INTERACTING EFFECTS OF FREQUENCY, VELOCITY AND AMPLITUDE ON VECTION FOR YAW AND ROLL VISUAL OSCILLATIONS

by

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A Thesis Submitted to

The Hong Kong University of Science and Technology

in Partial Fulfillment of the Requirements for

the Degree of Master of Philosophy

in Industrial Engineering and Logistics Management

August 2017, Hong Kong

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This is to certify that I have examined the above Mphil thesis

and have found that it is complete and satisfactory in all respects,

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the thesis examination committee have been made.

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18 August 2017

ACKNOWLEDGMENTS

I would like to express my grateful gratitude to my supervisor, Professor Richard SO, for his constant support, instructive advice, and valuable guidance in my research and my life. His insightful thoughts and scientific attitudes have inspired me a lot.

I am also grateful to Professor Michael WONG and Professor Ajay Joneja for serving on my thesis committee. They gave me many valuable suggestions on my research.

I greatly appreciate the helps from technicians Denil, Charles and Tin for the experiment setups, and strong supports from department secretaries Fona, Joyce, and Vera.

I also wish to thank my lab colleagues, Isabella, Isabel, Joyce, Zoe, Ye Hur, Nick, Tak Wah, Calvin, Shota, Du Bo, Coskun, and Buddhika. Thank you for your help and suggestions on my research. And sincere thanks to my lovely friends in Hong Kong, Yang Yihuan, Lu Lan, Liu Suyun, He Fangshu, Fan Xiaoshuai, Wang Wenwei, Ariel, Window, Song Zhongji, Zhang Guangyuan, Chin Jing Wei, Wu Liyu, Xiong Yao, and those I don’t mention. I memorize the happy time spent with them.

Last but not least, deepest appreciation to my parents and grandparents for their love and support.

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Interacting Effects of Frequency, Velocity and Amplitude on Vection for Yaw and Roll Visual Oscillations

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ABSTRACT

The phenomenon of vection (also termed as self-motion illusions) is commonly perceived by stationary observers when watching coherently moving visual stimuli. For oscillatory visual stimuli, the effects of oscillation frequency on vection along the fore-and-aft axis have been studied with fixed velocity and fixed amplitude by Chen (2014). The two-frequency-response hypothesis, which explained inconsistent effects of frequency in literature, was proposed. This dissertation extends his work to yaw and roll visual oscillations. Effects of frequency, velocity, and amplitude are investigated. Two experiments for yaw and roll vection were conducted respectively. In each experiment, there were five levels of frequency, rms velocity, and amplitude. Results showed that under constant rms velocity, yaw vection decreased as frequency increased; and under constant amplitude, yaw vection presented an inverted U-shape with increasing frequency. Thus, frequency response for yaw vection supported the two-frequency-response hypothesis. As for roll vection, vection dropped as frequency increased no matter whether rms velocity or amplitude was fixed. It was also found that visual oscillations of the same frequency but different amplitudes and velocities generated different vection magnitudes for both yaw and roll vection. Findings suggested that frequency alone should not be regarded as a sufficient predictor for perceived vection magnitude. Analyses of the effects of amplitude indicated that the larger the amplitude, the stronger the vection. As for the effects of velocity, yaw vection presented an inverted U-shape with increasing velocity; while roll vection decreased as velocity increased. Interestingly, three different frequency responses of vection provoked by constant amplitude visual oscillation were found for yaw, roll and fore-and-aft vection. This suggested that there might be different motion perception mechanisms for visual system along different directions.

CHAPTER 1 : INTRODUCTION

1.1 Illusory self-motion (Vection)

Illusory self-motion describes a phenomenon that self-motion is perceived while no physical movement is taking place in fact. This phenomenon is also termed as vection. Taking a typical experience for example, when people are sitting on a stopped train and watching a moving train which is next to the stopped one, people often feel that their train appears to move in the opposite direction of the near one and the train aside seems to be stationary. Vection is frequently perceived in everyday life, simulators, movie theatres, and virtual environment (Hettinger et al., 2014).

Vection can be generated through different sensory modalities. Visually induced self-motion illusions are most commonly seen phenomenon and have been extensively studied over a century (Dichgans and Brandt, 1978; Andersen and Dyer, 1987). Besides visual cues, other nonvisual cues, such as auditory (Riecke et al., 2009; Väljamäe, 2009), vestibular (Lepecq et al., 2006; Fetsch et al., 2009), tactile (Dichgans & Brandt, 1978) cues, can also contribute to producing vection. This dissertation is about visually induced vection.

Vection is successfully utilized to simulate self-motion and widely applied in entertainment industry. Vection provides a high degree of self-presence in virtual environment. In IMAX theatres, coherent optical flows and 3D special effects are combined to generate compelling self-motion illusions. It provides people with immersive experience. Another successful application is theme park rides in which multisensory cues are integrated to induce motion. For example, the most popular ride Soarin' at Disney's Epcot theme park brings the feeling of hang glider flight using a large projection dome and aerially captured footage. In the ride, people feel they are moving forward from one landmark to the next with only limited actual movements (Figure 1.1).

In recent years, with the rapid development of virtual reality (VR) technologies, vection has captured more and more attention. Facilitating vection to simulate self-motion in virtual environment can be very compelling. Riecke (2010) suggested that the nature of vection and the factors affecting vection should be carefully investigated to improve overall experience and effectiveness of VR.

In this study, research gaps concerning vection as functions of visual oscillation frequency, amplitude, and rms (root-mean-square) velocity along the yaw and roll axis are identified.

Figure 1.1 The theme park ride Soarin' using vection to facilitate forward motion (cited from https://disneyworld.disney.go.com/attractions/epcot/soarin/)

1.2 Vection induced by visual oscillations

Visual oscillating scenes can generate illusive feeling of body vibration. Suppose it is a sinusoidal oscillation, the relation between the three factors, which are rms velocity (v), frequency (f), and amplitude (A), is $v=\sqrt{2}\pi fA$. Frequency is thought to be one of the most important characteristics of visual oscillations. There have been a lot of studies about frequency responses of visually induced motion sickness (VIMS) trying to identify the band of frequency which is most likely to provoke sickness (Dul et al., 2004; Lin et al., 2005; Diels and Howarth, 2012; Chen et al., 2016).

However, only a few studies explored vection elicited by visual oscillation. Berthoz et al. (1975) found that vection magnitude decreased as oscillation frequency increased from 0.01 Hz to 1 Hz for horizontal linear optical flow stimuli. In the meanwhile, some studies argued that frequency was not the dominant factor determining vection. Firstly, velocity played a crucial role in illusions of self-motion. De Graaf et al. (1990) investigated that circular vection along yaw axis was determined by angular velocity instead of temporal frequency. And Chen (2014) discovered that linear vection along fore-and-aft axis was dominated by velocity rather than frequency. Secondly, amplitude of visual oscillation was also found to dominate vection. Chow et al. (2007) reported that vection changed significantly when visual oscillations were at the same RMS velocity but different amplitudes. Their works indicated that frequency, velocity, and amplitude had interactive effects on the level of vection magnitude. This thesis is intended to clarify the interaction effect. The experiment design of Chen (2014)'s study was adopted, which had five levels for each of the three factors, i.e., frequency, velocity, and amplitude.

Directions of visual oscillations are one of the key characteristics which have been studied with frequency response of visually induced motion sickness (VIMS) and vection. Previous studies showed that different rotational visual oscillations, i.e., pitch, yaw, and roll, have similar effects on the level of VIMS (Lo and So, 2001). As for translational visual oscillations (fore-and-aft, lateral, and vertical), there were no significant differences in vection magnitudes and the level of VIMS (Chen et al., 2011). This study is also intended to study the effects of different oscillating directions on vection. Oscillations along the yaw and roll axes were studied in the thesis.

1.3 Objectives and hypotheses

This study aims to investigate the effects of frequency, velocity, and amplitude of visual oscillations on yaw and roll vection, and the effects of oscillating directions on vection.

Major hypotheses of this dissertation are listed in the following,

H1: vection is not dominated by oscillation frequency alone, but is affected by frequency, velocity, and amplitude interactively.

H2: when visual oscillations are along different directions, the effects of frequency, velocity, and amplitude on vection are different.

1.4 Thesis outline

The followings are the summaries for each chapter of this thesis.

Chapter 1 briefly introduces the phenomenon "self-motion illusions (vection)". And then it leads in the research questions addressed in this thesis by reviewing studies on the frequency response of vection.

Chapter 2 reviews previous research on visually induced vection, and emphasis will be laid on vection induced by visual oscillations.

Chapter 3 summarizes experimental setups and measurements used in this study.

Chapter 4 presents the work of Experiment 1, which studied the effects of frequency, velocity, and amplitude of visual oscillation, along the yaw axis, on vection.

Chapter 5 presents the work of Experiment 2, which studied the effects of frequency, velocity, and amplitude of visual oscillation, along the roll axis, on vection.

Chapter 6 discusses the findings, implications, and limitations of this study.

CHAPTER 2 : LITERATURE REVIEW

2.1 Visual-vestibular interactions

Perception of self-motion is a multisensory integration process involving sensory information from visual, vestibular, somatosensory, and auditory systems (Borah et al., 1988; Greenlee et al., 2016). And it depends on visual and vestibular afferents to a great extent (Mergner et al., 2000). The interactions of visual and vestibular have been studied for a long history (Dichgans and Brandt, 1978).

The vestibular system provides information about movement and spatial orientation of the body. Body movements are divided into rotational movements and translational movements. Respectively, there are two components in vestibular responding to these two forms of movements. The semicircular canals detect rotational accelerations. And the otoliths sense linear accelerations and gravitation. However, both components fail to detect constant or low frequency velocity motion. Studies have found that it was less effective for the vestibular to sense low frequency motion, but more effective to sense high frequency (>1 Hz) accelerations (Benson et al., 1990; Diener et al., 1982). Howard (1986) observed that motion at frequency lower than 0.1 Hz was prone to be underestimated or even undetected. Thus, the vestibular contribution to self-motion perception is considered to possess high pass characteristics.

The limited ability of the vestibular system to perceive self-motion is compensated by other sensors. Visual inputs are considered to be the most important. It contains reliable information about movement velocity, distance, heading direction, and spatial position (Gibson, 1950). Vection is found to be more easily induced by visual inputs at lower frequency, and the visual system is featured by low pass characteristics (Andersen and Braunstein, 1985). One evidence was that vection magnitude dropped as visual oscillation frequency ranging from 0.01 Hz to 1 Hz (Berthoz et al., 1975).

The information provided by visual system and vestibular sometimes conflict. For an instance, if visual cues of acceleration motion are received but vestibular cues are not, a stationary observer would perceive weak self-motion or not perceive self-motion. In this situation, visual-vestibular conflict impairs vection. On the other hand, if visual system dominates self-motion perception (for example when a stationary observer views a visual motion of constant velocity), a strong self-motion illusion is likely to be sensed (Lishman and Lee, 1973).

In this dissertation, all visual motion stimuli are sinusoidal oscillations of which motion acceleration varies over the time. When stationary subjects are exposed to them, inputs from visual system and vestibular conflict due to the absence of vestibular cues. Palmisano et al. (2000) found that the larger the mismatch between actual vestibular cues and the expected vestibular cues, the larger the vection is impaired. There is more mismatch in roll vection than yaw vection because of the absence of the gravitational acceleration cue detected by the otoliths (Lo and So, 2001). Therefore, roll vection is expected to be weaker than yaw vection.

2.2 Measurements of vection

The sensation of vection is a subjective and complicated process to quantify yet. In laboratory study, measurement techniques can be mainly divided into psychological measures, behavioral measures, and physiological measures (Hettinger et al., 2014).

Vection intensity measures the strength of the perceived self-motion or how intense the sensation of self-motion is. Subjective scales are commonly used to assess it. Vection onset time or vection latency refers to the time it takes to perceive vection for the first time from exposure to vection generating stimuli. Other measures, such as duration of the vection sensation, estimations of the perceived displacement, illusory body tilt and self-motion velocity, are also frequently adopted regarding to research goals (Väljamäe, 2009).

