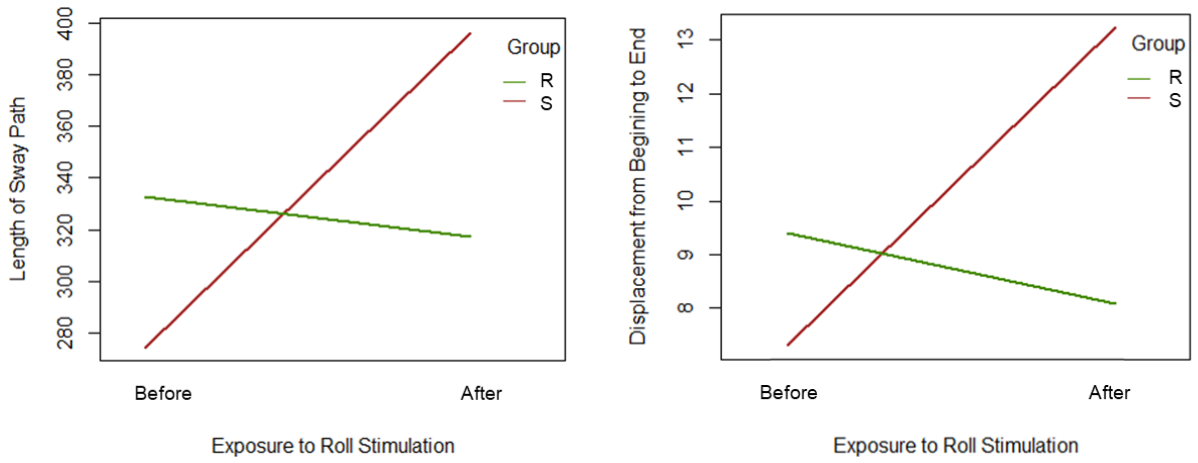


Figure 26. Eyes-open sway of Susceptible group was particularly larger after exposure to Roll stimulation (Left: sway path length; right: displacement from starting to ending)

When the postural sway along two axes were analyzed, it was revealed that the posture stability of susceptible group was significantly impaired especially along x axis (RMS-x: $p = 0.005$ and the range-x: $p = 0.005$).

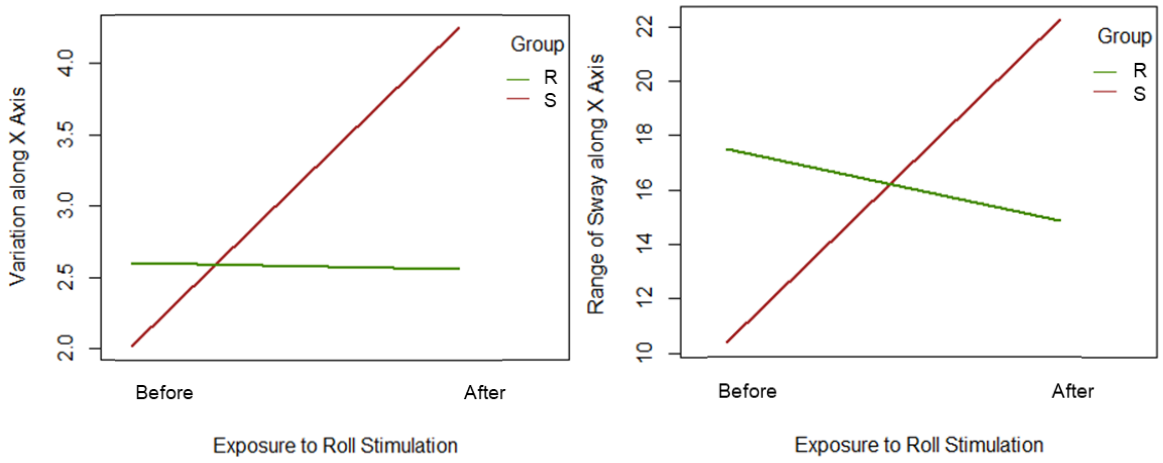


Figure 27. Eyes-open sway along x-axis of susceptible group was particularly larger after exposure to Roll stimulation (Left: variation of sway along x-axis; right: range-x)

6.4.2 Postural stability before and after habituation training (H3.2 and H3.3)

Before and after the training, the postural sway appeared to reduce especially in susceptible group. There were **twenty-three** participants who finished all 20-miniute posture data

recording in both pre-training behavioral tests and post-training behavioral tests. **One** participants' data was excluded because the postural data was polluted by extra motion. Three-way ANOVA (Time: 5min/10min/15min/20min; Group: Resistant/Susceptible; Training: Before/After) was conducted on the sway range along x axis (range-x). A significant interaction effects were found between Group and Training [$F = 6.217$, $p = 0.014$]. (If the polluted data of the excluded participants were included, the result was the same [Group × Training: $F = 5.273$, $p = 0.023$]). Post hoc analyses revealed that susceptible group had a lower sway range along x axis after habituation than before ($p < 0.001$), while there was no significant difference found in resistant group.

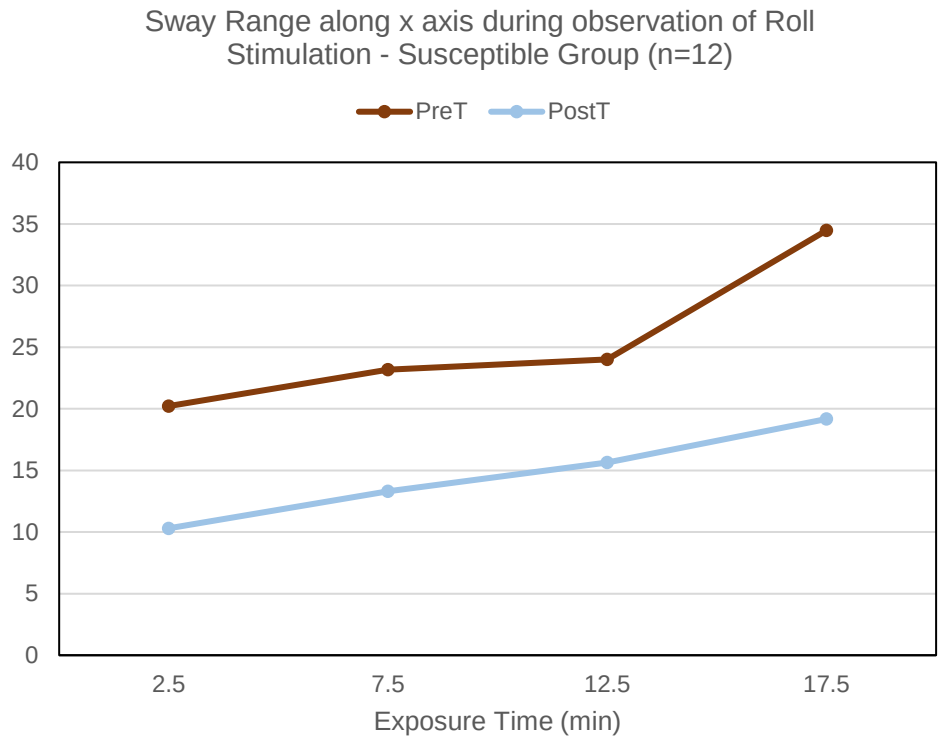


Figure 28. Sway range along x axis during the observation of Roll stimulation increased after habituation training in susceptible group

The same analysis on sway range along x axis measured with Pitch stimulation did not reveal a corresponding difference between pre-training and post-training.

6.5 Summary

Study Three verified the relationship between postural stability and VIMS. Exposures to the VIMS-provoking stimulations made the posture in quiet standing more unstable, no matter with

eyes open or eyes closed. In pre-training test, participants' sway range along x-axis with eyes closed increased after watching, in whom susceptible participants had greater and statistically significant increment. In addition, after watching the VIMS-provoking stimulation, susceptible participants demonstrated significant impairment in posture when they were standing with eyes open and focusing on a single illuminated point. It was supported by indicators in two-dimension, such as path-S and displacement, and indicators along x-axis, such as range-X and RMS-x.

Furthermore, the effect of habituation training on those who were previously susceptible to VIMS were significant. When they watched the roll stimulation again after the training, the sway range along x-axis were not as wider as before (as shown in Figure *28*). The postural stability improved in susceptible group after training, and the improvement significantly showed during Roll condition instead of Pitch condition.

The lack of consistent results across Roll and Pitch stimulations suggested that posture stability indicators of CoP acquired with current methods might not be a reliable and valid predictor for VIMS susceptibility. More exploration on the data source, more calculation methods like detrended fluctuation analysis and other non-linear indicators could be beneficial to find a qualified predictor for VIMS susceptibility, which will be the future work.

Chapter 7. Study Four – VIMS Susceptibility-related Stage Synchronization Analysis on the Effect of Habituation Training

7.1 Introduction

Being susceptible to certain visual motion stimulations means that one may have to make a trade-off between enjoying the joy from game and keeping away from the discomfort. Researchers have been working on how to reduce VIMS response for decades. Medicine like antihistamine and scopolamine can only be effective for a relatively short period (Wood et al., 1966). Studies on acupressure related treatments suggested an unstable effect depending on applied methods (S. Hu et al., 1995; Miller & Muth, 2004). The most traditional, relatively safe, and reliable way to modulate VIMS susceptibility could be the habituation training with repeated exposures. Although there were many studies to prove the efficacy of habituation training, the neural foundation of how it works has not been clear.

On the other hand, the PLV indicators in Study two (Section 5.4) were found to be related with the VIMS susceptibility. Some of them were particularly greater in Susceptible individuals, which could be related to the positive response to sensory conflict. Others of them were particularly greater in Resistant individuals, which were supposed to be related to neural coordination to relieve VIMS. Habituation training could reduce the VIMS severity response to sensory conflict with repeated exposures to the same visual stimulation or by enhancing the neural coordination among visual and vestibular areas.

Study four would test the hypotheses for the effects of habituation and validate the PLV indicators found in Study two.

7.2 Hypotheses

Study four focused on the hypotheses explaining how habituation training effected VIMS susceptibility by comparing pre-training and post-training EEG activity collected during visual motion stimulations processing.

(H4.1) **After the training** with roll stimulation, participants could have **less response to sensory conflict**, especially for those who were susceptible before, measured with roll stimulation (H4.1a) and pitch stimulation (H4.1b).

(H4.2) **After the training** with roll stimulation, participants, especially those in the susceptible group, could display **more neural coordination** to relieve sensory conflict between vestibular and visual regions to both **roll** stimulation (H4.2a) and **pitch** stimulation (H4.2b) **than before**.

7.3 Design of Experiment

Dependent Variables	PLV indicators found in Study Two: (Roll) +PLV301, -PLV410, -PLV325, (Pitch) +PLV253, -PLV429, -PLV426 etc.
Independent Variable A	Training: Before training; after training
Independent Variable B	VIMS susceptibility: susceptible group; resistant group

7.4 Result

7.4.1 VIMS response to sensory conflict reduced after habituation training (H4.1)

The theta-band phase synchronization between C3 and C4 (PLV301) reduced after training, no matter if it was measured with roll stimulation (paired t-test, $p = 0.005$) or pitch stimulation (paired t-test, $p = 0.003$), which may be a stimulation-independent neural indicator for VIMS response to sensory conflict.

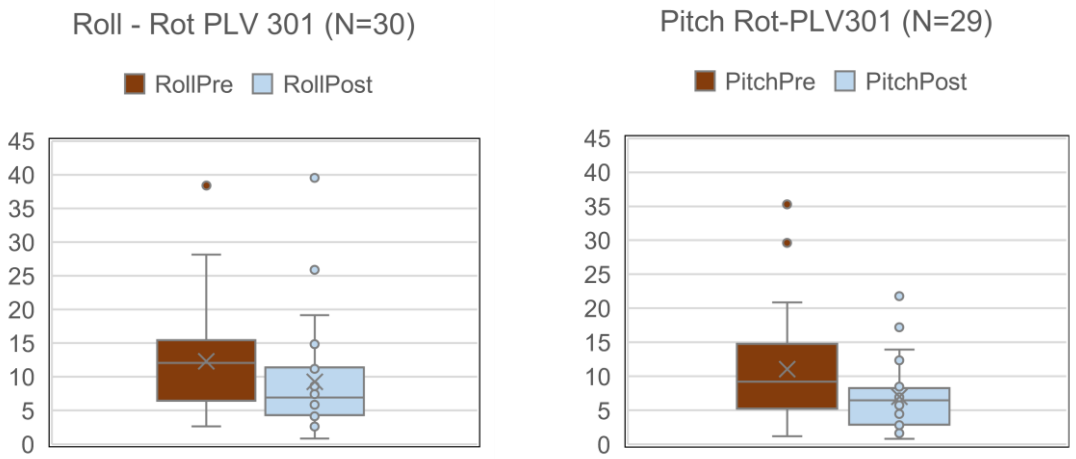


Figure 29. Phase synchronization between C3 and C4 (PLV301) reduced after training

The difference between pre-training PLV301 and post-training PLV301 were mainly from susceptible individuals. Difference in PLV301 between pre-training and post-training were only significant for susceptible group (n = 17), which was appliable for that measured with

roll stimulation (paired t-test, p = 0.028) and pitch stimulation (paired t-test, p = 0.003). In resistant group, no such significant differences in PLV301 were found.