Postural sway is a behavioral measure. It indirectly assesses vection intensity and is often combined with subjects' subjective vection intensities.

Researchers have also tried to develop physiological measurement technologies, including afternystagmus (nystagmus after exposure to vection generating stimuli), electrodermal activity and cardiovascular responses, EEG, MEG (magnetoencephalography), PET (positron emission tomography), fMRI (functional magnetic resonance) et al.

2.3 Factors affecting levels of visually induced vection

Researchers have tried to find out how the parameters of vection generating stimuli affect the sensation of vection for a long history, especially for visual stimuli. Some of the most important factors of visual stimuli are briefly presented below.

Velocity of optical flow is one of the important factors. Hu et al. (1989) found that vection magnitude increased as optokinetic drum rotation speed increased from 15 to 60 degrees per second, then vection dropped as rotation speed further increased to 90 degrees per second. There were 4 levels of constant rotation speed: 15, 30, 60, and 90 degrees per second in their study. Similar findings regarding to circularvection were observed by Young (1978). As for linearvection, there was a similar pattern that the sensation of vection increased to a saturated point then dropped as optical velocity increased. For vection induced by stimuli on a ground surface, Tamada and Seno (2015) found that subjective strength of vection increased by 50% as the speed increased from 0.375 m/s to 1.5 m/s.

The effects of spatial frequency of the visual stimuli on vection has been well investigated as well. In Brandt et al. (1975)'s study, it was found that roll vection magnitude increased as spatial frequency increased until 30% of the visual stimulus area was filled by pattern elements. In Hu et al. (1997)'s study, the interior of the optokinetic drum (360 degrees) was evenly covered by 6, 12, 24, 48, and 96 pairs of black-and-white stripes. And they found yaw vection magnitude peaked at the intermediate spatial frequency of 24 pairs.

Field of view (FoV) subtended by the visual stimulus is another important visual factor. Andersen and Braunstein (1985) observed that linear vection can be induced by a stimulus in the central visual field of size as small as 7.5 degrees. Brandt et al. (1973) found that vection magnitude was lower in condition where FoV is only 30 degrees than condition with full FoV. It indicated that the size of FoV significantly influenced vection magnitude. Basting et al. (2007) investigated the effect of the size of FoV on vection intensity using a head-mounted display (HMD) in a virtual environment (VE). They found that a decrease of the FOV invoked a decrease of the intensity of perceived vection.

In this dissertation, temporal frequency, amplitude, rms velocity, and directions of visual oscillation will be investigated. Discussions and literature review regarding these factors are presented in the following.

2.3.1 Directions of vection

Vection can be induced in different directions. The directions in which people feel themselves move are always in the opposite of the directions of the visual motions. Regarding the directions, vection is categorized into linearvection (including fore-and-aft, lateral, and vertical) and circularvection (including yaw, roll, and pitch) (Figure 2.1). Exposure to different types of visual stimuli, people may perceive linear motion, rotational motion, or combinations of linear and rotational motion.

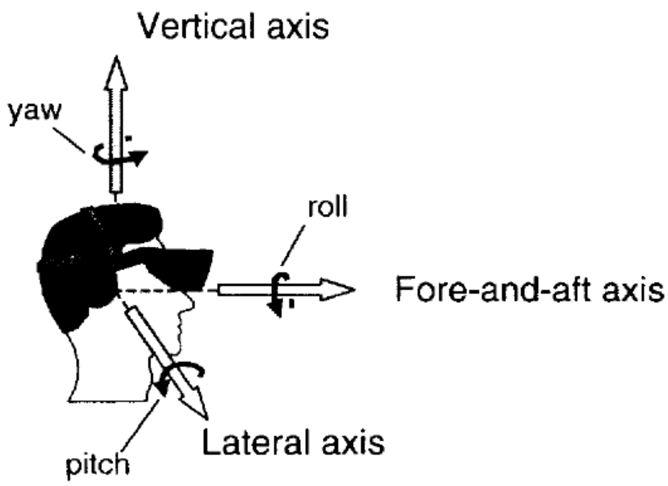

Figure 2.1 Six degrees of body-centric motion (So and Lo, 2001)

Yaw vection was first studied by Mach in 1875, probably the earliest study on vection. In laboratory, the optokinetic drum has been typically used to study yaw vection for a long history (Brandt et al., 1973; Teixeira and Lackner, 1979; Jong et al., 1981; Hu et al., 1989; Hu et al., 1992; Muth et al., 1995; Bubka et al., 2006; Ji et al., 2009). Yaw vection is the most frequently studied type of vection up to now. The experience of yaw vection can be divided into four stages: 1. once the visual stimulus is set to start moving at constant speed, subjects do not perceive any self-motion and the visual stimulus appears to be moving only; 2. some seconds later, subjects started to feel that the moving of the visual stimulus gradually slow down and their body seems to move increasingly fast in the opposite direction of the visual motion; 3. in the following, subjects feel a steady state of self-motion and visual motion, which indicates vection is the strongest and saturated (Brandt et al., 1973); 4. at last, perception of self-motion may disappear intermittently due to eye blink or other interruptions.

In early days without various display technologies, roll vection and pitch vection were induced by devices like circular disk or hollow sphere with coherent pattern (Dichgans et al., 1972; Howard et al., 1988). Nowadays, roll vection and pitch vection is commonly studied by HMD (Head Mounted Display), large-screen projectors, virtual reality devices and so on. The experience of roll vection and pitch vection is similar; however, it is different from yaw vection. Howard (1986) observed that, during the time vection is perceived, subjects feel that body is rotating continuously but is tilt around a fixed angle.

In 1970s and 1980s, linearvection was induced by devices such as moving rooms (Lee and Lishman, 1975), projection systems which projected linear motion on the walls of a stationary room (Berthoz et al., 1978). Recently, technologies, like virtual reality devices and large displays, have made it much easier to facilitate linearvection. The perception of linearvection is similar to yaw vection. Fore-and-aft vection has received most attention and been most frequently studied in linearvection.

As for directions effect on vection induced by visual oscillations, there are only a few studies directly related. Table 2.1 is a summary of them.

Table 2.1 Studies investigating effects of directions on vection induced by visual oscillation

	Oscillation direction	**FoV**	**Oscillation amplitude and rms velocity**	**Oscillation frequency**	**Results**
Chen (2006)	Fore-and-aft, Lateral, Vertical	48 deg. (horizontal) x 36 deg. (vertical)	Amplitude (+-18m) Rms velocity (15 m/s)	0.12 Hz	Between-subject design: Subjects experienced more feeling of vection when along lateral axis than the fore-and-aft and vertical axis.
					Within-subject design: There were no significant differences between the 3 directions.
Chow (2008)	Roll	200 deg. (horizontal) x 50 deg. (vertical)	Fixed rms velocity (49.5 deg./s)	0.05, 0.1, 0.2, 0.4, 0.8 Hz	The difference in vection magnitude between 2 directions was not significant for 5 frequency conditions.
	Fore-and-aft		Fixed rms velocity (44.5 m/s)		
Diels (2008)	Roll	65 deg. (horizontal) x 59 deg. (vertical)	Amplitude (+-60 deg.) Rms velocity (30 deg./s)	0.125 Hz	Vection magnitude was significantly higher when along the roll axis.
	Fore-and-aft		Rms velocity (18.4 deg./s)	0.025 Hz	
	Roll	65 deg. (horizontal) x 59 deg. (vertical)	Amplitude (+-60 deg.) Rms velocity (48 deg./s)	0.2 Hz	Vection magnitude was significantly higher when along the roll axis.
	Fore-and-aft		Rms velocity (24 deg./s)		

Chen (2006) investigated three translational directions (fore-and-aft, lateral, and vertical). In experiment adopted between-subject design, subjects experienced more feeling of vection when along the lateral axis than the fore-and-aft and vertical axis. Somehow, in within-subject design experiment, there were no significant differences between the 3 directions. Chow (2008) compared roll vection and fore-and-aft vection. And he found the difference in vection magnitude between 2 directions was not significant for 5 frequency conditions (0.05, 0.1, 0.2, 0.4, and 0.8 Hz). However, Diels (2008) observed that vection magnitude was significantly higher when along the roll axis than the fore-and-aft axis.

In this dissertation, yaw and roll vection produced by oscillatory visual stimuli were of interest to be studied and compared. As mentioned earlier, roll vection is associated with more sensory mismatch, and expected to be weaker than yaw vection. This mismatch is supposed to lead to different effects of these two directions on oscillatory vection.

More discussion about the effects of directions on vection induced by visual oscillations will be presented along with factors temporal frequency, rms velocity, and amplitude in the following.

2.3.2 Temporal frequency

For motion sickness induced by physical motion, temporal frequency, amplitude and the acceleration of the motion are considered to be important characteristics (Griffin, 2012). Kennedy et al. (1996) suggested that visual oscillation frequency should also play an important role in producing vection and VIMS. Table 2.2 is a summary of studies that investigated temporal frequency’s effects on vection.

Table 2.2 Studies investigating effects of temporal frequency on vection

	Oscillation direction	FoV	Frequency manipulation	Frequency band	Results
Berthoz et al. (1975)	Fore-and-aft			0.01 to 1 Hz	Vection magnitude decreased as frequency increased.
Post et al. (1989)	Yaw		Fixed amplitude (+-0.85 deg. and 3.4 deg.)	0.125, 0.25, 0.5, 1, 2, 4 Hz	Vection magnitude decreased as frequency increased.
Babler & Ebenholtz (1989)	Roll		Fixed amplitude (+-15 deg.)	0.013, 0.027, 0.053, 0.107, 0.213 Hz	For vection-sensitive subjects, vection peaked at 0.213 Hz.
Previc et al. (1993)	Roll	115 deg. (horizontal) x 105 deg. (vertical)	Fixed amplitude (+-20 deg.)	0.03, 0.06, 0.12, 0.25, 0.50 Hz	Vection magnitude peaked at 0.25 Hz.
Chen (2006)	Fore-and-aft	48 deg. (horizontal) x 36 deg. (vertical)	Fixed amplitude (+-18 m)	0.0375, 0.1, 0.1875, 0.375, 0.75, 1.875 Hz	Vection magnitude was significantly higher when the frequency was 0.75 Hz.
	Lateral		Fixed amplitude (+-18 m)	0.0375, 0.1, 0.1875, 0.375 Hz	Vection magnitude was significantly higher when the frequency was 0.1875 Hz.
	Yaw		Fixed amplitude (+-41 deg.)	0.0375, 0.1, 0.1875, 0.375 Hz	Vection magnitude was significantly lower when the frequency was 0.0375 Hz.
Diels (2008)	Fore-and-aft	65 deg. (horizontal) x 59 deg. (vertical)	Fixed rms velocity (24 deg./s)	0.025, 0.05, 0.1, 0.2 Hz	There was no significant difference between conditions with different frequency.
				0.2, 0.4, 0.8, 1.6 Hz	Vection magnitude decreased as frequency increased.
Chow (2008)	Roll	200 deg. (horizontal) x 50 deg. (vertical)	Fixed rms velocity (49.5 deg./s)	0.05, 0.1, 0.2, 0.4, 0.8 Hz	Vection magnitude decreased as frequency increased.
	Fore-and-aft		Fixed rms velocity (44.5 m/s)		Vection magnitude decreased as frequency increased.
Chen (2014)	Fore-and-aft	200 deg. (horizontal) x 50 deg. (vertical)	Fixed amplitude (+-12.5, 25, 50, 100, 200 deg.)	0.05, 0.1, 0.2, 0.4, 0.8 Hz	With the same amplitude, vection magnitude increased as frequency increased.
			Fixed rms velocity (11, 22, 44, 89, 178 deg./s)		With the same rms velocity, vection magnitude decreased as frequency increased.
Chen et al. (2016)	Fore-and-aft	220 deg. (horizontal) x 56 deg. (vertical)	Fixed rms velocity (44.5m/s)	0.05, 0.1, 0.2, 0.8 Hz	Vection magnitude decreased as frequency increased.

As we can see, among the studies, different apparatus, directions of visual oscillation, visual stimuli, size of FoV, and frequency ranges were applied. And another important difference is the manipulation of frequency, which was observed by Chen (2014). In some studies, frequency changed with varying amplitude while rms velocity was constant. In other studies, frequency was manipulated by changing rms velocity while oscillation amplitude was kept constant. We summarized frequency manipulations for studies in Table 2.2.

From the view of oscillation directions, vection along fore-and-aft has been most frequently investigated. Studies found that vection magnitude decreased as frequency increased (Diels, 2008; Chow, 2008; Chen, 2014; Chen et al., 2016). In their studies, rms velocity was fixed and frequency changed with amplitude. However, in studies where frequency was manipulated by changing rms velocity while keeping amplitude constant, different findings were obtained. Chen (2006) observed that vection magnitude peaked at 0.75 Hz, and Chen (2014) found that vection magnitude increased as frequency increased. What in common in these two studies was that there were an increasing trend when frequency was lower than 0.75 Hz. From discussion above, it indicates that different manipulation of frequency results in different frequency responses of vection. In fact, Chen (2014) pointed out there were two types of frequency responses for vection according to whether the amplitude or the rms velocity of the visual motion was fixed. In his study, along the fore-and-aft axis, vection magnitude increased as frequency increased when the amplitude was fixed; while vection decreased as frequency increased when the rms velocity was fixed.

For yaw vection (Table 2.2.1), findings regarding to effects of frequency were inconsistent. Post et al. (1989) found that vection became weaker with increasing frequency if the oscillation magnitude was small (peak-to-peak amplitude < 7 degrees). Differently, Chen (2006) found that vection was significantly smaller at the lowest frequency (0.0375 Hz). The same frequency manipulation (varying rms velocity and fixing amplitude) was found to be used in their studies. Somehow, the frequency ranges they studied were different. In Post's study, frequency ranged from 0.125 to 4 Hz. In Chen's study, frequency ranged from 0.0375 to 0.375 Hz. In addition, the oscillation amplitude was much larger in Chen's study (peak-to-peak amplitude = 82 degrees). These differences in experiment design might cause inconsistent conclusions. To sum up, the effects of frequency remain unclear for yaw vection; therefore, more work is needed.

Table 2.2.1 Studies investigating effects of temporal frequency on yaw vection

	Oscillation direction	FoV	Frequency manipulation	Frequency band	Results
Post et al. (1989)	Yaw		Fixed amplitude (+-0.85 deg. and 3.4 deg.)	0.125, 0.25, 0.5, 1, 2, 4 Hz	Vection magnitude decreased as frequency increased.
Chen (2006)	Yaw	48 deg. (horizontal) x 36 deg. (vertical)	Fixed amplitude (+-41 deg.)	0.0375, 0.1, 0.1875, 0.375 Hz	Vection magnitude was significantly lower when the frequency was 0.0375 Hz.

As for roll vection (Table 2.2.2), Chow (2008) found that vection magnitude decreased as frequency increased. In his study, frequency was manipulated by changing amplitude and keeping rms velocity constant. Differently, Babler and Ebenholtz (1989) and Previc et al. (1993) found there was an increasing trend in roll vection with increasing frequency below 0.213 Hz. In their studies, they varied rms velocity and fixed amplitude to manipulate frequency. Their work indicate there might be two types of frequency responses for roll vection according to different frequency manipulations.

Table 2.2.2 Studies investigating effects of temporal frequency on roll vection

	Oscillation direction	FoV	Frequency manipulation	Frequency band	Results
Babler & Ebenholtz (1989)	Roll		Fixed amplitude (+-15 deg.)	0.013, 0.027, 0.053, 0.107, 0.213 Hz	For vection-sensitive subjects, vection peaked at 0.213 Hz.
Previc et al. (1993)	Roll	115 deg. (horizontal) x 105 deg. (vertical)	Fixed amplitude (+-20 deg.)	0.03, 0.06, 0.12, 0.25, 0.50 Hz	Vection magnitude peaked at 0.25 Hz.
Chow (2008)	Roll	200 deg. (horizontal) x 50 deg. (vertical)	Fixed rms velocity (49.5 deg./s)	0.05, 0.1, 0.2, 0.4, 0.8 Hz	Vection magnitude decreased as frequency increased.

Comparing vection along fore-and-aft axis and along roll axis, if the same frequency manipulation was applied, the trends of frequency response of vection were similar. An important difference was that, when frequency was manipulated by changing rms velocity and fixing amplitude, the peak frequency was 0.75 Hz for fore-and-aft vection (Chen, 2006), but around 0.2 Hz for roll vection (Babler & Ebenholtz, 1989; Previc et al., 1993). It indicates that there might be a shift of frequency responses for vection along different directions.

Since there were so many differences in their studies, it is hard to draw a conclusion about temporal frequency's effects on vection for different directions. In this dissertation, the same apparatus were used for roll and yaw vection. And frequency band was designed to range from 0.00625 to 1.6 Hz. In addition, both two manipulations of frequency were examined.

2.3.3 Rms velocity and amplitude

From the discussion above, it is clear that temporal frequency has a significant effect on vection induced by visual oscillation. As mentioned in Chapter 1, however, some studies showed that rms velocity and oscillation amplitude also played an important role, and argued that vection was not dominated by temporal frequency.

In fact, due to the mathematical relation between temporal frequency (f), rms velocity (v), and oscillation amplitude (A) ($v=\sqrt{2}\pi fA$), when effects of frequency was investigated under constant amplitude, rms velocity also changed with frequency.

Although there were very few studies directly investigating rms velocity's effects, the effects can be inferred from studies on temporal frequency. Table 2.3 summarizes the effects of rms velocity on vection. In particular, column "Effects of rms velocity" of Table 2.3 is inferred from studies on frequency, except Chow (2008).

Table 2.3 Effects of rms velocity on vection

	Oscillation direction	FoV	Rms velocity manipulation	Freq	Rms velocity	Effects of rms velocity
Babler & Ebenholtz (1989)	Roll		Fixed amplitude (+-15 deg.)	0.013, 0.027, 0.053, 0.107, 0.213 Hz	0.87, 1.80, 3.53, 7.13, 14.20 deg./s	For vection-sensitive subjects, vection peaked at 14.20 deg./s.
Post et al. (1989)	Yaw		Fixed amplitude (+-0.85 deg.)	0.125, 0.25, 0.5, 1, 2, 4 Hz	0.47, 0.94, 1.89, 3.78, 7.5, 15 deg./s	Vection decreased as rms velocity increased.
			Fixed amplitude (+-3.4 deg.)		1.89, 3.78, 7.5, 15, 30, 60 deg./s	Vection decreased as rms velocity increased.
			Fixed frequency			Vection increased as velocity increased.
Previc et al. (1993)	Roll	115 deg. (horizontal) x 105 deg. (vertical)	Fixed amplitude (+-20 deg.)	0.03, 0.06, 0.12, 0.25, 0.50 Hz	2.67, 5.33, 10.66, 22.21, 44.43 deg./s	Vection magnitude peaked at 22.21 deg./s.
Chow (2008)	Roll	200 deg. (horizontal) x 50 deg. (vertical)	Fixed frequency	0.05 Hz	35, 70, 100, 140 deg./s	Vection was lower for the 35°/s velocity condition than 70°/s and 100°/s conditions.
Chen (2014)	Fore-and-aft	200 deg. (horizontal) x 50 deg. (vertical)	Fixed amplitude (+-12.5 m)	0.05, 0.1, 0.2, 0.4, 0.8 Hz	2.78, 5.55, 11.11, 22.21, 44.43 m/s	Vection magnitude increased as rms velocity increased.
			Fixed amplitude (+-25 m)		5.55, 11.11, 22.21, 44.43, 88.86 m/s	
			Fixed amplitude (+-50 m)		11.11, 22.21, 44.43, 88.86, 177.72 m/s	
			Fixed amplitude (+-100 m)		22.21, 44.43, 88.86, 177.72, 355.43 m/s	
			Fixed amplitude (+-200 m)		44.43, 88.86, 177.72, 355.43, 710.86 m/s	
Chen (2006)	Fore-and-aft	48 deg. (horizontal) x 36 deg. (vertical)	Fixed amplitude (+-18 m)	0.0375, 0.1, 0.1875, 0.375, 0.75, 1.875 Hz	3, 8, 15, 30, 60, 150 m/s	Vection was significantly higher when the rms velocity was 60 m/s.
	Lateral		Fixed amplitude (+-18 m)	0.0375, 0.1, 0.1875, 0.375 Hz	3, 8, 15, 30 m/s	Vection was significantly higher when the rms velocity was 15 m/s.
	Yaw		Fixed amplitude (+-41 deg.)	0.0375, 0.1, 0.1875, 0.375 Hz	6.83, 18.22, 34.15, 68.31 deg./s	Vection was significantly lower when the rms velocity was 6.83 deg./s.

From Table 2.3, studies showed inconsistent results for the effect of rms velocity. When vection was along the fore-and-aft axis, Chen (2014) found that vection increased as rms velocity increased over a large range of rms velocity (from 11.1 to 177.7 m/s); while Chen (2006) observed that vection peaked at an intermediate rms velocity (60 m/s).

As for yaw vection (Table 2.3.1), results are not consistent as well. Vection magnitude decreased as rms velocity increased when amplitude was small (peak-to-peak amplitude = 1.7 and 6.8 deg.) (Post et al, 1989). Somehow, for larger amplitude (82 deg.), vection was significantly small when velocity was slow (6.83 deg./s) (Chen, 2006). More work is needed to draw a conclusion about velocity's effects for yaw vection.

Table 2.3.1 Effects of rms velocity on yaw vection

	Oscillation direction	**FoV**	**Rms velocity manipulation**	**Frequency**	**Rms velocity**	**Effects of rms velocity**
Post et al. (1989)	Yaw		Fixed amplitude (+-0.85 deg.)	0.125, 0.25, 0.5, 1, 2, 4 Hz	0.47, 0.94, 1.89, 3.78, 7.55, 15.11 deg./s	Vection decreased as rms velocity increased.
			Fixed amplitude (+-3.4 deg.)		1.89, 3.78, 7.55, 15.11, 30.21, 60.42 deg./s	Vection decreased as rms velocity increased.
			Fixed frequency			Vection magnitude was larger when rms velocity was larger.
Chen (2006)	Yaw	48 deg. (horizontal) x 36 deg. (vertical)	Fixed amplitude (+-41 deg.)	0.0375, 0.1, 0.1875, 0.375 Hz	6.83, 18.22, 34.15, 68.31 deg./s	Vection was significantly lower when the rms velocity was 6.83 deg./s.

For roll vection (Table 2.3.2), Babler & Ebenholtz (1989) found that vection peaked at 14.20 deg./s, where amplitude was kept at 15 degrees. Previc et al. (1993) observed vection peaked at 22.21 deg./s, where amplitude was kept at 20 degrees. Their findings indicated a shift in effect of rms velocity regarding to different oscillation amplitudes. As for Chow's (2008) study, where rms velocity was manipulated by fixed frequency, it was found that vection was significantly lower for the 35°/s velocity condition than 70°/s and 100°/s conditions.

Table 2.3.2 Effects of rms velocity on roll vection

	Oscillation direction	FoV	Rms velocity manipulation	Freq	Rms velocity	Effects of rms velocity
Babler & Ebenholtz (1989)	Roll		Fixed amplitude (+-15 deg.)	0.013, 0.027, 0.053, 0.107, 0.213 Hz	0.87, 1.80, 3.53, 7.13, 14.20 deg./s	For vection-sensitive subjects, vection peaked at 14.20 deg./s.
Previc et al. (1993)	Roll	115 deg. (horizontal) x 105 deg. (vertical)	Fixed amplitude (+-20 deg.)	0.03, 0.06, 0.12, 0.25, 0.50 Hz	2.67, 5.33, 10.66, 22.21, 44.43 deg./s	Vection magnitude peaked at 22.21 deg./s.
Chow (2008)	Roll	200 deg. (horizontal) x 50 deg. (vertical)	Fixed frequency	0.05 Hz	35, 70, 100, 140 deg./s	Vection was significantly lower for the 35°/s velocity condition than 70°/s and 100°/s conditions.