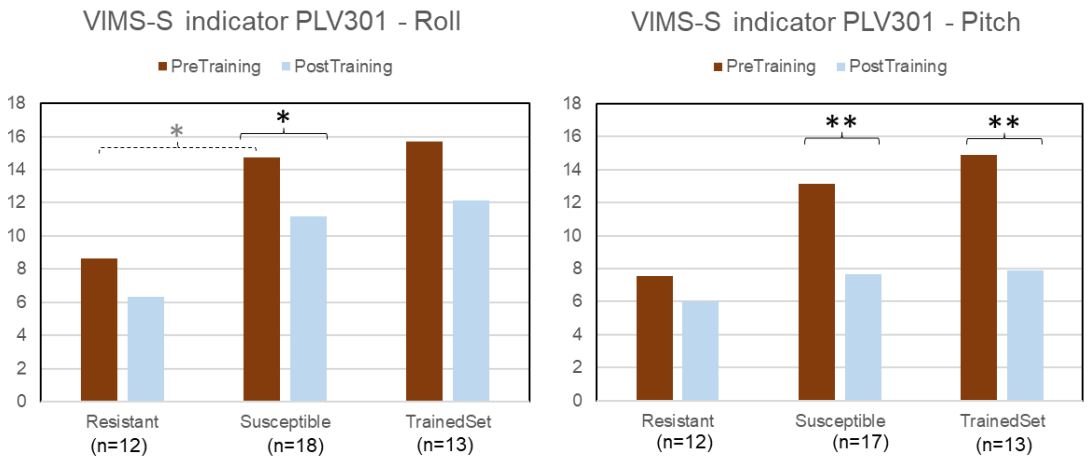


Figure 30. PLV301 reduction after training mainly from susceptible group

PLV301 reduced especially in Susceptible people after habituation training. Together with the evidence in Study Two (Chapter 4), the synchronization between C3 and C4 could be the indicator to VIMS response.

7.4.2 Neural coordination to relieve VIMS increased after training (H4.2)

For Roll stimulation, thirty participants finished the training. The phase synchronization between FCz and Pz under ROT condition (PLV240) measured with Roll stimulation increased significantly after the habituation training (paired t-test, p = 0.024). However, it did not happen to PLV240 measured with pitch stimulation. As a negative indicator for VIMS susceptibility, PLV240 measured with Roll stimulation before training were significantly smaller than that measured after training, when all participants were included. The increment was not significant when only the susceptible participants or the trained subset were included. There was no significant difference between PLV240 measured with Pitch stimulation before training and after training. The phase synchronization between FCz and Pz (PLV240) cannot be evoked to increase significantly under the Pitch stimulation after training, and it may not be a reliable indicator for VIMS resistance.

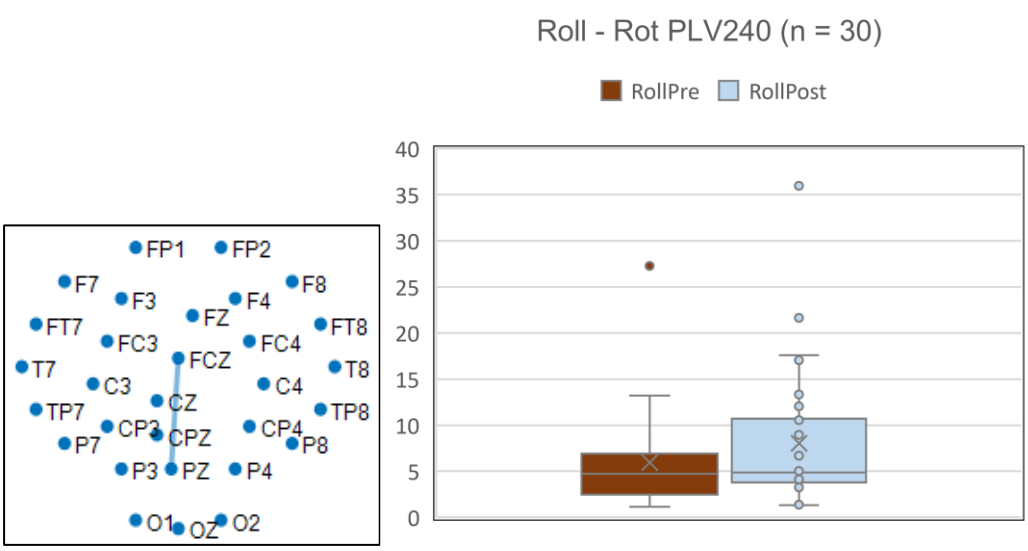


Figure 31. Phase synchronization between FCz and Pz (PLV240) measured with Roll stimulation increased after training (right) and its position (left)

For those susceptible people who were successfully trained to be resistant to VIMS induced by roll stimulation (n = 13), it was found that PLV410 increased significantly under roll condition (paired t-test, p = 0.012). The result was also discovered with pitch stimulation, PLV410 increased for susceptible group (n = 17, paired t-test, p = 0.031) and for the subset of those trained to be resistant (n = 13, paired t-test, p = 0.009).

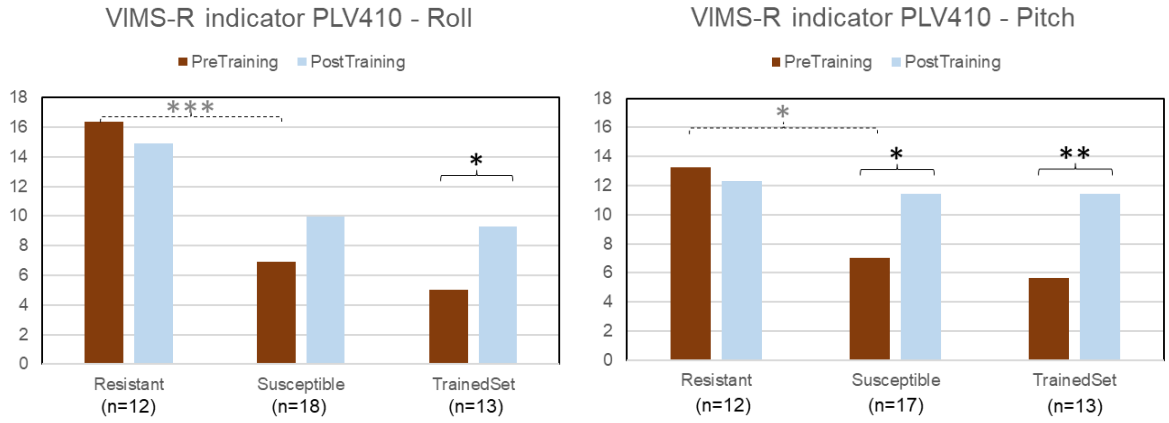


Figure 32. Phase synchronization between P7 and P4 (PLV410) decreased for those who turned to be resistant from susceptible after training

The PLV410 might be related with the neural coordination to relief VIMS and sensory conflict induced by visual stimulation.

7.5 Discussion

In this study, the PLV indicators revealed in study two (Section 5) were analyzed between before training and after training. Two PLV indicators demonstrated significantly change after the habituation training, especially for the susceptible and trained-to-be-resistant participants. They were PLV301 between C3 and C4 and PLV410 between P4 and P7.

7.5.1 Position of VIMS-susceptibility PLV indicator: PLV301

PLV301 were positively correlated with VIMS: susceptible people had higher PLV301 than resistant people. Participants, especially those who were susceptible, demonstrated significantly decreased PLV301 after training. PLV301 could be a stimulation-independent VIMS-susceptibility indicator, as these results was consistant discoveried with the PLV301 indicator measured with short exposures to both roll and pitch stimulations. The indicator showed the phase synchronization between C3 and C4 electrodes, which were found to be closed to somatosensory cortex (Holmes et al., 2019). The results implied that if an individual was more prone to VIMS, the inter-hemispheric synchronization of somatosensory cortex could be higher in the early exposure to the VIMS-provoking stimulation; and the synchronization of inter-hemispheric somatosensory activity was reduced after repeated exposures in the habituation training, no matter if the EEG activity was measured with roll or pitch stimulation.

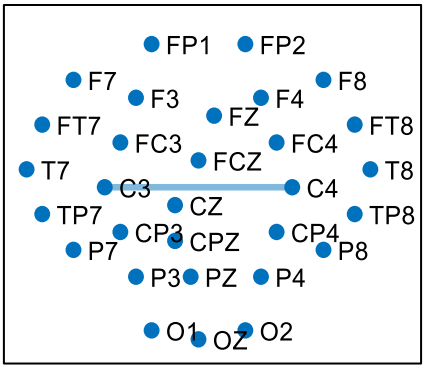


Figure 33. Recording sites of the VIMS-susceptibility indicators PLV310-C3C4

As VIMS-susceptibility indicator was positively correlated with the severity, another potential function of it is to distinguish high and low VIMS-provoking stimulations. To examine the possibility, the PLV310 measured before training with two stimulations were compared. Majority participants rated higher and more severe VIMS for roll stimulation (n=31). The comparison results on this group of participants is displayed in Figure 34. PLV301 measured with roll stimulation were significantly higher than that measured with pitch stimulation ($p=0.009$, paired t test).

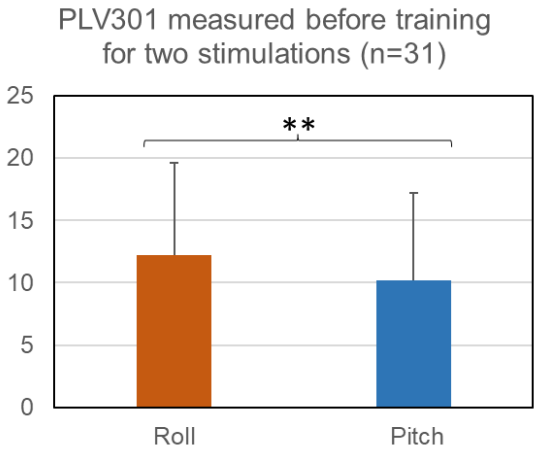


Figure 34. PLV301 measured with roll stimulation were significantly higher than that measured with pitch stimulation.

7.5.2 Position of VIMS-resistance PLV indicator: PLV410

Also being a negative indicator for VIMS susceptibility, PLV410 measure with Roll or Pitch stimulation after training were significantly greater than that measured after training, for those who had a transition from susceptible to resistant (trained-to-be resistant) after the habituation training. The enhancement of habituation training on the phase synchronization between P7 and P4 (PLV410) was independent with the type of stimulation, but only appeared on those trained to be resistant. The habituation training increased the synchronization between right and left parietal areas and meanwhile decreased VIMS. It is possible that PLV410 is an indicator related to suppress VIMS symptoms directly.

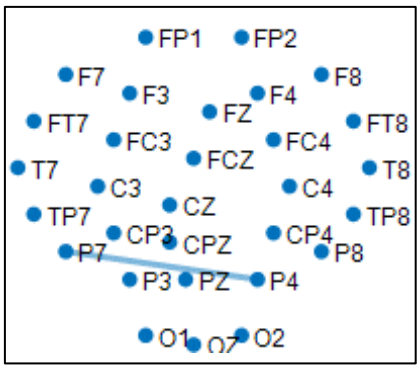


Figure 35. Recording sites of the VIMS-susceptibility indicators PLV410-P4P7

According to the study on visual-vestibular interaction during vection (Brandt et al., 1998), bilateral parietal-occipital areas were activated during circular vection compared to the control condition. The VIMS-resistance indicator PLV410 was the inter-hemispheric synchronization between right medial parietal (P4) and left lateral parietal (P7) recording sites. The medial

parietal-occipital cortex was found to corresponds to a visual area in the parieto-occipital fissure in response to circular vection stimulation (Dupont et al., 1994). The synchronization between two parietal regions was higher in VIMS-resistant participants and that of VIMS-susceptible participants turned to be significantly higher after they were trained to be resistant to VIMS. The increased VIMS resistance was supposed to be related to the synchronized activity between inter-hemipheric parietal regions.

Chapter 8. Summary, Limitation and Conclusion

8.1 VIMS susceptibility prediction

The research aims to investigate the neurological foundation of VIMS susceptibility and possibly develop a new approach to predict VIMS susceptibility more accurately.