Similar to rms velocity, summary of oscillation amplitude's effects is presented in Table 2.4. There were no analyses on effects of amplitude in the original paper. The column "Effects of amplitude" in Table 2.4 is my analyses of their data.

Table 2.4 Effects of amplitude on vection

	Oscillation direction	FoV	Amplitude manipulation	Frequency	Amplitude	Effects of amplitude
Post et al. (1989)	Yaw		Fixed frequency	0.125 Hz	0.85, 3.4 deg.	Vection was larger when amplitude was larger.
				0.25 Hz		
				0.5 Hz		
				1 Hz		
				2 Hz		
				4 Hz		
Diels (2008)	Fore-and-aft	65 deg. (horizontal) x 59 deg. (vertical)	Fixed rms velocity (24 deg./s)	0.025, 0.05, 0.1, 0.2 Hz	216, 108, 54, 27 deg.	There was no significant difference between conditions with different amplitude.
				0.2, 0.4, 0.8, 1.6 Hz	27, 13.5, 6.8, 3.4 deg.	Vection magnitude increased as amplitude increased.
Chow (2008)	Roll	200 deg. (horizontal) x 50 deg. (vertical)	Fixed rms velocity (49.5 deg./s)	0.05, 0.1, 0.2, 0.4, 0.8 Hz	222, 111, 55, 27.9, 13.9 deg.	Vection magnitude increased as amplitude increased.
	Fore-and-aft		Fixed rms velocity (44.5 m/s)		200, 100, 50, 25, 12.5 m	
	Roll		Fixed frequency and varying peak velocity (35, 70, 100, 140 deg./s)	0.05 Hz	111, 222, 318, 446 deg.	Vection magnitude was significantly lower for the 111 amplitude condition.
Chen (2014)	Fore-and-aft	220 deg. (horizontal) x 56 deg. (vertical)	Fixed rms velocity (11 m/s)	0.05, 0.1, 0.2, 0.4, 0.8 Hz	50, 25, 12.5, 6.25, 3.1 m	Vection magnitude increased as amplitude increased.
			Fixed rms velocity (22 m/s)		100, 50, 25, 12.5, 6.25 m	
			Fixed rms velocity (44 m/s)		200, 100, 50, 25, 12.5 m	
			Fixed rms velocity (89 m/s)		400, 200, 100, 50, 25 m	
			Fixed rms velocity (178 m/s)		800, 400, 200, 100, 50 m	
Chen et al. (2016)	Fore-and-aft	220 deg. (horizontal) x 56 deg. (vertical)	Fixed rms velocity (44.5m/s)	0.05, 0.1, 0.2, 0.8 Hz	200, 100, 50, 12.5 m	Vection magnitude increased as amplitude increased.

Table 2.4.1 Effects of amplitude on yaw vection

	Oscillation direction	FoV	Amplitude manipulation	Frequency	Amplitude	Effects of amplitude
Post et al. (1989)	Yaw		Fixed frequency	0.125 Hz	0.85, 3.4 deg.	Vection was larger when amplitude was larger.
				0.25 Hz		
				0.5 Hz		
				1 Hz		
				2 Hz		
				4 Hz		

Table 2.4.2 Effects of amplitude on roll vection

	Oscillation direction	FoV	Amplitude manipulation	Frequency	Amplitude	Effects of amplitude
Chow (2008)	Roll	200 deg. (horizontal) x 50 deg. (vertical)	Fixed rms velocity (49.5 deg./s)	0.05, 0.1, 0.2, 0.4, 0.8 Hz	222, 111, 55, 27.9, 13.9 deg.	Vection magnitude increased as amplitude increased.
	Roll		Fixed frequency and varying peak velocity (35, 70, 100, 140 deg./s)	0.05 Hz	111, 222, 318, 446 deg.	Vection magnitude was significantly lower for the 111 amplitude condition.

In Table 2.4, 2.4.1, and 2.4.2, we found that vection magnitude increased as amplitude increased for all studies listed.

2.4 Summary of literature review

From the discussion above, although vection was found to be positively related with oscillation amplitude, the effects of temporal frequency and rms velocity on vection remain unclear. The effects of frequency on vection were confounded with effects of velocity and amplitude. Previous studies indicated that temporal frequency, rms velocity, and oscillation amplitude affected the vection interactively. Research gaps concerning vection as functions of visual oscillation frequency, amplitude, and rms velocity are identified.

It is also found that effects of oscillation directions on vection have been little studied. For yaw and roll vection (two types of rotational vection), roll vection is associated with more sensory mismatch. This mismatch is supposed to lead to different effects on oscillatory vection. Somehow, there has not been any study comparing yaw and roll vection. This dissertation first compared frequency responses of vection along the yaw and roll axes.

CHAPTER 3 : EXPERIMENTAL SETUPS AND MEASUREMENTS

3.1 Apparatus

An optokinetic drum is a large rotating cylinder with stimuli pattern on its interior surface (Figure 3.1). During the experiment, stationary subjects sit in the drum and watch the inner side of the rotating drum.

Figure 3.1 A rotating optokinetic drum (cited from http://newswise.com/articles/the-nauseating-taste-of-bitter)

In both of the experiments in this dissertation, a virtual optokinetic drum is set up to apply visual stimuli with a large field of view (FoV). As illustrated in Figure 3.2, it is composed of three projectors and a cylindrical projector screen with a radius of around 115 centimeters. The visual stimuli are produced by a Visual Basic program in Microsoft Visual Basic 2008, and separated into three scenes by Triplehead2Go (Matrox Electronic Systems) simultaneously. Straight after that, the separated scenes are projected by the three projectors respectively into a coherent scene of 1920×480 pixel resolution. The scene is 120 cm high and 460 cm wide. The three projectors A, B, and C are mounted above the screen and tilted about 15 degrees below the horizontal. There are about 20 degrees overlap between the adjacent projected scenes. Distortions and overlaps were adjusted by a filter. The drum provided a large nominal 220°×55° (horizontal × vertical) FoV when subject sat at the center of the drum. The stimulus was played at 60 Hz refresh rate.

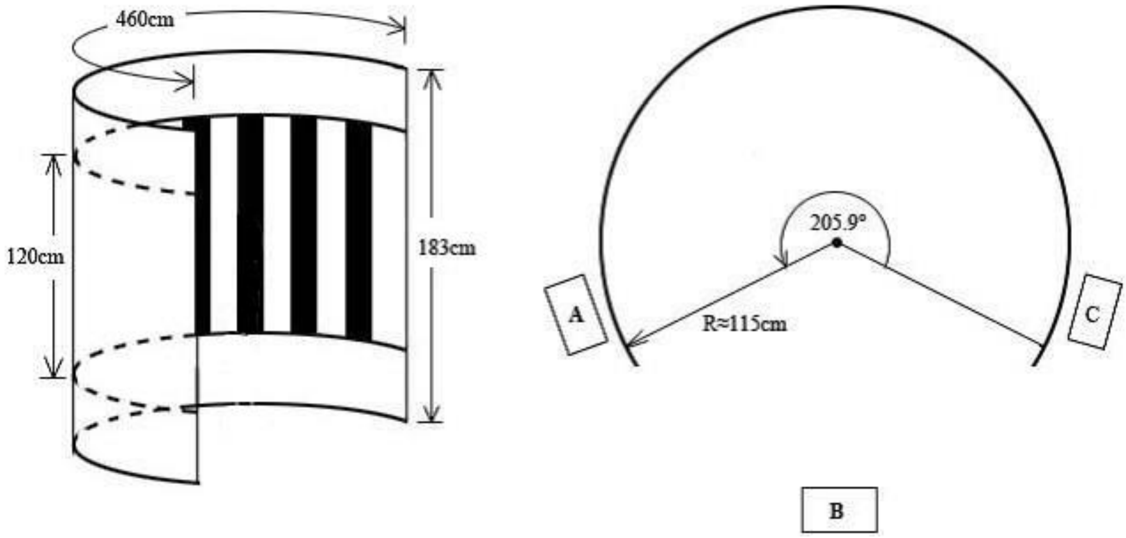

Figure 3.2 Setup of the virtual optokinetic drum (Guo, 2010)

The chin-rest was fixed at the center of the drum to keep subjects' head stationary, and of the same height with the projected scene's center. Before the experiment, the chair was adjusted to a suitable height so that subject can rest their head comfortably on the chin-rest. The experiment was conducted in a dark room.

Figure 3.3 shows a picture that a subject was doing Experiment 1. Subjects sat on an adjustable chair and put their head on the chin-rest. Videos were recorded to ensure that subjects fixed their eyes on the red cross and did not move their head. The setup of Experiment 2 was the same as Experiment 1 except that the visual stimuli were different.

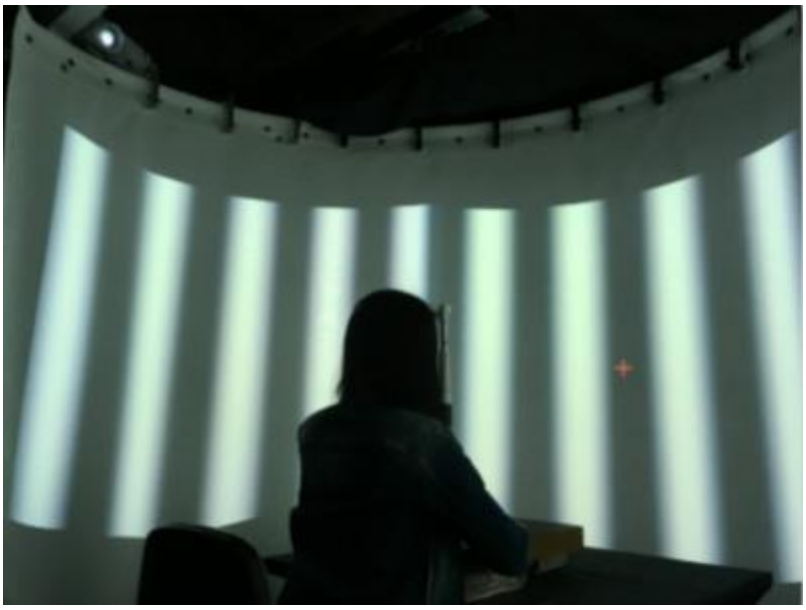

Figure 3.3 Photo that a subject was taking experiment

The details of the apparatus are shown in Table 3.1.

Table 3.1 Specifications of apparatus

Apparatus	Specifications
Stimuli generating computer	Intel® core 2™computer; NVidia GeForce 7600 GT graphics card; 2GB RAM; 2.4GHz CPU.
Projectors	NEC LT-380 LCD projectors.
Graphics expansion module	Triplehead2Go (Matrox Electronic Systems).

3.2 Vection generating stimuli

In experiment 1 for yaw vection, the visual stimulus was composed of vertical alternated black-and-white stripes (Figure 3.4), which was similar to the ones used by previous studies (Hu et al., 1997; Bonato et al., 2004; Palmisano and Gillam, 1998). This kind of visual pattern is typically used to induce vection along the yaw axis. The primary dissimilarity was that a smooth sine wave gradient was applied to the pattern. It transited between the white stripe and black stripe in order to decrease flickering generated by aliasing. Each black stripe and white stripe extended a visual angle of 7.5° in width. The visual stimulus oscillated sinusoidally along the yaw axis.

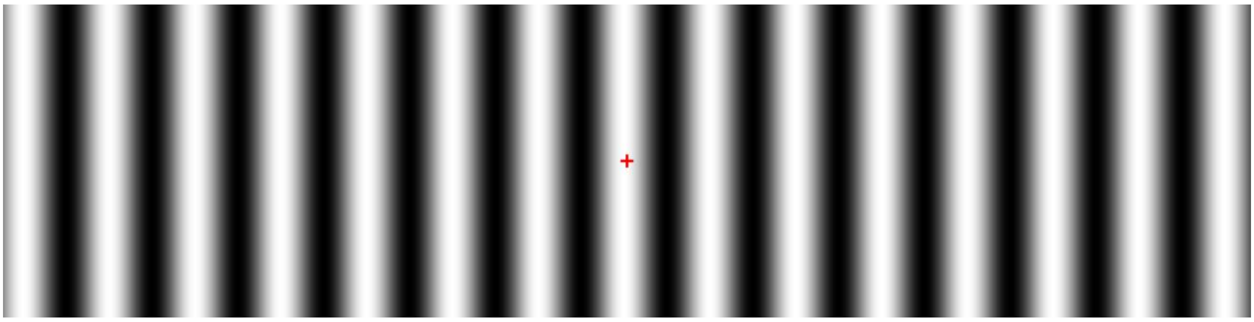

Figure 3.4 Yaw vection generating stimulus in Experiment 1

In Experiment 2 for roll vection, a checkerboard patterned tunnel visual stimulus was adopted to induce roll vection (Figure 3.5). Similar to the stimulus used by Duh et al. (2004), it was a radial pattern with eight pairs of black-and-white stripes. The tunnel was constructed in Autodesk 3ds Max 2013, and oscillations of the tunnel were rendered in Autodesk 3ds Max 2013. Each frame of the oscillations was captured from the view into the tunnel. Then each frame was filtered with a 2-D Gaussian smoothing kernel with standard deviation of 2 in MATLAB R2015b, through which to decrease flickering generated by aliasing. The velocity of the visual stimulus varied sinusoidally along the roll axis.

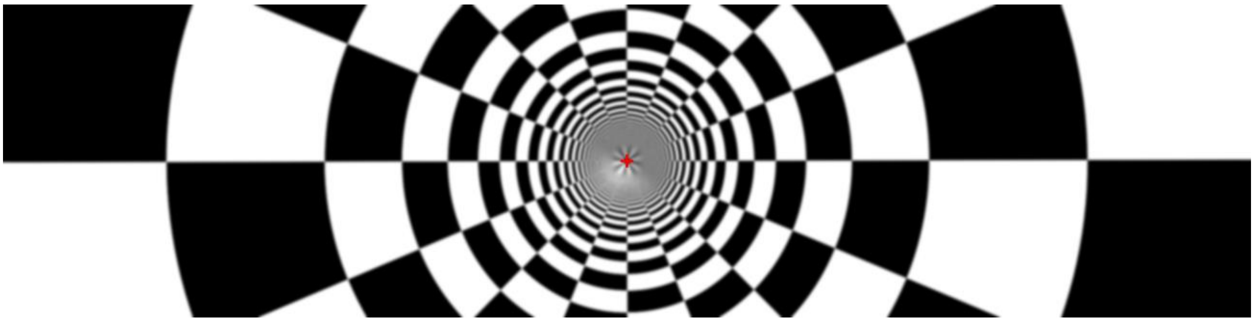

Figure 3.5 Roll vection generating stimulus in Experiment 2

In both of the stimuli, a red cross was drawn in the central of the scene. During the experiments, subjects were instructed to fix their eyes on the cross.

3.3 Measurements

3.3.1 Visual acuity

All subjects participating in the experiments were required to have normal or correct-to-normal visual acuity. Normal vision is known as 20/20 vision. Stereo Optical's Model 2000 Vision Tester was adopted to test subjects' visual acuity (Figure 3.6). Subjects needed to pass both near and far point visual acuity tests for both eyes and each eye separately. For near point vision test, the viewing distance between the targets and subjects' eyes is 14 inches, and for far point vision test, the distance is 20 feet. There are 14 targets corresponding to visual acuity from 20/200 to 20/13 in near or far point vision test. Each target is composed of 1 complete ring and 3 broken rings, and subjects need to point out the position of the complete ring. All vision tests were carried out in a dark room.

Figure 3.6 Optec 2000 Vision Tester (Stereo Optical Corp.)

3.3.2 Motion sickness susceptibility questionnaire short-form (MSSQ-short)

A short form of motion sickness susceptibility questionnaire (MSSQ-short) was filled by all subjects. The questionnaire is designed to find out how susceptible to motion sickness subjects are (Golding, 1998). MSSQ-short and the scoring method are attached in Appendix 3.1. It asks how often subjects feel sick or nauseated for following types of transport or entertainment: cars, buses or coaches, trains, aircraft, small boats, ships, swings in playgrounds, roundabouts in playgrounds, and big dippers or funfair rides. Same questions are asked for twice. One asks experience as a child (before age 12), and the other asks experience over the last 10 years. Based on the answers, MSSQ raw scores are computed to indicate subjects' susceptibility to motion sickness.

3.3.3 Simulator sickness questionnaires (SSQ)

Simulator sickness questionnaires (SSQ) were filled by all the subjects before and after the exposure of visual motion, to evaluate how sick or not subjects feel. SSQ is developed by Kennedy et al. (1993), and provides a more valid evaluation for simulator sickness as distinguished from motion sickness. SSQ is a symptom checklist for sickness. Table 3.2 shows 26 symptoms on the checklist. Each symptom is with four scales, which are "None", "Slightly", "Moderate", and "Severe".

Table 3.2 SSQ symptom checklist

1. General discomfort	10. Nausea	19. Aware of breathing
2. Fatigue	11. Difficulty concentrating	20. Stomach awareness
3. Boredom	12. Mental depression	21. Loss of appetite
4. Drowsiness	13. "Fullness of the head"	22. Increased appetite
5. Headache	14. Blurred vision	23. Desire to move bowels
6. Eyestrain	15. Dizziness eyes open Dizziness eyes close	24. Confusion
7. Difficulty focusing	16. Vertigo	25. Burping
8. Salivation increase Salivation decrease	17. Visual flashbacks	26. Vomiting
9. Sweating	18. Faintness	27. Other

Total scores and three sub-scores (nausea score, oculomotor score, and disorientation score) are obtained to rate the level of sickness (Kennedy et al., 1993). SSQ and the scoring method are attached in Appendix 3.2. In this dissertation, if subjects reported a total score larger than 7.48 before exposure, they were required to take a rest of at least five minutes. After rest, they filled the questionnaire again. If the total score is still larger than 7.48, they were asked to do the experiment on another day (Stanney et al., 2002).

3.3.4 Perceived Speed

Perceived speed was subjectively measured in both experiments. The definition of perceived speed is "how fast subjects are feeling the patterns are travelling". And subjects were instructed to know that perceived speed was not "the number of cycles of oscillations completed by the moving patterns per unit time".

Perceived speed was measured by a ratio-scale method (Chen, 2014). Subjects were asked to report the ratio of the average perceived speed of the signal condition relative to the reference condition. The average speed of the reference was assigned as 1, and there were 9 choices of ratios provided: 1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, and 16. In each condition of the experiment, subjects were first presented with a reference oscillation for 20 seconds, then a signal oscillation as long as subjects needed to estimate. Perceived speed was orally reported by subjects during the signal oscillation period.

This task requires the skills of ratio scaling. Therefore, a line-length estimation test was carried out to ensure that subjects were able to compare and scale the average velocity. In the test, participants were asked to estimate the ratios of the length of a set of lines to a reference line. There were 7 ratio choices provided: 1/8, 1/4, 1/2, 1, 2, 4, and 8. Participants who failed the test with an R square less than 0.9 were excluded in the experiment (Parker et al., 1975).

3.3.5 Vection

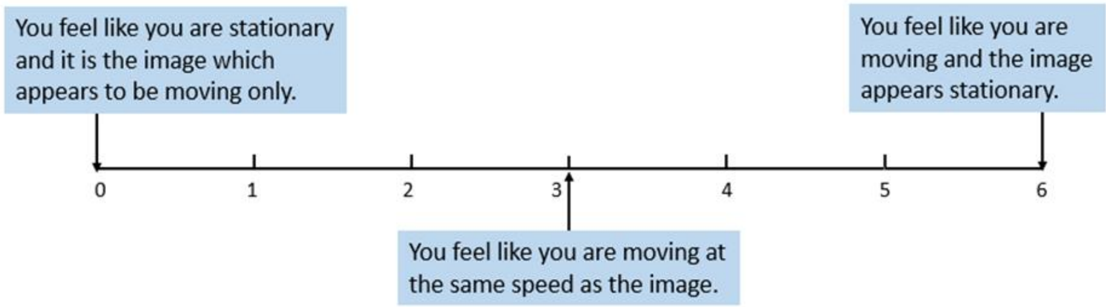

Figure 3.7 Description of vection magnitudes for each point

In both experiments, vection magnitude was subjectively measured to find out the level of intensity that subjects experience self-motion illusions. Vection magnitude was rated in a 7-point Likert scale ranging from 0 to 6, adopted from Chen (2014). Point 0 refers to feeling that “you are stationary and it is the image which appears to be moving only”; point 3 refers to feeling that “you are moving at the same speed as the image”; and point 6 refers to feeling that “you are moving and the image appears stationary” (Figure 3.7). If the sensation is more intensive, the rate is higher. During the experiment, subjects orally reported the vection magnitude ratings to the experimenter in the signal oscillation period.

CHAPTER 4 : EFFECTS OF FREQUENCY, VELOCITY AND AMPLITUDE ON VECTION FOR YAW VISUAL OSCILLATIONS

This chapter presents the work of Experiment 1, which studied effects of frequency, velocity, and amplitude of visual oscillations for yaw vection. Frequency consists of five levels: 0.025, 0.05, 0.1, 0.2, and 0.4 Hz; rms velocity consists of five levels: 8, 16, 32, 64, and 128 degrees per second; and amplitude consists of five levels: 18, 36, 72, 144, and 288 degrees. The experiment consisted of four repeated sessions in separate days adopting a within subjects design. Fourteen subjects (7 males) participated in the experiment. They were exposed to a virtual optokinetic drum, with alternated black-and-white stripes oscillating sinusoidally. Results supported the two-freqeuncy-response hypothesis proposed by Chen (2014). It was also found that visual oscillations of the same frequency produced different levels of vection (Vection increased at first and then decreased as rms velocity (or amplitude) increased). Analyses of the effects of amplitude indicated that the larger the amplitude, the stronger the vection. As for the effects of velocity, yaw vection presented an inverted U-shape with increasing velocity.

4.1 Research gaps and objectives

A detailed survey of literature in Chapter 2 showed that the effects of oscillation frequency, rms velocity, and amplitude on yaw vection for oscillatory visual stimuli remained unclear. The effects of frequency on vection were confounded with effects of velocity and amplitude. Experiment 1 aimed to fill this research gap. In this study, it is hypothesized that vection is not dominated by oscillation frequency alone, but is affected by frequency, velocity, and amplitude interactively.

4.2 Methods

This experiment was approved by the Human Subject and Research Ethics Committee in the Hong Kong University of Science and Technology. All of the subjects were asked to sign an informed consent form (see Appendix I). And they were compensated for the participation in the experiment at the rate of 50 HKD per hour.

4.2.1 Participants

One participant quitted after the first session of Experiment 1 due to extreme discomfort. And there were 14 students or research assistants (7 males), from Hong Kong University of Science and Technology, completing all of the four sessions in Experiment 1. These 14 participants aged between 19 and 35 years with an average of 24.7 and a standard deviation of 3.6. All of them had normal or correct-to-normal visual acuity, and normal vestibule function. And none of them was under any medical treatment. The Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-Short) was filled by participants to find out how susceptible they were to motion sickness (Golding, 1998; Golding, 2006). An average percentile score of 53.97% indicated that the sample was slightly susceptible.

4.2.2 Apparatus and stimulus

Apparatus and stimulus for Experiment 1 have been illustrated in detail in Chapter 3.