8.1.1 VIMS susceptibility prediction with questionnaire

In subsection 4.5.2.2, the prediction with questionnaire scores were conducted. The MSSQ score was a predictor for the post-SSQ scores after the behavioral test and maximal nausea scores. The results are organized in Table *13*. The prediction on VIMS with MSSQ scoresTable *13*.

Table 13. The prediction on VIMS with MSSQ scores

Prediction with MSSQ scores	Roll	Pitch
Post-SSQ	R-square=0.178, p=0.013	R-square=0.177, p=0.013
MaxNausea	R-squared=0.162, p=0.018	R-squared=0.193, p=0.009

8.1.2 VIMS susceptibility prediction with EEG indicators

In Study Two on the EEG indicators for VIMS susceptibility (Section 5.4), a series of EEG indicators were discovered with hypothetical neurophysiological meaning. In addition, slight better predictions were also acquired by models only with EEG indicators. Coincidently, those models all consist of only one positive indicator and only one negative indicator, which is consistent with the hypothesis that VIMS severity is predictable with the difference between sensory conflict and neural coordination for relief (H2.3).

Table 14. VIMS Prediction results with EEG indicators

Indicator Combination	Roll PostSSQ	Roll Nausea	Pitch PostSSQ	Pitch Nausea
R301-R325	R^2=0.279 p = 0.006			
R301-R410		R^2=0.358 p = 0.001		
R301-R410				R^2=0.432 p < 0.001
P253-P426	R^2=0.324 p = 0.002			
P253-P429		R^2=0.260 p = 0.009		R^2=0.279 p = 0.006

8.1.3 Contributions, limitations, and future work

This research explored the possibility to predict future VIMS severity with EEG signals and achieved promising results. As to optimized models shown in Table 15, the coefficients of those indicators found to be higher in resistant group were all consistent negative; the coefficients of those indicators found to be higher in susceptible group were all consistent positive in predict VIMS susceptibility. Furthermore, when combine the EEG indicators and MSSQ, the prediction could be much more accurate. The prediction model was developed for Roll post-SSQ with PLV indicators measured with Roll stimulation as an example (like 45.4% of variation).

Table 15. Roll post-SSQ prediction with MSSQ and EEG indicator measured with Roll stimulation

Variables of FirstSSQ	**Coefficient**	**P-value**	**Location**
(Intercept)	0.434	0.970	
MSSQ	1.070	0.004	
PreR325	-1.238	0.004	Between Cz and Pz
PreR.Rot301	1.633	0.015	Between C3 and C4
Multiple R-squared	0.454	**P-value**	<0.001

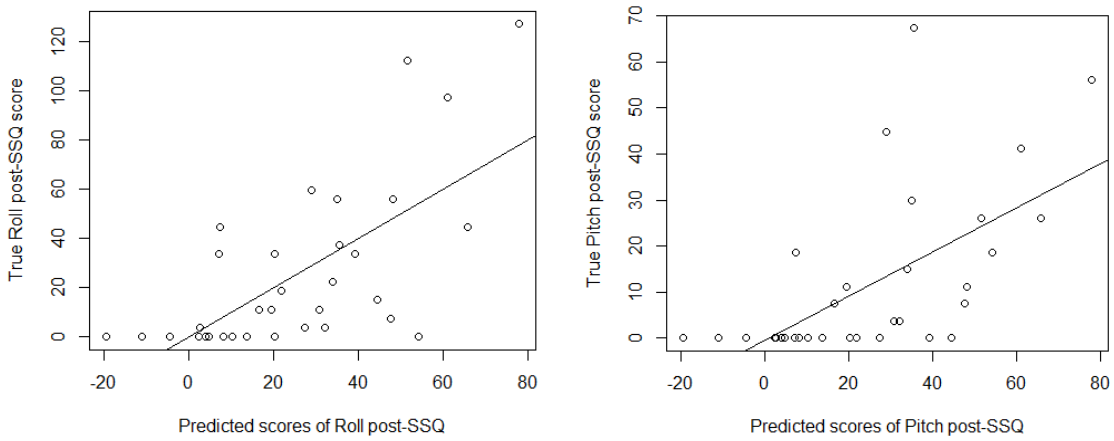


Figure 36. Roll (left) and Pitch (right) post-SSQ prediction with MSSQ and EEG indicator measured with Roll stimulation

Although the prediction with EEG indicators could be slightly better than that only with MSSQ scores, there are still many problems with the development of EEG indicator models for VIMS susceptibility:

1. EEG signal measurement and data processing
2. Selection of EEG indicators for model development
3. The consistence between VIMS responses for different VIMS-provoking stimulations

To overcome the latter two limitations, the future work could start with more type of VIMS-provoking stimulations and paradigms of EEG indicators. The comparison among different types of VIMS-provoking stimulation would shed light on the entire prediction model of VIMS susceptibility, in which there could be another latent variable for indicating the ability of a VIMS stimulation in inducing sensory conflict. There is a certain difference in both VIMS-provoking stimulations and individuals' response to them. Taking the difference interactions with VIMS-provoking stimulations into consideration would be a necessary step to predict VIMS response.

8.2 Neurophysiological foundation of VIMS susceptibility

In the EEG study comparing two groups with different VIMS susceptibility, the PLV calculated in theta band under ROT condition between certain pairs of electrodes were correlated with the subjective ratings for VIMS.

8.2.1 PLV indicators related to Resistance to VIMS

There were some pairs of electrodes around central-parietal areas to occipital areas whose signals with higher phase synchronization within-pair in resistant group, which could be an indicator of neural coordination to reduce VIMS.

8.2.2 PLV indicators related to VIMS susceptibility

There were a few pairs of electrodes around central-frontal areas between hemispheres, whose signals with higher phase synchronization within-pair in susceptible group, which could be an indicator of VIMS severity, or more specifically, possible indicator for sensory conflict response.

8.2.3 PLV indicator validated by Habituation training

With the comparison on two EEG datasets acquired before and after training, the hypothetical meanings of positive indicator (sensory conflict/VIMS severity) and negative indicators (neural coordination/VIMS relieve) were supported. The phase synchronization between C3 and C4 (PLV301) reduced after training; phase synchronization between FCz and Pz (PLV240)

measured with Roll stimulation increased after training; and the phase synchronization between P7 and P4 (PLV410) decreased for those who turned to be resistant from susceptible after training.

8.2.4 Limitations and future work

The EEG studies were limited by the low spatial resolution. Future work would be the phase synchronization analyses based on the estimated source. Facilities with higher spatial resolution could also be considerate, like MRI. Besides, although we intended to investigate the PLV indicators which could be valid regardless the VIMS-provoking stimulation used in short exposure, only two visual stimulations were adopted. Therefore, the "cross-stimulation" or "stimulation-independent" claims in the current research were limited to the roll stimulation and pitch stimulation. More types of VIMS-provoking stimulations were needed in future work to verify the generalization of these PLV indicators.

8.3 Habituation training with repeated exposures to Roll stimulation

8.3.1 Summary of findings

In the post-training behavioral test with Roll stimulation, the VIMS responses were reduced significantly, especially for those who were susceptible.

The VIMS responses to Pitch stimulation were only reduced significantly for susceptible individuals who had been trained to be resistant (Figure *14*).

Most participants (86.2%) could be trained to resistant: reporting a maximal nausea score no more than 2 - "slight discomfort".

Habituation training led to the significantly reduction in the angles of RND test for Susceptible individuals but did not change that of resistant group.

The posture sway range along x-axis during watching roll stimulation was significantly shorter after training in susceptible group, suggestion an improvement in postural stability.

8.3.2 Contribution

This research examined the characteristic of habituation training with a roll circular vection inducing stimulation. Most susceptible participants needed a 7-day training to get habituation, and a few susceptible individuals needed a 10-day training.

The effects of habituation training on tasks with visual-vestibular interaction involved were analyzed. It was found that the postural control during VIMS exposure, visual dependence, and VIMS to pitch, were all significantly changed by habituation training for those individuals who were susceptible and had a transition from susceptible to resistant.

8.3.3 Limitation and future work

There were more postural stability indicators to be investigated, which could introduce some more reliable and repeatable postural indicators for VIMS susceptibility. There were three participants who did not appear to get resistance to VIMS even with extended training sessions. The efficacy of habituation training needs to be explored to explain the phenomenon. Also, as only two stimulations were utilized in the research and only the roll stimulation was adopted in the habituation training, the training effect across stimulation was referred to the effects on VIMS symptoms to pitch stimulation. Future work involving more diversity VIMS-provoking stimulations is desirable.

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APPENDIX – A VIMS susceptibility survey

VIMS Susceptibility Survey

Start of Block: Introduction and Consent

1

Welcome to VIMS Susceptibility Survey

This survey is conducted to learn about people's susceptibility to MS* and VIMS* from their experiences in various visual exposures, like watching movies or playing video games and its distribution in the population. MS: The term **Motion Sickness** (MS) refers to symptoms, such as dizziness, fatigue, nausea, headache, sweating, and vomiting, which can be evoked in susceptible individuals by the perception of various kinds of periodic motion.

VIMS: When motion sickness occurs under visual stimulation without physical motion, it is referred to as **Visually Induced Motion Sickness (VIMS).**

The following questionnaire will take about 7 minutes.

○ I consent to take part in the survey. My replies to the questions are correct to the best of my belief, and I understand that they will be treated as confidential by the experimenter. (7)

*

2 Please state your e-mail

_____

End of Block: Introduction and Consent

Start of Block: For each of the following types of transport or entertainment, please indicate:

12 As a CHILD (before age of 12), how often have you felt sick or nauseated (tick boxes)

	Not Applicable- Never Travelled (1)	Never Felt Sick (2)	Rarely Felt Sick (3)	Sometimes Felt Sick (4)	Frequently Felt Sick (5)
Cars (1)	○	○	○	○	○
Buses or Coaches (2)	○	○	○	○	○
Trains (3)	○	○	○	○	○
Aircrafts (4)	○	○	○	○	○
Small Boats (5)	○	○	○	○	○
Ships, e.g. Channel Ferries (6)	○	○	○	○	○
Swings in playgrounds (7)	○	○	○	○	○
Roundabouts in playgrounds (8)	○	○	○	○	○
Big Dippers, Funfair Rides (9)	○	○	○	○	○

13 Over the LAST 10 YEARS, how often have you felt sick or nauseated (tick boxes)

	Not Applicable- Never Travelled (1)	Never Felt Sick (2)	Rarely Felt Sick (3)	Sometimes Felt Sick (4)	Frequently Felt Sick (5)
Cars (1)	○	○	○	○	○
Buses or Coaches (2)	○	○	○	○	○
Trains (3)	○	○	○	○	○
Aircrafts (4)	○	○	○	○	○
Small Boats (5)	○	○	○	○	○
Ships, e.g. Channel Ferries (6)	○	○	○	○	○
Swings in playgrounds (7)	○	○	○	○	○
Roundabouts in playgrounds (8)	○	○	○	○	○
Big Dippers, Funfair Rides (9)	○	○	○	○	○

End of Block: For each of the following types of transport or entertainment, please indicate:

Start of Block: MSSS

Q28 In the past 12 months how often have you experienced **motion sickness** while traveling as a passenger the following situations? (e.g., If you travel by bus 300 times a year and experience motion sickness 30 times, that would be 10% of the time.)

	0% (1)	1%-10% (2)	11%-40% (3)	41%-74% (4)	75%-100% (5)
Car/Taxi (1)	○	○	○	○	○
Buses (2)	○	○	○	○	○
Cross-Ferry (3)	○	○	○	○	○
Jet-Foil (4)	○	○	○	○	○
Trains (5)	○	○	○	○	○
Elevators (6)	○	○	○	○	○

Q30 Please circle the symptoms experienced while in the following situations:
(For one items, if 0% was selected in last questions, then do not click any symptoms)

	Sweating (1)	Nausea (2)	Dizziness (3)	Headache (4)	Vomiting (5)
Car/Taxi (1)	☐	☐	☐	☐	☐
Buses (2)	☐	☐	☐	☐	☐
Cross-Ferry (3)	☐	☐	☐	☐	☐
Jet-Foil (4)	☐	☐	☐	☐	☐
Trains (5)	☐	☐	☐	☐	☐
Elevators (6)	☐	☐	☐	☐	☐

Q31 In general, how susceptible to motion sickness are you?

- Not at all (1)
- Slightly (2)
- Moderately (3)
- Very (4)
- Extremely (5)

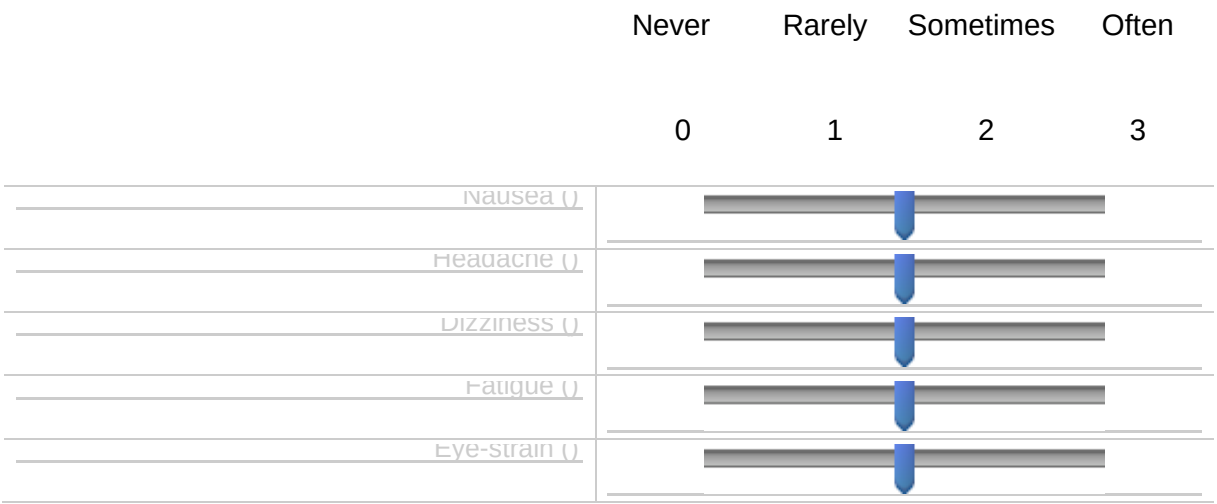
End of Block: MSSS

Start of Block: VIMSSQ

7
How often have you experienced each of the following symptoms when using any of these devices? (Please answer this question based on the device which leads to the most severe symptoms.)

Visual display or entertainment devices include movie theatre or cinema, smartphones & tablets with movies or games, video games, virtual reality glasses or head mounted displays, large public moving display advertising or information screens.

Please answer these questions solely with respect to your experiences during adulthood (older than 18 years) and ignore childhood experiences.



8 Have any of these symptoms stopped you from using any of these devices or made you avoid viewing such displays? (Please answer this question based on the device which leads to the most severe symptoms.)

- ○ Never (1)
- ○ Rarely (2)
- ○ Sometimes (3)
- ○ Often (4)

---

9 If your symptoms have stopped or avoided you from using the devices, please list the devices or displays that you avoid.

- ☐ Movie Theatre or Cinema (4)
- ☐ Smartphones & Tablets with movie or video games (5)
- ☐ Video Games (6)
- ☐ Virtual Reality Glasses or Head Mounted Displays (7)
- ☐ Large Public Moving Display Advertising or Information Screens (8)
- ☐ Other (9) _____

---

10 Do you have a past history of headaches and/or migraines? If so, please state how often it happens (per week).

- ○ Yes (4) _____
- ○ Maybe (5)
- ○ No (6)

---

11 Do you have a preference for AND participate in extreme sports (not limited to cliff jumping and rock climbing)? If so, please state the frequency (per year).

- ○ Yes (1) _____
- ○ Maybe (2)
- ○ No (3)

End of Block: VIMSSQ

Start of Block: Game and ITQ

14 Choose the following:

	Extremely Easily (1)	Most Easily (2)	Probably Easily (3)	Somewhat Easily (4)	Probably Not Easily (5)	Most Likely Hard (6)	Extremely Hard (7)
How easily can you allocate or focus your attention on specific tasks or activities for more than 30 minutes? (13)	○	○	○	○	○	○	○
How easily can you switch your attention from the task in which you are currently involved in to a new task? (22)	○	○	○	○	○	○	○
How easily can you block out external distractions when working on a task? (23)	○	○	○	○	○	○	○
How easily do you concentrate on enjoyable activities? (24)	○	○	○	○	○	○	○
How easily do you concentrate on disagreeable tasks? (25)	○	○	○	○	○	○	○
How easily do you get excited during a chase or fight scene on TV or in the movies? (26)	○	○	○	○	○	○	○
How easily do you get scared/startled when watching a scary movie? (27)	○	○	○	○	○	○	○

Are you easily distracted when working on a task? (30)	○	○	○	○	○	○	○

15 How many hours per day do you engage in the following activities? (Based on the average level in recent two weeks.)

_____ Mobile Games (6)
_____ Other Video Games (4)
_____ Watching TV (5)
_____ Physical activities (7)

16 Choose the following:

	Frequently (1)	Most Frequently (2)	Somewhat Frequently (3)	Moderately Frequently (4)	Somewhat Not Frequently (5)	Seldom (6)	Never (7)
Have you ever remained apprehensive or fearful long after watching a scary movie? (1)	○	○	○	○	○	○	○
How frequently do you get emotionally involved (angry, sad, or happy) when engaging in gaming experience or movies/TV drama? (3)	○	○	○	○	○	○	○
How frequently do you find yourself closely identifying with the characters in a story line? (15)	○	○	○	○	○	○	○
How frequently do you find yourself involved in a daydream such that you are not aware of things happening around you? (17)	○	○	○	○	○	○	○

Do you ever have dreams that are so real that you feel disoriented when you awake? (18)	○	○	○	○	○	○	○

17 During or after a visual experience (like watching a 2D/3D/VR movie, or playing video/VR games with little physical motion)..

	Always (1)	Almost always (2)	Somewhat always (3)	Moderately (4)	Somewhat never (5)	Seldom (8)	Never (9)
Do you ever feel discomfort without physical motion? (1)	○	○	○	○	○	○	○
Do you ever become so involved that you lose track of time? (2)	○	○	○	○	○	○	○
Do you ever become so involved that people have problems getting your attention? (3)	○	○	○	○	○	○	○
Do you ever become so involved that it is as if you are a character of the movie or inside the video game rather than watching the screen? (6)	○	○	○	○	○	○	○

19 Do you experience any psychological disorder such as major depressive disorder? If so, please describe.

_____

_____

_____

_____

_____

End of Block: Game and ITQ

Start of Block: Demographics

3 Please state your age

_____

4 Please state your biological sex

- ○ Male (1)
- ○ Female (2)
- ○ Prefer not to say (3)

5 Please choose your racial/ethnic identity (Check all that apply)

- ☐ Chinese (1)
- ☐ Indonesian (2)
- ☐ Filipino (3)
- ☐ White (4)
- ☐ Indian (5)
- ☐ Pakistani (6)
- ☐ Nepalese (7)
- ☐ Japanese (8)
- ☐ Thai (9)
- ☐ Other Asian (10)
- ☐ African (11)
- ☐ Hispanic/Latino (12)
- ☐ Others (13) _____

Q36 Are you right-handed?

- ○ Yes (4)
- ○ No (5)

---

6 Current situation (Please state your grade if it is applicable):

- ○ Undergraduate (1) _____
- ○ Postgraduate (2) _____
- ○ Employed (3)
- ○ Others (4) _____

Q37 Other Contact Methods (Optional)

- ○ WhatsApp (1) _____
- ○ WeChat (2) _____
- ○ Other (3) _____

End of Block: Demographics

APPENDIX – B VIMSS behavioral test record

VIMSS Behavioral Test Record

Start of Block: Pre-SSQ

Q1 Subject Information

- Subject Number (1) _____
- Subject Name (2) _____
- View height (cm) (3) _____

Q2 Visual Stimulation

- Roll (1)
- Pitch (2)

Q3 Pre-exposure instruction: please fill in this questionnaire. Circle below if any of the symptoms apply to you now.

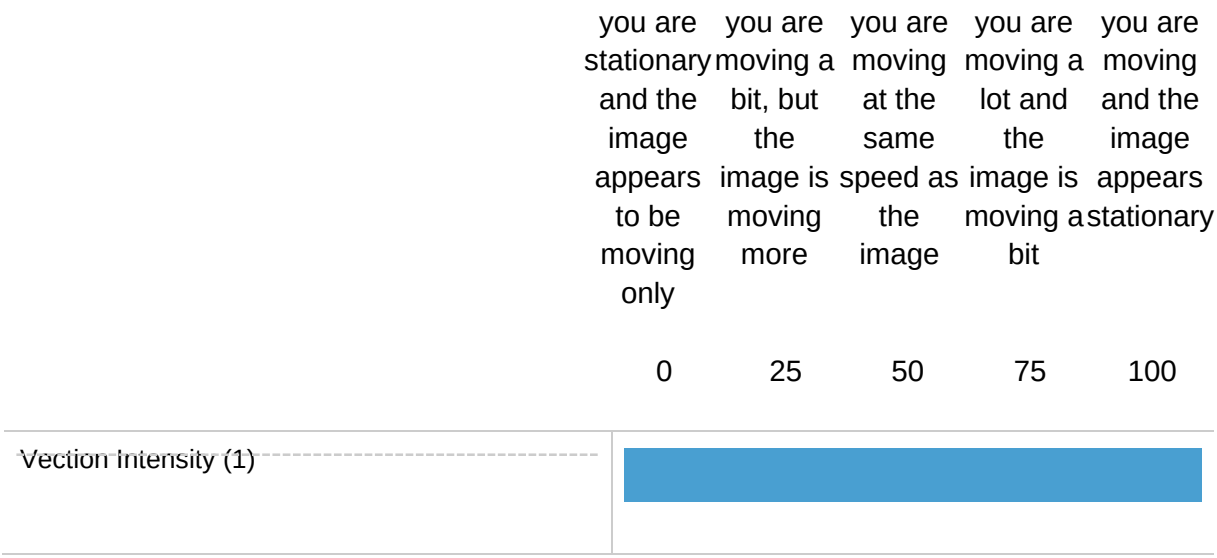
	None (1)	Slight (2)	Moderate (3)	Severe (4)
General discomfort 一般不適 (1)	○	○	○	○
Fatigue 疲倦 (2)	○	○	○	○
Boredom 沉悶 (3)	○	○	○	○
Drowsiness 想睡 (4)	○	○	○	○
Headache 頭痛 (5)	○	○	○	○
Eyestrain 眼痛 (6)	○	○	○	○
Difficulty focusing 很難集中視力 (7)	○	○	○	○
Salivation increase 口水分泌增加 (8)	○	○	○	○
Salivation decrease 口水分泌減少 (9)	○	○	○	○
Sweating 出汗 (10)	○	○	○	○
Nausea 作嘔 (11)	○	○	○	○
Difficulty concentrating 很難集中精神 (12)	○	○	○	○
Mental depression 精神的壓抑 (13)	○	○	○	○
“Fullness of the head" 頭脹 (14)	○	○	○	○
Blurred vision 視野模糊 (15)	○	○	○	○
Dizziness eyes open 眼花（開） (16)	○	○	○	○

Dizziness eyes close 眼花 （合） (17)	○	○	○	○
Vertigo 眩暈 (18)	○	○	○	○
Visual flashbacks 幻覺 (19)	○	○	○	○
Faintness 昏厥 (20)	○	○	○	○
Aware of breathing 呼吸異樣 (21)	○	○	○	○
Stomach awareness 胃感覺異樣 (22)	○	○	○	○
Loss of appetite 沒有胃口 (23)	○	○	○	○
Increased appetite 胃口增加 (24)	○	○	○	○
Desire to move bowels 想去洗手間 (25)	○	○	○	○
Confusion 迷惘 (26)	○	○	○	○
Burping 打嗝 (27)	○	○	○	○
Vomiting 嘔吐 (28)	○	○	○	○
Other 其他 (29)	○	○	○	○

End of Block: Pre-SSQ

○ **Start of Block: Long Exposure 20 min**

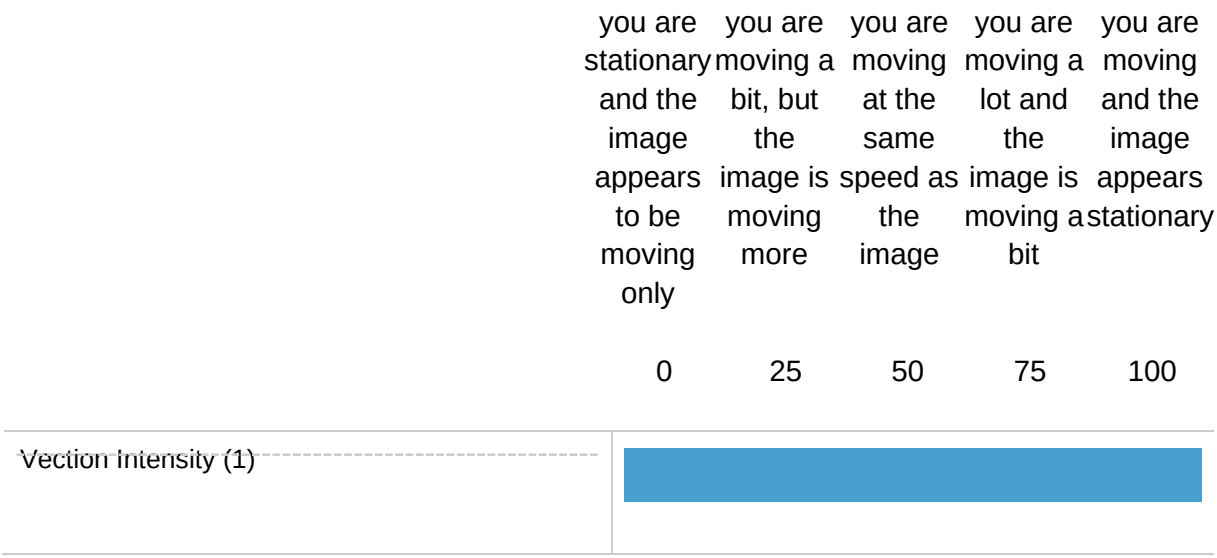
Q7 Long Exposure (5min): you feel like



Q8 Nausea Rating (5min)