4.2.3 Experimental design

The framework of Chen (2014)'s experimental design was adopted. In this experiment, three independent variables were designed. Since the mathematical relationship between rms velocity (v), frequency (f), and amplitude (A) ($v=\sqrt{2}\pi fA$), there were three ways to express independent variables: 1. repetition, frequency, and amplitude; or 2. repetition, frequency, and rms velocity; or 3. repetition, rms velocity, and amplitude. Frequency consists of five levels: 0.025, 0.05, 0.1, 0.2, and 0.4 Hz; rms velocity consists of five levels: 8, 16, 32, 64, and 128 degrees per second; and amplitude consists of five levels: 18, 36, 72, 144, and 288 degrees. The following Table 4.1 presents all the 37 conditions of different combinations of velocity, amplitude, and frequency.

Table 4.1 Design of Experiment 1: 37 conditions

Con #	freq (Hz)	rms v (deg./s)	amp (deg.)	Con #	freq (Hz)	rms v (deg./s)	amp (deg.)	Con #	freq (Hz)	rms v (deg./s)	amp (deg.)
1	.4	8	4.5	**14**	.2	32	36	**27**	.4	256	144
2	.2	8	9	**15**	.4	64	36	**28**	.00625	8	288
3	.4	16	9	**16**	.8	128	36	**29**	.0125	16	288
4	.025	2	18	**17**	.025	8	72	**30**	.025	32	288
5	.05	4	18	**18**	.05	16	72	**31**	.05	64	288
6	.1	8	18	**19**	.1	32	72	**32**	.1	128	288
7	.2	16	18	**20**	.2	64	72	**33**	.2	256	288
8	.4	32	18	**21**	.4	128	72	**34**	.4	512	288
9	.8	64	18	**22**	.0125	8	144	**35**	.025	64	576
10	1.6	128	18	**23**	.025	16	144	**36**	.05	128	576
11	.025	4	36	**24**	.05	32	144	**37**	.025	128	1152
12	.05	8	36	**25**	.1	64	144				
13	.1	16	36	**26**	.2	128	144				

Perceived vection magnitude and perceived speed were designed as dependent variables. Vection magnitude was measured by a 7-point Likert scale ranging from 0 to 6. Perceived speed was measured based on a ratio-scale method. The ratio of the average perceived speed of the signal condition relative to the reference condition was supposed to be estimated by subjects. Reference condition was the “middle one” (Con# 19) with frequency of 0.1 Hz (the middle of the frequency range), rms velocity of 32 deg./s (the middle of the rms velocity range), and amplitude of 72 degrees (the mddle of the amplitude range). The average speed of the reference was assigned as 1, and there were 9 choices of ratios provided: 1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, and 16. More details of these two measurements have been presented in Chapter 3.

The experiment used a within-subject design.

4.2.4 Experiment procedures

Before the experiment, visual acuity test and line length estimation test were conducted. Then in a training session, participants who passed these two tests would be instructed about their tasks and matters needing attention in the experiment. Instructions for Experiment 1 is attached in Appendix 4.1.

There were 4 repeated sessions for each subject. To reduce effects of habituation, the time interval, between two successive repeated sessions, was at least 7 days (Regan, 1995).

In one session, each subject was exposed to all 37 conditions and each condition appeared once. Before each session, subjects filled the Pre-exposure Simulator Sickness Questionnaire

(SSQ). If the pre-SSQ total score was larger than 7.48, subjects were required to rest for 5 minutes and filled the questionnaire again. If still larger than 7.48, subjects were asked to do the experiment on another day (Stanney et al., 2002). Then the formal session started. The 37 conditions in a session were separated into 4 groups randomly. Each group contained 9 or 10 conditions, and the order of the conditions was also random. In each group, subjects completed the 9 or 10 conditions successively. Between each group, there was a 10-minute rest at least until no symptoms is 'Moderate' in SSQ. At the end, subjects completed the post-SSQ.

For each condition in a group, Figure 4.1 shows the procedure. During the signal oscillation presenting, perceived speed and vection were orally reported by subjects. Subjects could have enough time to estimate. Then program will be switched to next condition.

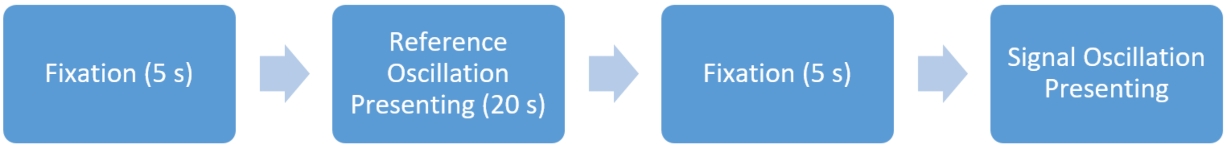

Figure 4.1 Experiment procedure for one condition

4.3 Results

Results of perceived speed and vection magnitude are shown respectively in the following. For each measurement, learning effects, effects of the three factors, and discussion on the results are presented. Correlation of vection and perceived speed accuracy is analyzed at last.

4.3.1 Perceived speed

4.3.1.1 Learning Effects

Table 4.2 shows the descriptive statistics for perceived speed in the four repetitions. It can be seen from the table that the average of perceived speeds decreased as repetitions went on. Therefore, learning effects were tested first.

Table 4.2 Descriptive statistics for perceived speeds in 4 repetitions (deg./s)

	Mean	Std. deviation	Minimum	25th percentile	Median	75th percentile	Maximum
Repetition 1	96.89	134.73	2	16	32	128	512
Repetition 2	94.12	136.48	2	16	32	128	512
Repetition 3	93.43	131.97	2	16	32	128	512
Repetition 4	89.35	128.78	2	16	32	128	512

The perceived speeds were not normally distributed ($p<0.001$, Shapiro-Wilk). Thus, non-parametric tests were adopted here. Results showed that repetitions had a significant influence on perceived speed for 4 repetitions ($p=0.013$, Friedman). When the data from Repetition 1 were excluded, the effects of repetition did not exist ($p=0.071$, Friedman). However, when the data from Repetition 1 and 2 were excluded, learning effects were significant ($p=0.023$, Friedman). Thus, subjects were still learning in repetition 4. However, the learning trend does not bury the effects of frequency, rms velocity, and amplitude on perceived speed. The subsequent analysis is based on the average ratings of repetition 1, 2, 3, and 4 of each participant for each condition.

4.3.1.2 Perceived speed under constant frequency

Conditions of the same frequency were grouped together to see how perceived speed is affected by amplitude and rms velocity. Figure 4.2 plots the medians of perceived speed for five levels of frequencies: (a). 0.025 Hz, (b). 0.05 Hz, (c). 0.1 Hz, (d). 0.2 Hz, and (e). 0.4 Hz. There are two abscissas in the figure. The lower one represents rms velocity, and the upper one represents amplitude. Error bars for each condition represent the first and third quartiles of the participants' ratings. Wilcoxon signed rank tests showed that perceived speed was significantly different for every pair of conditions under constant frequency ($p<0.05$).

As the figure shows, perceived speed increased with increasing rms velocity (or amplitude). This is to our expectations because perceived speed and rms velocity should be strongly linear correlated.

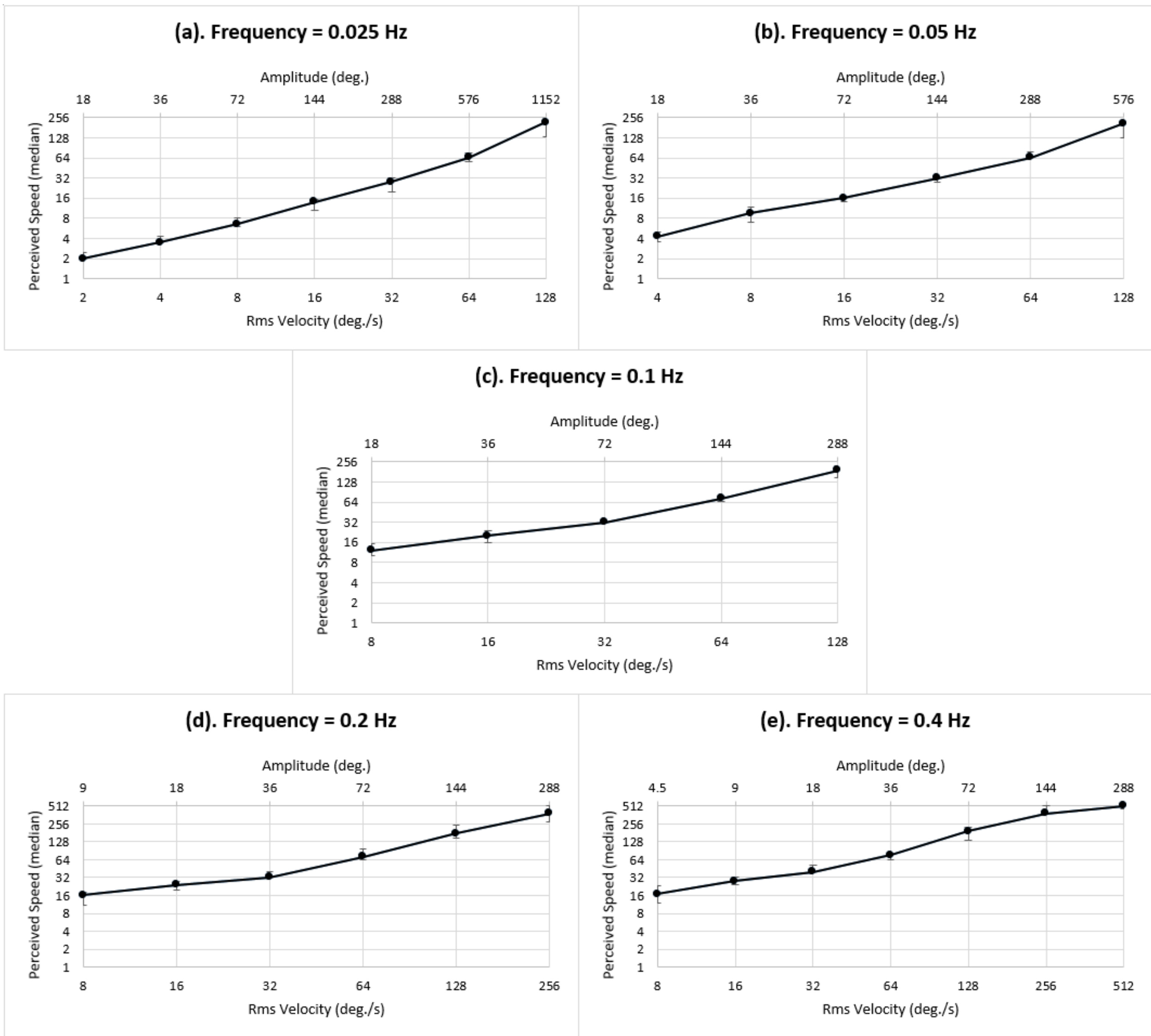

Figure 4.2 Medians of perceived speed under constant frequency for five levels of frequencies: (a). 0.025 Hz; (b). 0.05 Hz; (c). 0.1 Hz; (d). 0.2 Hz; (e). 0.4 Hz.