- ○ No symptoms (1)
- ○ Any unpleasant symptoms, however slight (2)
- ○ Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea (3)
- ○ Mild nausea (4)
- ○ Mild to moderate nausea (5)
- ○ Moderate nausea but can continue (6)
- ○ Moderate nausea, want to stop (7)

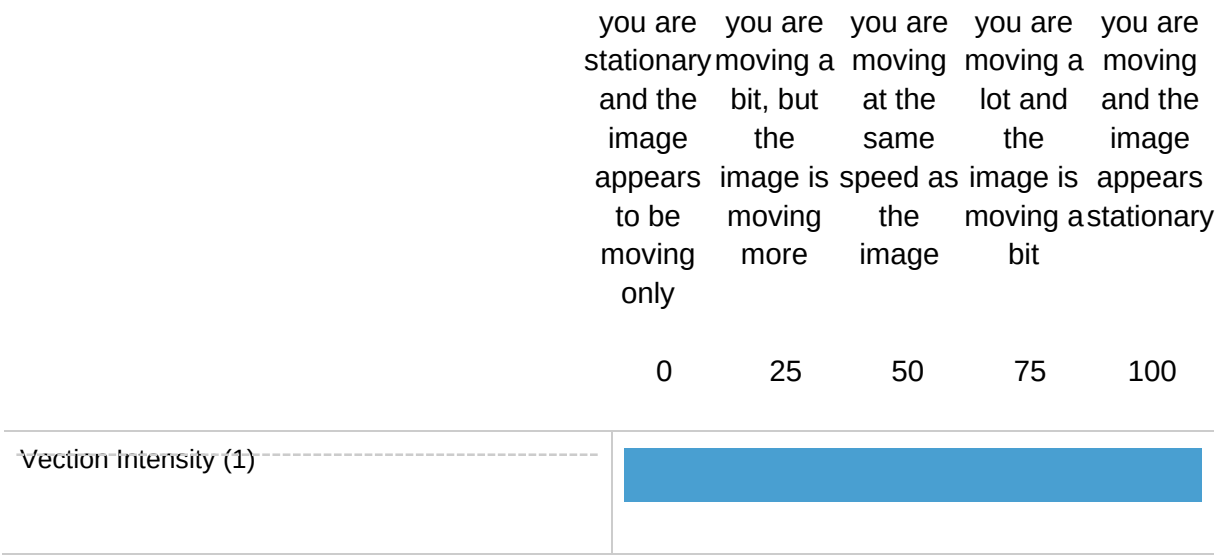
Q9 Long Exposure (10min): you feel like



Q10 Nausea Rating (10min)

- ○ No symptoms (1)
- ○ Any unpleasant symptoms, however slight (2)
- ○ Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea (3)
- ○ Mild nausea (4)
- ○ Mild to moderate nausea (5)
- ○ Moderate nausea but can continue (6)
- ○ Moderate nausea, want to stop (7)

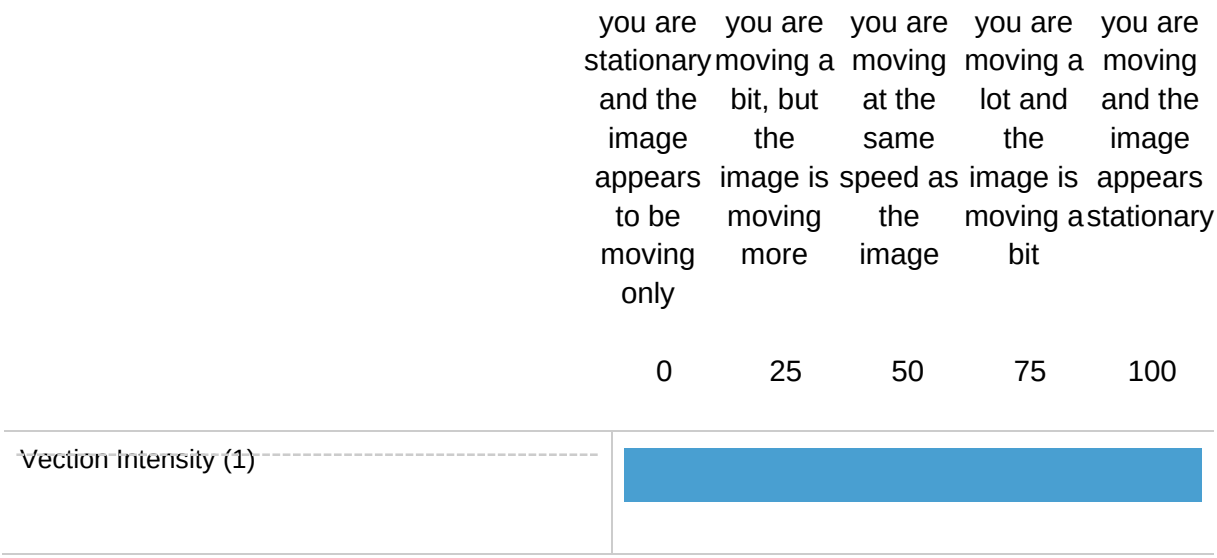
Q11 Long Exposure (15min): you feel like



Q12 Nausea Rating (15min)

- ○ No symptoms (1)
- ○ Any unpleasant symptoms, however slight (2)
- ○ Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea (3)
- ○ Mild nausea (4)
- ○ Mild to moderate nausea (5)
- ○ Moderate nausea but can continue (6)
- ○ Moderate nausea, want to stop (7)

Q13 Long Exposure (20min): you feel like



Q14 Nausea Rating (20min)

- No symptoms (1)
- Any unpleasant symptoms, however slight (2)
- Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea (3)
- Mild nausea (4)
- Mild to moderate nausea (5)
- Moderate nausea but can continue (6)
- Moderate nausea, want to stop (7)

End of Block: Long Exposure 20 min

Start of Block: Post SSQ

Q15 Post-exposure instruction: please fill in this questionnaire. Circle below if any of the symptoms apply to you now.

	None (1)	Slight (2)	Moderate (3)	Severe (4)
General discomfort 一般不適 (1)	○	○	○	○
Fatigue 疲倦 (2)	○	○	○	○
Boredom 沉悶 (3)	○	○	○	○
Drowsiness 想睡 (4)	○	○	○	○
Headache 頭痛 (5)	○	○	○	○
Eyestrain 眼痛 (6)	○	○	○	○
Difficulty focusing 很難集中視力 (7)	○	○	○	○
Salivation increase 口水分泌增加 (8)	○	○	○	○
Salivation decrease 口水分泌減少 (9)	○	○	○	○
Sweating 出汗 (10)	○	○	○	○
Nausea 作嘔 (11)	○	○	○	○
Difficulty concentrating 很難集中精神 (12)	○	○	○	○
Mental depression 精神的壓抑 (13)	○	○	○	○
“Fullness of the head" 頭脹 (14)	○	○	○	○
Blurred vision 視野模糊 (15)	○	○	○	○
Dizziness eyes open 眼花（開） (16)	○	○	○	○

Dizziness eyes close 眼花 （合） (17)	○	○	○	○
Vertigo 眩暈 (18)	○	○	○	○
Visual flashbacks 幻覺 (19)	○	○	○	○
Faintness 昏厥 (20)	○	○	○	○
Aware of breathing 呼吸異樣 (21)	○	○	○	○
Stomach awareness 胃感覺異樣 (22)	○	○	○	○
Loss of appetite 沒有胃口 (23)	○	○	○	○
Increased appetite 胃口增加 (24)	○	○	○	○
Desire to move bowels 想去洗手間 (25)	○	○	○	○
Confusion 迷惘 (26)	○	○	○	○
Burping 打嗝 (27)	○	○	○	○
Vomiting 嘔吐 (28)	○	○	○	○
Other 其他 (29)	○	○	○	○

Q16 Do you think you were motion sick?

○ Yes (1)

○ No (2)

End of Block: Post SSQ

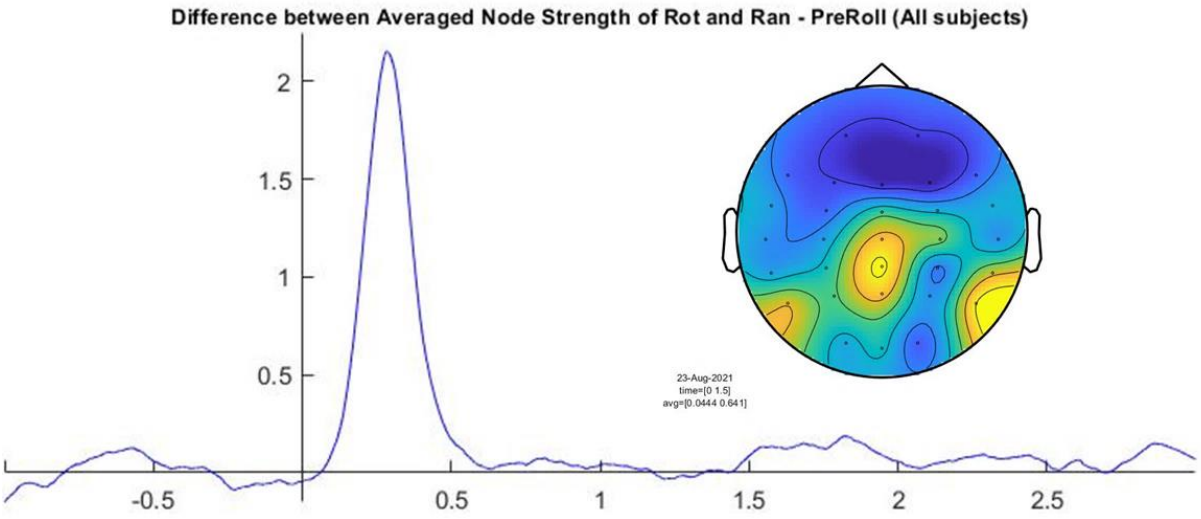
APPENDIX – C VIMS susceptibility PLV indicators: difference between ROT and RAN conditions

In Roll Stimulation Condition:

(Finding 1.1:) the synchronization in response to Rotation Condition (ROT) was higher than that in response to Random Condition (RAN).

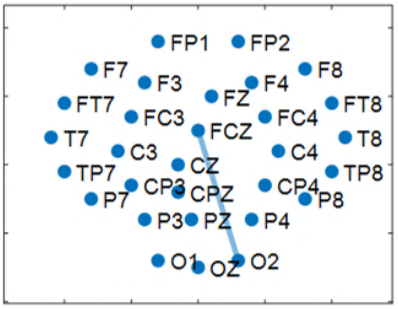
There are 30 electrodes numbered from 1 to 30. For each electrode, the relationships between itself with 29 other channels are of interest. Therefore, there are 435 combinations by excluding repeated linkages in total. The phase synchronization between two electrodes were represented with PLV and a number which is the order of this linkage in all 435 combinations. For example, PLV240 represents for the PLV of the 240th channel pairs, which is the pair of electrodes FCz and Pz.

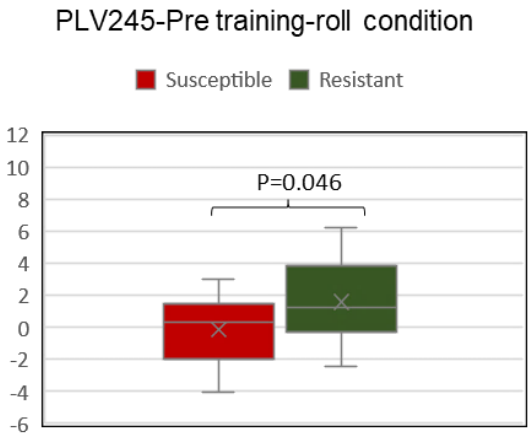
Within susceptible group, when comparing ROT and RAN

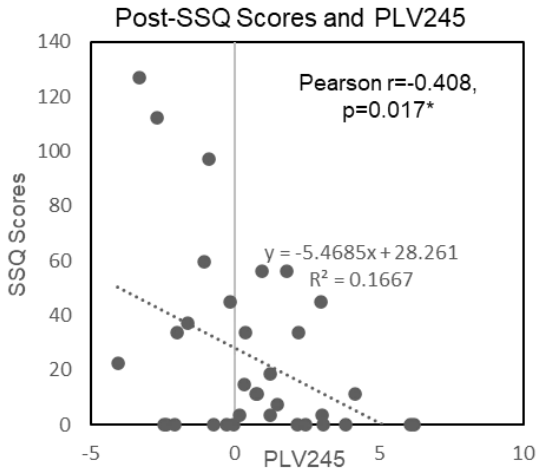


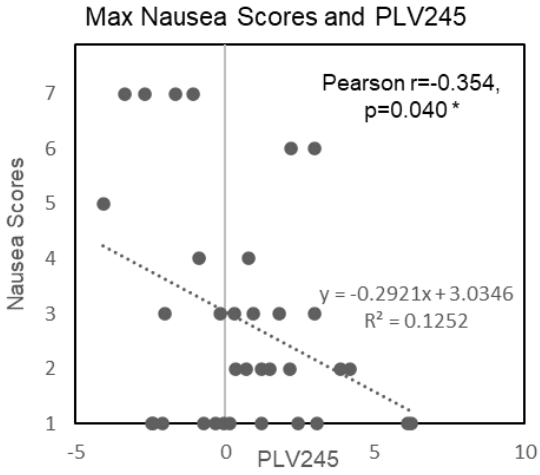
(Finding 1.2) synchronization between frontal-central area and occipital area was higher in resistant group than that in susceptible group and it was negatively correlated with the VIMS severity.

PLV245: the phase synchronization indicator between electrode FCz and O2 at theta band.



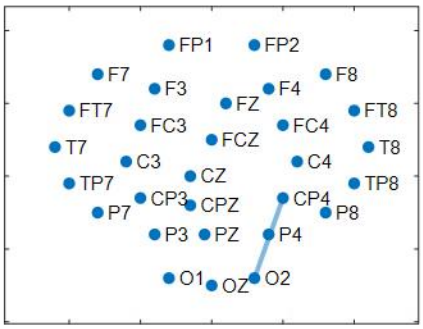


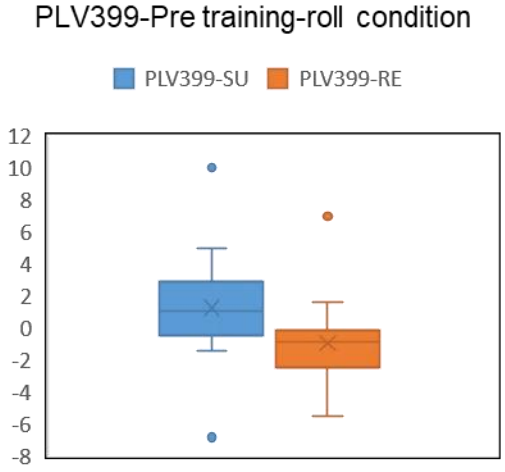




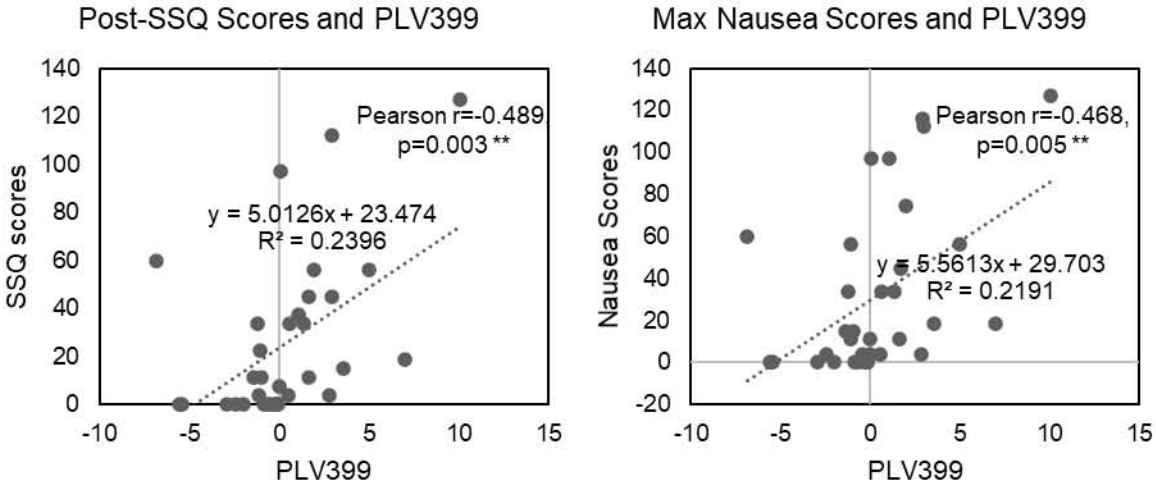
Finding 1.3: synchronization between right central-parietal area and occipital area was higher in susceptible group than that in resistant group and it was positively correlated with the VIMS severity.

PLV399: the phase synchronization indicator between electrode CP4 and O2 at theta band.



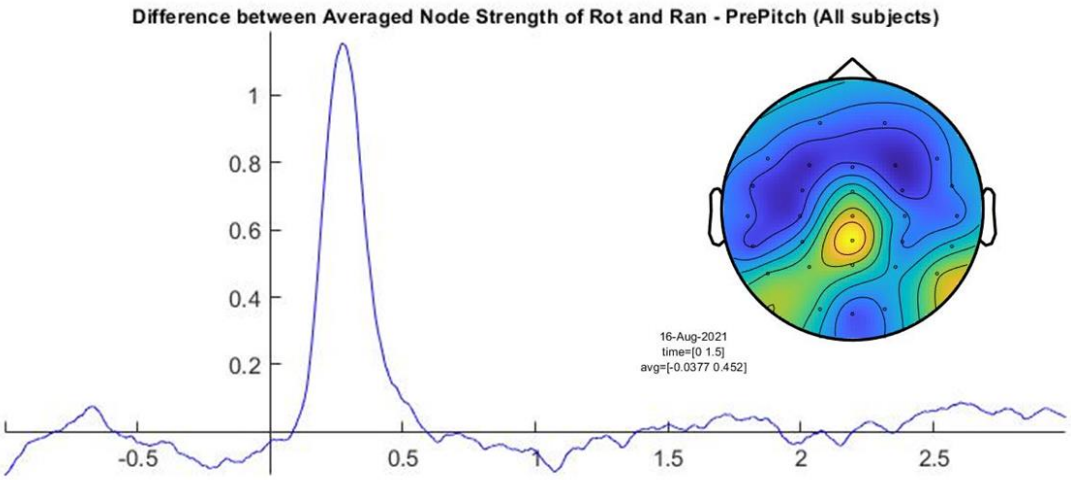


The difference in PLV399 between susceptible subjects and resistant subjects was marginally significant (p = 0.051).

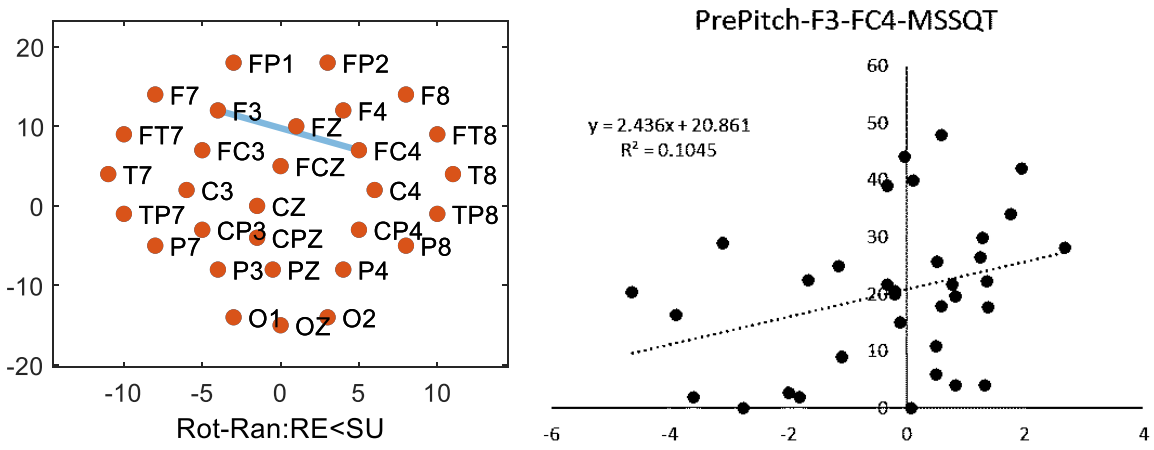


In Pitch Stimulation condition:

As for the Pitch stimulation condition, there difference between averaged node strength of ROT and RAN also showed a distribution around parietal.

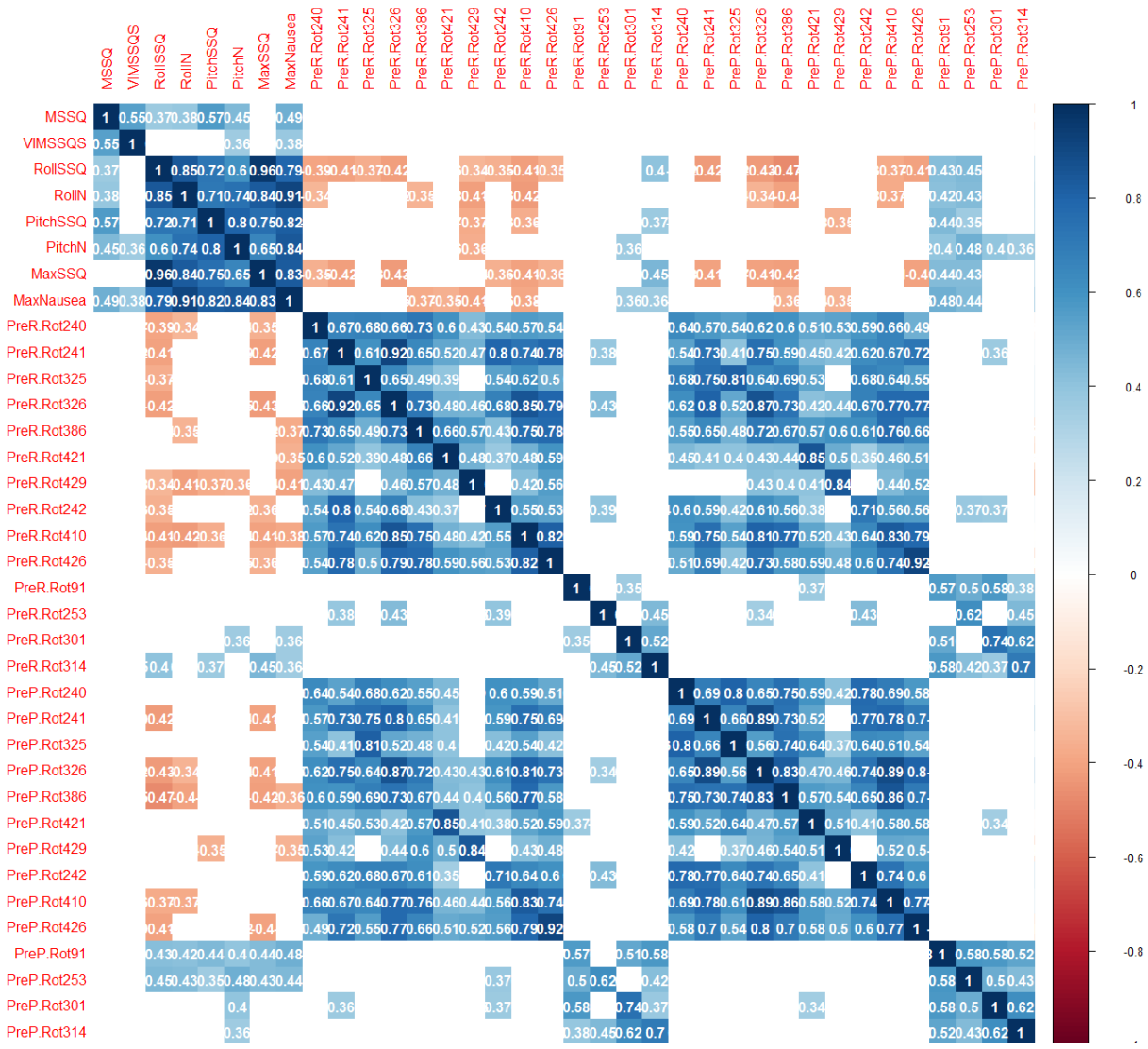


When the ROT-RAN was taken as the dependent variable compared between two groups, the significant higher PLV between F3 and FC4 (PLV91) were found in susceptible group than resistant group. In addition, there was a moderate correlation between PLV91 and MSSQ total scores.