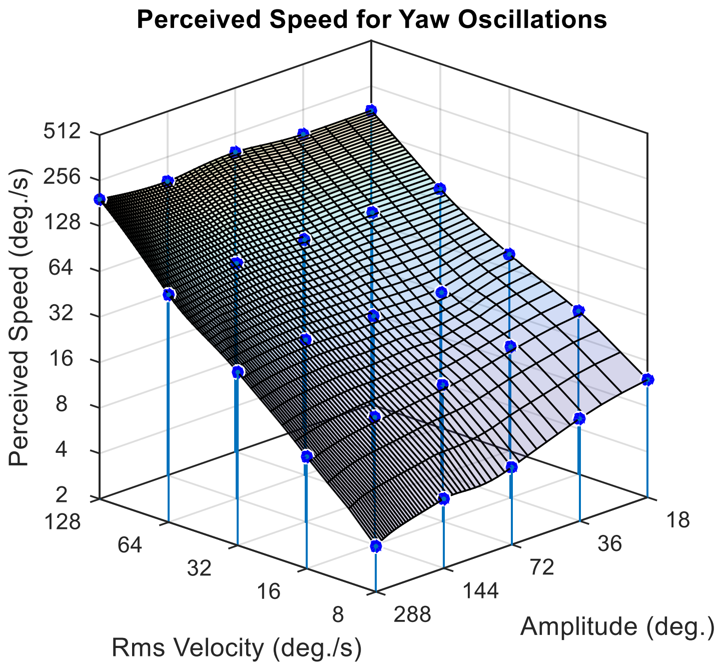

Figure 4.2.1 Medians of perceived speed for conditions with different levels of rms velocity and amplitude

4.3.1.3 Perceived speed under constant amplitude

Under constant amplitude, Figure 4.3 shows the medians of the perceived speed for five levels of amplitudes: (a). 18 degrees, (b). 36 degrees (c). 72 degrees, (d). 144 degrees, and (e). 288 degrees. The lower abscissa represents frequency, and the upper one represents rms velocity. Error bars for each condition represent the first and third quartiles of the participants' ratings. Wilcoxon signed rank tests showed that perceived speed was significantly different for every pair of conditions under constant frequency ($p<0.05$).

As the figure shows, perceived speed linearly increased with increasing frequency (or rms velocity). It is not surprising because perceived speed should change linearly with the visual oscillation rms velocity.

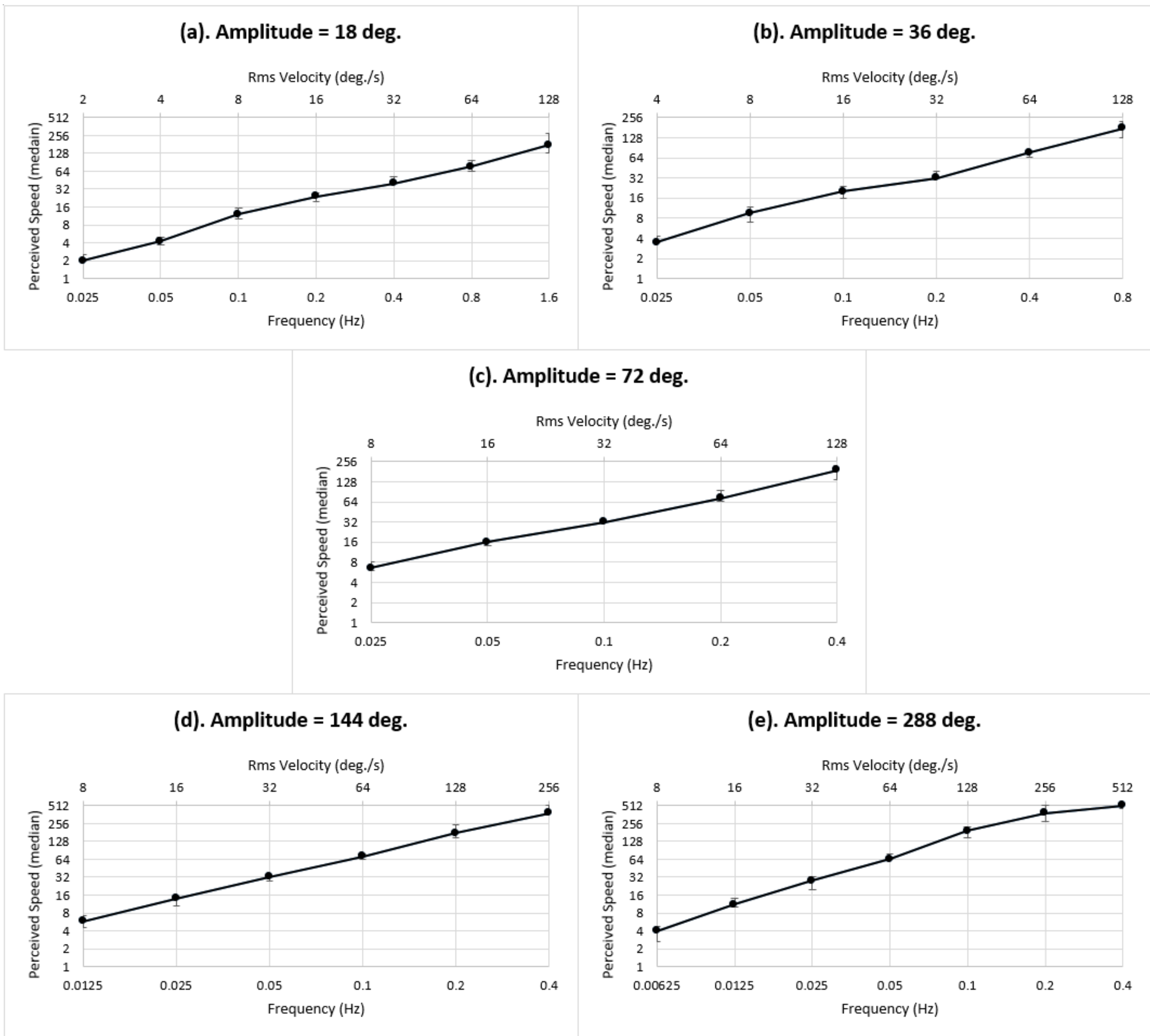

Figure 4.3 Medians of perceived speed under constant amplitude for five levels of amplitudes: (a). 18 degrees; (b). 36 degrees; (c). 72 degrees; (d). 144 degrees; (e). 288 degrees.

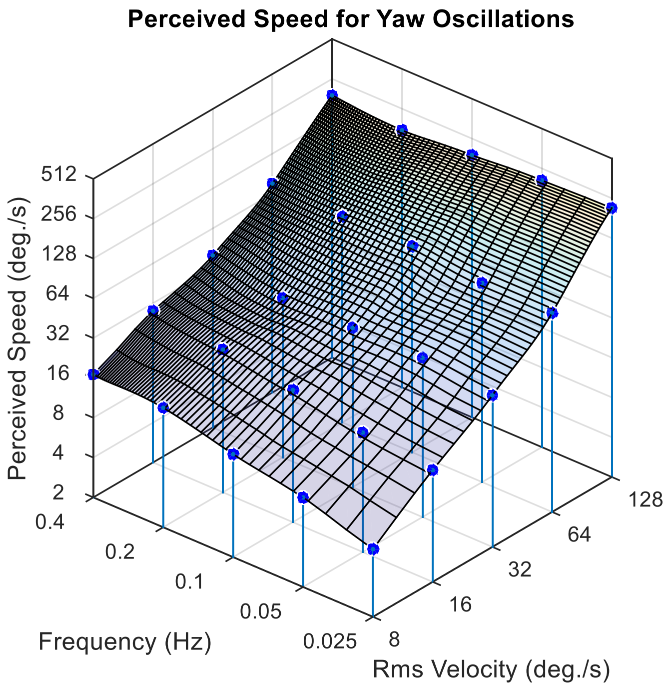

Figure 4.3.1 Medians of perceived speed for conditions with different levels of rms velocity and frequency

4.3.1.4 Perceived speed under constant rms velocity

Under constant rms velocity, Figure 4.4 shows the medians of the perceived speed for five levels of rms velocities: (a). 8 deg./s, (b). 16 deg./s, (c). 32 deg./s, (d). 64 deg./s, and (e). 128 deg./s. The lower abscissa represents frequency, and the upper one represents amplitude. Error bars for each condition represent the first and third quartiles of the participants' ratings. The horizontal double sided arrows indicate significant differences in two conditions ($p<0.05$, Wilcoxon).

These pairs of significantly different conditions show that perceived speed increased as frequency increased (or amplitude decreased). Especially when rms velocity was kept at 8 and 16 deg./s, the trend was apparent. It was also observed that, when rms velocity was fixed at 8 and 16 deg./s, perceived speed was underestimated if frequency was below around 0.05 Hz and overestimated if frequency was above around 0.05 Hz. Somehow, when rms velocity was fixed at 32, 64, and 128 deg./s, frequency response for perceived speed was flat.

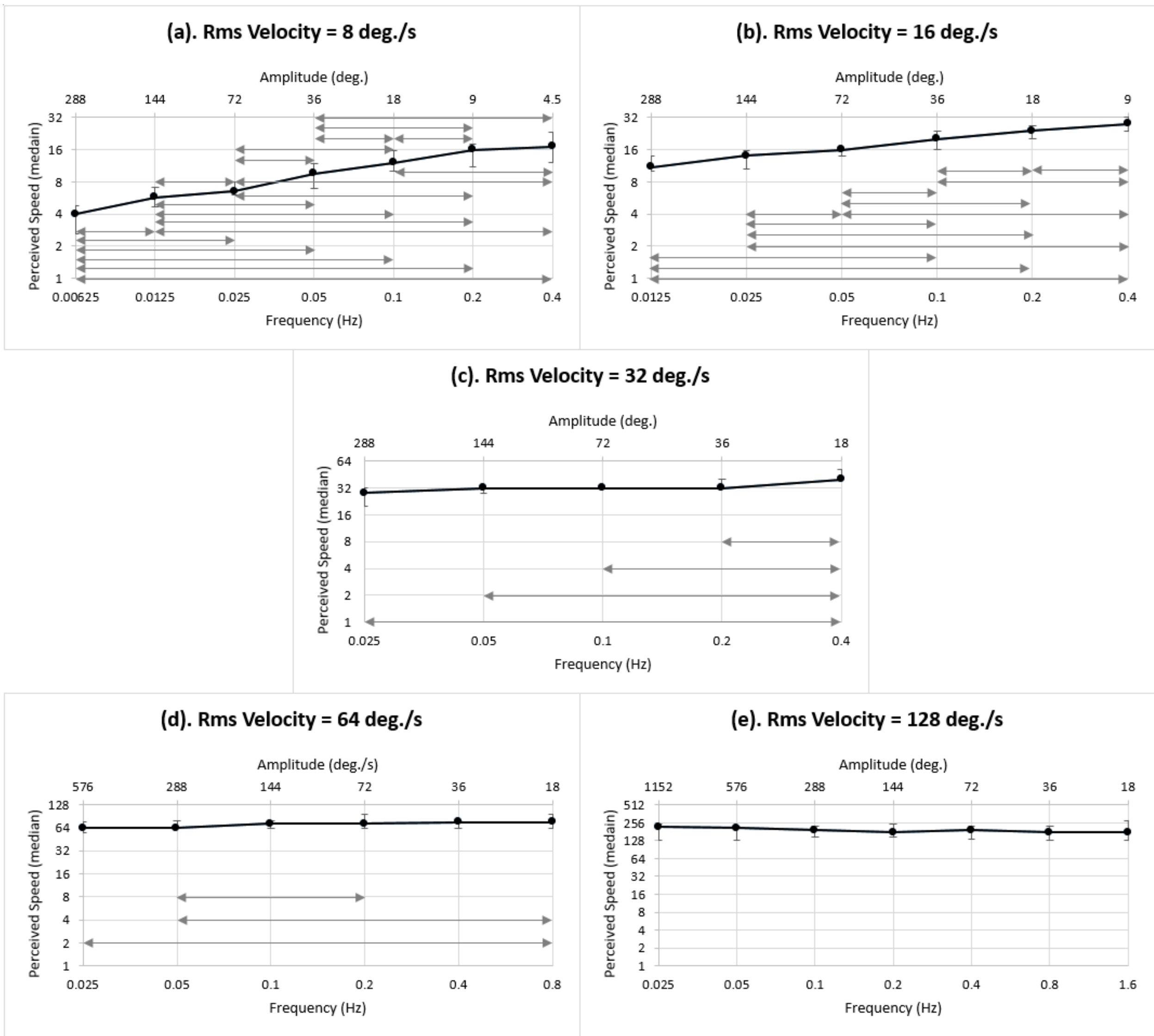

Figure 4.4 Medians of perceived speed under constant rms velocity for five levels of rms velocities: (a). 8 deg./s; (b). 16 deg./s; (c). 32 deg./s; (d). 64 deg./s; (e). 128 deg./s.