APPENDIX – D Correlation between VIMS ratings and EEG PLV indicators measured with two stimulations

The Spearman correlations between VIMS subjective rating and EEG PLV indicators measured under Roll and Pitch stimulation were demonstrated in the following figure. Each colored point indicated a significant correlation coefficient.



There were moderate correlations between PLV indicators measured under Roll condition and those measured under Pitch condition.

APPENDIX – E Codes to generate stimulations in EEG recording

```
% Generate the Roll Stimulation

% Clear the workspace
close all;
clear all;
sca;

numberOfBlocks=18;

OnsetDelay(1:numberOfBlocks)=0;
VectionIntensity(1:numberOfBlocks)=0;
timerecord(1:8,1:numberOfBlocks)=0;
fixR=1;
%% Output info set
% Enter participate No
% error messagewhich is printed to command window
FailMessage='Program aborted. Wrong input';
prompt1 = {'Enter participant number:'};
prompt2 = {'Enter Block number'};
prompt3 = {'Enter Trial number'};
dlg_title ='Participant Number Information';
num_lines = 1;
def = {'1'};
answer1 = inputdlg(prompt1,dlg_title,num_lines,def);
switch isempty(answer1)
    case 1
        error(FailMessage);
    case 0
        subject = (answer1{1});
end
answer2 = inputdlg(prompt2,dlg_title,num_lines,def);
switch isempty(answer2)
   case 1
       error(FailMessage);
   case 0
       b = (answer2{1});
       block = [b 'r'];
end

%% Here we call some default settings for setting up Psychtoolbox
PsychDefaultSetup(2);

%%
%--------------------------------------------------------------------------
%                   Basic Information of the screen
%--------------------------------------------------------------------------
% Get the screen numbers
screens = Screen('Screens');

% Draw to the external screen if avaliable
% screenNumber = max(screens);
screenNumber = 2;
% Define black and white
white = WhiteIndex(screenNumber);
black = BlackIndex(screenNumber);
grey = 0.53;

% Open an on screen window
```

```
[window, windowRect] = PsychImaging('OpenWindow', screenNumber, black);
HideCursor;

% Get the size of the on screen window
[screenXpixels, screenYpixels] = Screen('WindowSize', window);

% Get the centre coordinate of the window
[xCenter, yCenter] = RectCenter(windowRect);

% Query the frame duration
ifi = Screen('GetFlipInterval', window);

% Set up alpha-blending for smooth (anti-aliased) lines
Screen('BlendFunction', window, 'GL_SRC_ALPHA', 'GL_ONE_MINUS_SRC_ALPHA');

%%
%--------------------------------------------------------------------
%                       Parameters Defination
%--------------------------------------------------------------------
% scale factor should be 83.4/57.5;
dotNo = 3442;
dotDiaMin = 5;
dotDiaMax = 14;
%% experiment session defination

%% Define a checherboard
checksize = 10;
checkNoV = 18;
checkNoH = 24;
contr=1;
checkerboard = repmat(eye(2)*contr, checkNoV/2, checkNoH/2);
imageTexture(1) = Screen('MakeTexture', window, checkerboard);
imageTexture(2) = Screen('MakeTexture', window, contr-checkerboard);
[s1, s2] = size(checkerboard);
dstRect = [0 0 s2 s1] .* checksize;
dstRect = CenterRectOnPointd(dstRect, xCenter, yCenter);
dstRect2 =dstRect;
dstRect2(1:2) =dstRect(1:2)-10;
dstRect2(3:4) =dstRect(3:4)+10;

% Time we want to wait before reversing the contrast of the checkerboard
checkFlipTimeSecs = 1/8.6; %%center fliker frequency is 8.5714
checkFlipTimeFrames = round(checkFlipTimeSecs / ifi);
flowFlipTimeSecs =1/12; %%peripehral fliker frequency is 12
Flipfrequency=round(flowFlipTimeSecs / ifi);
flipCounter=0;
frameCounter = 0;

% Texture cue that determines which texture we will show
textureCue = [1 2];
%% Define a fix point
baseRect = [0 0 7 7];
centeredRect = CenterRectOnPointd(baseRect, xCenter, yCenter);
centeredBArea= CenterRectOnPointd(baseRect*20, xCenter, yCenter);
rectColor = [1 0 0];

%% Define dots
RandotSpeed =(yCenter*pi)*32/360*ifi;
r = randi([dotDiaMin,dotDiaMax],1,dotNo);
MaxCanvasX=2061;
MinCanvasX=-141;
MaxCanvasY=1641;
```

```
MinCanvasY=-561;
xPos = randi([MinCanvasX MaxCanvasX],1,dotNo);
yPos = randi([MinCanvasY MaxCanvasY],1,dotNo);
R = sqrt((xPos - xCenter).^2+(yPos-yCenter).^2);
Angle = atan2((yPos-yCenter),(xPos-xCenter));
RandomAngle = deg2rad(randi([0,360],1,dotNo));
dotColor = [0.25 0.25 0.25;0.45 0.45 0.45];

%%
%--------------------------------------------------------------------
%                          Movement Defination
%--------------------------------------------------------------------
%% movement parameter defination
% Angular increment per frame
anglePerFrame =  (pi/4) * ifi* (32/45);

%%
% Maximum priority level
topPriorityLevel = MaxPriority(window);
Priority(topPriorityLevel);

% Sync us to the vertical retrace
vbl = Screen('Flip', window);
waitframes = 1;

%% keyboard defination
% The avaliable keys to press
KbName('UnifyKeyNames');
escapeKey = KbName('ESCAPE');
rightKey = KbName('RightArrow');
quitKey = KbName('q');

i = 1;
j = 1;
SelfMotion = nan(1, 200);
ObjectMotion = nan(1, 200);
%% welcome page
TimeCounter = 1;

if TimeCounter == 1
        textString = ['Please Focus on the Central Red Dot','\n\n',...
            'And Try Your Best to Avoid Eye Movement and Eye
Blink','\n\n',...
            'Press Right Arrow When You Have Self-motion
Feeling','\n\n',...
            'Press Any Key to Start When You Understand This Instruction'];
        Screen('TextSize', window, 20);
        Screen('TextFont', window, 'Aril');
        % write the beginning message
        DrawFormattedText(window, textString, 'center', 'center', [0.5 0.5
0.5]);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
        KbStrokeWait;
        ObjectMotion(j) = GetSecs;
        j = j+1;
end

% This is the cue which determines whether we exit the demo
OriginalS = 0;
address = hex2dec('E030');
Starttime=GetSecs;
timerecord(1:5,1:13)=0;
```

```
VecStarttime=0;
epochcounter=0;
for l=1:numberOfBlocks

     %% 1(16). Black Baseline 1.5s
    Starttime=GetSecs;
  % sent block start trigger
    ioObj = io64;
    status = io64(ioObj);
    data_out = 16;
    io64(ioObj,address,data_out);                %output command
    clear io64;
    timerecord(1,l)=Starttime;
   while (Starttime + 3> GetSecs)
        % fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
        Screen('FillOval', window, [fixR 0 0], centeredRect);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
   end

   %% 2(17). Rotating stimuli = vection latency+3s
      OriginalS = 0;
      Starttime=GetSecs;
      mFlag=0;
      % sent block start trigger
        ioObj = io64;
        status = io64(ioObj);
        data_out = 17;
        io64(ioObj,address,data_out);                %output command
        clear io64;
        timerecord(2,l)=Starttime;
      %% start presenting rotation stimuli
    while (VecStarttime + 3> GetSecs)||(mFlag==0)
        [keyIsDown,secs, keyCode] = KbCheck;
        if (keyIsDown == 1) && (OriginalS < keyIsDown)
           if keyCode(escapeKey)
                ShowCursor;
                sca;
                return
            elseif keyCode(rightKey)
                SelfMotion(i) = GetSecs;VecStarttime=SelfMotion(i);
                OnsetDelay(l)=SelfMotion(i)-Starttime;
                mFlag=1; i = i+1;
                     %% 3(18). sent response trigger
                ioObj = io64;
                status = io64(ioObj);data_out = 18;
                io64(ioObj,address,data_out);                %output command
                clear io64;
                timerecord(3,l)=VecStarttime;
                timerecord(8,l)=OnsetDelay(l);
                epochcounter=epochcounter+1;
                timerecord(9,l)=numberOfBlocks*(str2num(b)-1)+epochcounter;
           elseif keyCode(quitKey)
               break;
            end
            OriginalS = 1;
        end
        if keyIsDown == 0
            OriginalS = 0;
        end
```

```
        %% Dots rotating define
        xPos = xCenter + R .* cos(Angle);
        yPos = yCenter + R .* sin(Angle);
        DotPositionMatrix = [xPos ; yPos];
        Screen('DrawDots', window, DotPositionMatrix, r, dotColor(1,:), [],
2);
        % Increment the angle
        Angle = Angle - anglePerFrame;

        %% fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
        Screen('FillOval', window, [fixR 0 0], centeredRect);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
    end

       %% 4(19). Black Baseline 0.5s      %1.5s
    Starttime=GetSecs;
  % sent block start trigger
    ioObj = io64;
    status = io64(ioObj);
    data_out = 19;
    io64(ioObj,address,data_out);               %output command
    clear io64;
    timerecord(4,1)=Starttime;
   while (Starttime + 0.5> GetSecs)
        % fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
        Screen('FillOval', window, [fixR 0 0], centeredRect);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
    end

    % vection report screen
    textString = ['Please report vection intensity!',' \n\n',...
        '1 =',' \n\n',...
        'you are stationary;only dots are rotating',' \n\n',...
        '3 =',' \n\n',...
        'both dots and you are rotating at the same speed',' \n\n',...
        '5 =',' \n\n',...
        'dots are stationary;only you are rotating',' \n\n',...
        'Press a numeric key to continue','\n\n','when you are ready~'];
    Screen('TextSize', window, 20);
    Screen('TextFont', window, 'Aril');
   % write the end message
    DrawFormattedText(window, textString, 'center', 'center', [0.5 0 0]);
    vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
    [~,VectionCode,~] = KbStrokeWait();
    VectionIntensity(l) = find(VectionCode==1, 1, 'last' )-96;
    timerecord(7,l) = VectionIntensity(l);

    ioObj = io64;
    status = io64(ioObj);
    data_out = VectionIntensity(l);
    io64(ioObj,address,data_out);               %output command
    clear io64;

       %%  Black Baseline 3s
    Starttime=GetSecs;
    timerecord(4,l)=Starttime;
   while (Starttime + 3> GetSecs)
       % fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
```

```
        Screen('FillOval', window, [fixR 0 0], centeredRect);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
   end
   %% 5(20). Random Baseline 3s
      OriginalS = 0;
      Starttime=GetSecs;
    % sent block start trigger
        ioObj = io64;
        status = io64(ioObj);
        data_out = 20;
        io64(ioObj,address,data_out);               %output command
        clear io64;
        timerecord(5,1)=Starttime;
    while (GetSecs<Starttime+3)
        %% Dots rotating define
        xPos=xPos+ cos(RandomAngle)*RandotSpeed;
        yPos=yPos+ sin(RandomAngle)*RandotSpeed;
        for n = 1:dotNo;
            if yPos(n)>= MaxCanvasY
            yPos(n) = yPos(n) - MaxCanvasY;
            elseif yPos(n)<= MinCanvasY
            yPos(n) = yPos(n) + MinCanvasY;
            end
            if xPos(n)>= MaxCanvasX
            xPos(n) = xPos(n) - MaxCanvasX;
            elseif xPos(n)<= MinCanvasX
            xPos(n) = xPos(n) + MinCanvasX;
            end
        end
        DotPositionMatrix = [xPos ; yPos];
        Screen('DrawDots', window, DotPositionMatrix, r, dotColor(1,:), [],
2);

        %% fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
        Screen('FillOval', window, [fixR 0 0], centeredRect);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
    end
end

%% LastCol(22) end of experiment
Endtime=GetSecs;
%5s5ent exp end trigger
ioObj = io64;
status = io64(ioObj);
data_out = 22;
io64(ioObj,address,data_out);               %output command
clear io64;
timerecord(1,1+1)=Endtime;

%%show exp end instructions
    textString = ['End of This Session',' \n\n','Thank You'];
    Screen('TextSize', window, 30);
    Screen('TextFont', window, 'Aril');
    % write the end message
    DrawFormattedText(window, textString, 'center', 'center', [0.5 0.5
0.5]);
    vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);

 %% creat path and name for the result file
mkdir(['s' subject]);
```

```
outfile = ['D:\Margaux\VS2020\vs3\s' subject '\s' subject 'r' block
'.xlsx'];
xlswrite(outfile,timerecord);
KbStrokeWait;
sca;
ShowCursor;
Screen('CloseAll');
disp(mean(OnsetDelay));
disp(std(OnsetDelay));
rethrow(lasterror);
```

```
% Generate the Pitch Stimulation

% Clear the workspace
close all;
clear all;
sca;

numberOfBlocks=18;
speed = 4;

OnsetDelay(1:numberOfBlocks)=0;
VectionIntensity(1:numberOfBlocks)=0;
timerecord(1:8,1:numberOfBlocks)=0;
fixR=1;
%% Output info set
FailMessage='Program aborted. Wrong input';
prompt1 = {'Enter participant number:'};
prompt2 = {'Enter Block number'};
prompt3 = {'Enter Trial number'};
dlg_title ='Participant Number Information';
num_lines = 1;
def = {'1'};
answer1 = inputdlg(prompt1,dlg_title,num_lines,def);
switch isempty(answer1)
    case 1
        error(FailMessage);
    case 0
        subject = (answer1{1});
end
answer2 = inputdlg(prompt2,dlg_title,num_lines,def);
switch isempty(answer2)
   case 1
       error(FailMessage);
   case 0
       b = (answer2{1});
       block = [b 'p'];
end

%% Here we call some default settings for setting up Psychtoolbox
PsychDefaultSetup(2);

%%
%--------------------------------------------------------------------
%                   Basic Information of the screen
%--------------------------------------------------------------------
% Get the screen numbers
screens = Screen('Screens');

% Draw to the external screen if avaliable
```

```
screenNumber = 2;

% Define black and white
white = WhiteIndex(screenNumber);
black = BlackIndex(screenNumber);
grey = 0.53;

% Open an on screen window
[window, windowRect] = PsychImaging('OpenWindow', screenNumber, black);
HideCursor;

% Get the size of the on screen window
[screenXpixels, screenYpixels] = Screen('WindowSize', window);

% Get the centre coordinate of the window
[xCenter, yCenter] = RectCenter(windowRect);

% Query the frame duration
ifi = Screen('GetFlipInterval', window);

% Set up alpha-blending for smooth (anti-aliased) lines
Screen('BlendFunction', window, 'GL_SRC_ALPHA', 'GL_ONE_MINUS_SRC_ALPHA');

%%
%--------------------------------------------------------------------------
%                       Parameters Defination
%--------------------------------------------------------------------------
dotNo = 3442;
dotDiaMin = 5;
dotDiaMax = 14;
%% Define a fix point
baseRect = [0 0 7 7];
centeredRect = CenterRectOnPointd(baseRect, xCenter, yCenter);
centeredBArea= CenterRectOnPointd(baseRect*20, xCenter, yCenter);
rectColor = [1 0 0];

%% Define dots
RandotSpeed =(yCenter*pi)*32/360*ifi;
r = randi([dotDiaMin,dotDiaMax],1,dotNo);

% with 1920*1080 resolution
MaxCanvasX=2061;
MinCanvasX=-141;
MaxCanvasY=1641;
MinCanvasY=-561;

xPos = randi([MinCanvasX MaxCanvasX],1,dotNo);
yPos = randi([MinCanvasY MaxCanvasY],1,dotNo);
R = sqrt((xPos - xCenter).^2+(yPos-yCenter).^2);
Angle = atan2((yPos-yCenter),(xPos-xCenter));
RandomAngle = deg2rad(randi([0,360],1,dotNo));
dotColor = [0.25 0.25 0.25;0.45 0.45 0.45];

%%
%--------------------------------------------------------------------------
%                         Movement Defination
%--------------------------------------------------------------------------
%% movement parameter defination
% Linear increment (pitch rotation) per frame
increment = speed; % increment at center y=1080/2: alpha*0.3765 (12)
ObservationD = 100;
```

```
ScrHeight = 83.4;
%%
% Maximum priority level
topPriorityLevel = MaxPriority(window);
Priority(topPriorityLevel);

% Sync us to the vertical retrace
vbl = Screen('Flip', window);
waitframes = 1;

%% keyboard defination
% The avaliable keys to press
KbName('UnifyKeyNames');
escapeKey = KbName('ESCAPE');
rightKey = KbName('RightArrow');
quitKey = KbName('q');

i = 1;
j = 1;
SelfMotion = nan(1, 200);
ObjectMotion = nan(1, 200);
%% welcome page
TimeCounter = 1;

if TimeCounter == 1
        textString = ['Please Focus on the Central Red Dot','\n\n',...
            'And Try Your Best to Avoid Eye Movement and Eye
Blink','\n\n',...
            'Press Right Arrow When You Have Self-motion
Feeling','\n\n',...
            'Press Any Key to Start When You Understand This Instruction'];
        Screen('TextSize', window, 20);
        Screen('TextFont', window, 'Aril');
        % write the beginning message
        DrawFormattedText(window, textString, 'center', 'center', [0.5 0.5
0.5]);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
        KbStrokeWait;
        ObjectMotion(j) = GetSecs;
        j = j+1;
end

% This is the cue which determines whether we exit the demo
address = hex2dec('E030');
epochcounter=0;
VecStarttime=0;
for l=1:numberOfBlocks

     %% 1(16). Black Baseline 1.5s
    Starttime=GetSecs;
  % sent block start trigger
    ioObj = io64;
    status = io64(ioObj);
    data_out = 16;
    io64(ioObj,address,data_out);               %output command
    clear io64;
    timerecord(1,l)=Starttime;
   while (Starttime + 3> GetSecs)
        % fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
        Screen('FillOval', window, [fixR 0 0], centeredRect);
```

```
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
    end

    %% 2(17). Rotating stimuli = vec+3s
       OriginalS = 0;
       Starttime=GetSecs;
       mFlag=0;
       % sent block start trigger
         ioObj = io64;
         status = io64(ioObj);
         data_out = 17;
         io64(ioObj,address,data_out);               %output command
         clear io64;
         timerecord(2,1)=Starttime;
       %% start presenting rotation stimuli
      % xPos = randi([MinCanvasX MaxCanvasX],1,dotNo);
       yPos = randi([MinCanvasY MaxCanvasY],1,dotNo);
     while (VecStarttime + 3> GetSecs)||(mFlag==0)
         [keyIsDown,secs, keyCode] = KbCheck;
         if (keyIsDown == 1) && (OriginalS < keyIsDown)
            if keyCode(escapeKey)
                 ShowCursor;
                 sca;
                 return
             elseif keyCode(rightKey)
                 SelfMotion(i) = GetSecs;VecStarttime=SelfMotion(i);
                 OnsetDelay(1)=SelfMotion(i)-Starttime;
                 mFlag=1; i = i+1;
                      %% 3(18). sent response trigger
                 ioObj = io64;
                 status = io64(ioObj);data_out = 18;
                 io64(ioObj,address,data_out);               %output command
                 clear io64;
                 epochcounter=epochcounter+1;
                 timerecord(3,1)=VecStarttime;
                 timerecord(8,1)=OnsetDelay(1);
                 timerecord(9,1)=numberOfBlocks*(str2num(b)-1)+epochcounter;
            elseif keyCode(quitKey)
                break;
             end
             OriginalS = 1;
         end
         if keyIsDown == 0
             OriginalS = 0;
         end

         %% Dots rotating define
         Incre= increment./cos(atan((yCenter-
yPos)*(ScrHeight/ObservationD/screenYpixels)));
         yPos = yPos-Incre;
        % yPos = yPos - increment;
         yPos = yPos + (yPos<MinCanvasY) * (MaxCanvasY - MinCanvasY);

         DotPositionMatrix = [xPos ; yPos];
         Screen('DrawDots', window, DotPositionMatrix, r, dotColor(1,:), [],
2);

         %% fixation point
         Screen('FillOval', window, [0 0 0], centeredBArea);
         Screen('FillOval', window, [fixR 0 0], centeredRect);
         vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
```

```
    end

       %% 4(19). Black Baseline 0.5s     % 1.5s
    Starttime=GetSecs;
%   sent block start trigger
    ioObj = io64;
    status = io64(ioObj);
    data_out = 19;
    io64(ioObj,address,data_out);               %output command
    clear io64;
   while (Starttime + 0.5> GetSecs)
        % fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
        Screen('FillOval', window, [fixR 0 0], centeredRect);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
   end

    %% vection report screen
    textString = ['Please report vection intensity!',' \n\n',...
        '1 =',' \n\n',...
        'you are stationary;only dots are rotating',' \n\n',...
        '3 =',' \n\n',...
        'both dots and you are rotating at the same speed',' \n\n',...
        '5 =',' \n\n',...
        'dots are stationary;only you are rotating',' \n\n',...
        'Press a numeric key to continue','\n\n','when you are ready~'];
    Screen('TextSize', window, 20);
    Screen('TextFont', window, 'Aril');
    % write the end message
    DrawFormattedText(window, textString, 'center', 'center', [0.5 0 0]);
    vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
 %% 6(Vection Intensity 1-5). Press Button (Reaction Time)=Onset of Black
Baseline (3s)
    %    KbStrokeWait;
    [~,VectionCode,~] = KbStrokeWait();
    VectionIntensity(l) = find(VectionCode==1, 1, 'last' )-96;
    timerecord(7,l) = VectionIntensity(l);

    ioObj = io64;
    status = io64(ioObj);
    data_out = VectionIntensity(l);
    io64(ioObj,address,data_out);               %output command
    clear io64;

       %%  Black Baseline 3s
    Starttime=GetSecs;
    timerecord(4,l)=Starttime;
   while (Starttime + 3> GetSecs)
        % fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
        Screen('FillOval', window, [fixR 0 0], centeredRect);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
   end

  %% 7(20). Random Baseline 3s
      OriginalS = 0;
      Starttime=GetSecs;
    % sent block start trigger
        ioObj = io64;
        status = io64(ioObj);
        data_out = 20;
```

```
        io64(ioObj,address,data_out);               %output command
        clear io64;
        timerecord(5,l)=Starttime;
    while (GetSecs<Starttime+3)
        %% Dots rotating define
        xPos=xPos+ cos(RandomAngle)*RandotSpeed;
        yPos=yPos+ sin(RandomAngle)*RandotSpeed;
        for n = 1:dotNo;
            if yPos(n)>= MaxCanvasY
            yPos(n) = yPos(n) - MaxCanvasY;
            elseif yPos(n)<= MinCanvasY
            yPos(n) = yPos(n) + MinCanvasY;
            end
            if xPos(n)>= MaxCanvasX
            xPos(n) = xPos(n) - MaxCanvasX;
            elseif xPos(n)<= MinCanvasX
            xPos(n) = xPos(n) + MinCanvasX;
            end
        end
        DotPositionMatrix = [xPos ; yPos];
        Screen('DrawDots', window, DotPositionMatrix, r, dotColor(1,:), [],
2);

        %% fixation point
        Screen('FillOval', window, [0 0 0], centeredBArea);
        Screen('FillOval', window, [fixR 0 0], centeredRect);
        vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);
    end


end

%% Last Col (22). end of experiment
Endtime=GetSecs;
%sent exp end trigger
ioObj = io64;
status = io64(ioObj);
data_out = 22;
io64(ioObj,address,data_out);               %output command
clear io64;
timerecord(1,l+1)=Endtime;

%%show exp end instructions
    textString = ['End of This Session',' \n\n','Thank You'];
    Screen('TextSize', window, 30);
    Screen('TextFont', window, 'Aril');
    % write the end message
    DrawFormattedText(window, textString, 'center', 'center', [0.5 0.5
0.5]);
    vbl = Screen('Flip', window, vbl + (waitframes-0.5) * ifi);

 %% creat path and name for the result file
mkdir(['s' subject]);
outfile = ['D:\Margaux\VS2020\vs3\s' subject '\s' subject 'p' block
'.xlsx'];
xlswrite(outfile,timerecord);
KbStrokeWait;
sca;
ShowCursor;
Screen('CloseAll');
disp(mean(OnsetDelay));
```

```
disp(std(OnsetDelay));
disp(mean(VectionIntensity));
disp(std(VectionIntensity));
rethrow(lasterror);
```

APPENDIX – F List of Publication

- **Wang Y***, Du B, Wei Y and So RHY (2021) Visually Induced Roll Circular Vection: Do Effects of Stimulation Velocity Differ for Supine and Upright Participants? Frontiers in Virtual Reality. 2:611214.

- **Wang, Y.X.** and So, R.H.Y. (2020) SSVEP power shift during vection differs with visually induced motion sickness. Proceedings of 7th International Symposium on Visually Induced Motion Sensations (VIMS2020), HKUST, Hong Kong. 14-16 Dec., 2020.

- **Chan, T.T.*, Wang, Y*,** So, R.H.Y., Jia, J. (2021) Predicting Subjective Discomfort Associated with Lens Distortion in VR Headsets During Vestibulo-Ocular Response to VR Scenes. Manuscript submitted for publication. (IEEE TVCG 1st revision)