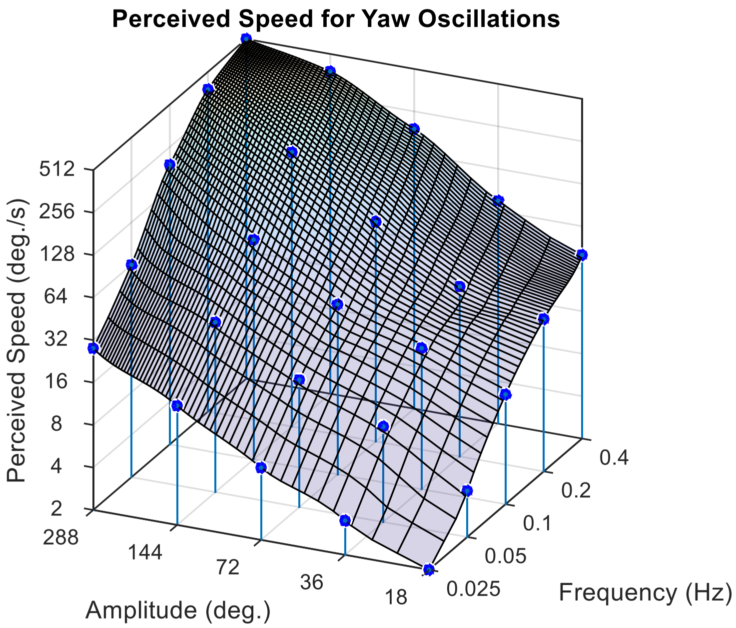

Figure 4.4.1 Medians of perceived speed for conditions with different levels of frequency and amplitude

4.3.1.5 Discussion

Chen (2014) found that there were two frequency responses for perceived speed when visual oscillations were along the fore-and-aft axis. In his study, he described the two patterns:

> *"One type of patterns is that when keeping the r.m.s. velocities of the stimuli constant, the frequency response curves are generally flat between 0.05 Hz to 1.6 Hz but they gradually take on an increase trend with increasing frequency for r.m.s. velocities at 22 m/s or below. For the other pattern, perceived speeds increase significantly with increasing frequency when the amplitudes of the oscillating stimuli are kept constant."*

In this dissertation, similar two-frequency-response was obtained when oscillations were along the yaw axis. When rms velocity was fixed, perceived speed increased as frequency increased if rms velocity was fixed at 8 and 16 deg./s; and perceived speed presented a flat frequency response if rms velocity was fixed at 32, 64, and 128 deg./s. When amplitude was fixed, perceived speed increased as frequency increased.

4.3.2 Vection magnitude

4.3.2.1 Learning effects

Table 4.3 shows the descriptive statistics for vection magnitude in the four repetitions. It can be seen from the table that the average of vection magnitudes increased as repetitions went on. Therefore, learning effects were tested first.

Table 4.3 Descriptive statistics for vection magnitudes in 4 repetitions

	Mean	Std. deviation	Minimum	25^{th} percentile	Median	75^{th} percentile	Maximum
Repetition 1	1.674	1.725	0	0	1	3	6
Repetition 2	1.782	1.538	0	0	2	3	6
Repetition 3	1.969	1.536	0	1	2	3	6
Repetition 4	1.992	1.603	0	1	2	3	6

The perceived vection magnitudes were not normally distributed ($p<0.001$, Shapiro-Wilk). Thus, non-parametric tests were adopted here. Results showed that repetitions had a significant influence on vection for 4 repetitions ($p=0.038$, Friedman). When the data from Repetition 1 were excluded, the effects of repetition still existed ($p=0.004$, Friedman). When the data from Repetition 1 and 2 were excluded, there was no learning effects ($p=0.661$, Friedman). Subjects' performance was supposed to be stable in repetition 3 and 4. And the subsequent analysis is based on the average ratings of repetition 3 and 4 of each participant for each condition.

4.3.2.2 Vection magnitude under constant frequency

Conditions of the same frequency were grouped together to see how vection is affected by amplitude and rms velocity. Figure 4.5 plots the medians of the vection magnitude for five levels of frequencies: (a). 0.025 Hz, (b). 0.05 Hz, (c). 0.1 Hz, (d). 0.2 Hz, and (e). 0.4 Hz. There are two abscissas in the figure. The lower one represents rms velocity, and the upper one represents amplitude. When rms velocity doubles, amplitude doubles to maintain the same frequency. Error bars for each condition represent the first and third quartiles of the participants' ratings. The horizontal double sided arrows indicate significant differences in two conditions ($p<0.05$, Wilcoxon). These pairs of significantly different conditions show that when frequency is kept constant at 0.025 Hz and 0.05 Hz, there is a significant increase in the vection magnitude as rms velocity (or amplitude) increases. And when frequency is kept at 0.1 Hz, 0.2 Hz, and 0.4 Hz, the vection magnitude increases first then decreases significantly as rms velocity (or amplitude) becomes larger.

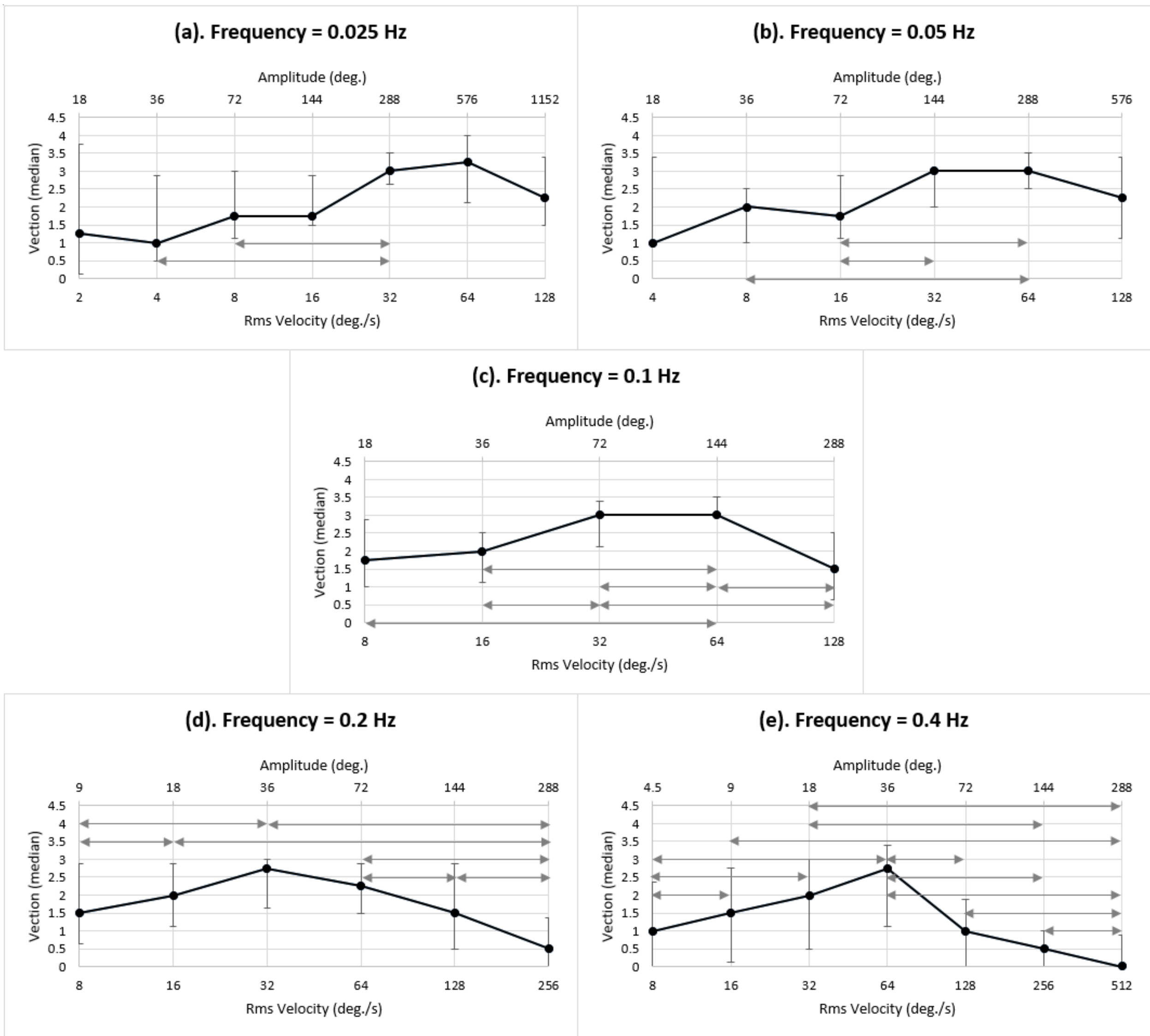

Figure 4.5 Medians of vection magnitude under constant frequency for five levels of frequencies: (a). 0.025 Hz; (b). 0.05 Hz; (c). 0.1 Hz; (d). 0.2 Hz; (e). 0.4 Hz.

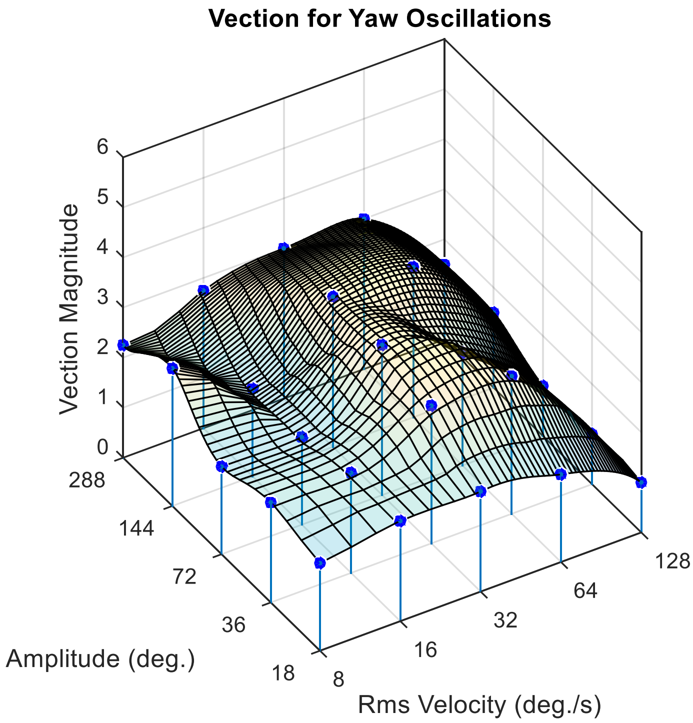

Figure 4.5.1 Medians of vection magnitude for conditions with different levels of rms velocity and amplitude

Friedman two-way analyses of variance show there are significant differences in vection magnitude ratings when the frequency is kept at 0.025 Hz (p=0.032), 0.1 Hz (p=0.001), 0.2 Hz (p=0.006), and 0.4 Hz (p=0.000). It indicates significant effects of rms velocity (or amplitude) on vection magnitude.

4.3.2.3 Vection magnitude under constant amplitude

Under constant amplitude, Figure 4.6 shows the medians of the vection magnitude ratings for five levels of amplitudes: (a). 18 degrees, (b). 36 degrees (c). 72 degrees, (d). 144 degrees, and (e). 288 degrees. The lower abscissa represents frequency, and the upper one represents rms velocity. Error bars for each condition represent the first and third quartiles of the participants' ratings. The horizontal double sided arrows indicate significant differences in two conditions (p<0.05, Wilcoxon). From the plots, it can be roughly seen that as the frequency (or rms velocity) increases, the median of vection magnitude increases first and then decreases. Significantly different pairs show that, as frequency (or rms velocity) increases, vection magnitude drops significantly when amplitude is retained at 36, 144, and 288 degrees. While amplitude is kept at 72 degrees, vection magnitude increases first then decreases with increasing frequency (or rms velocity).

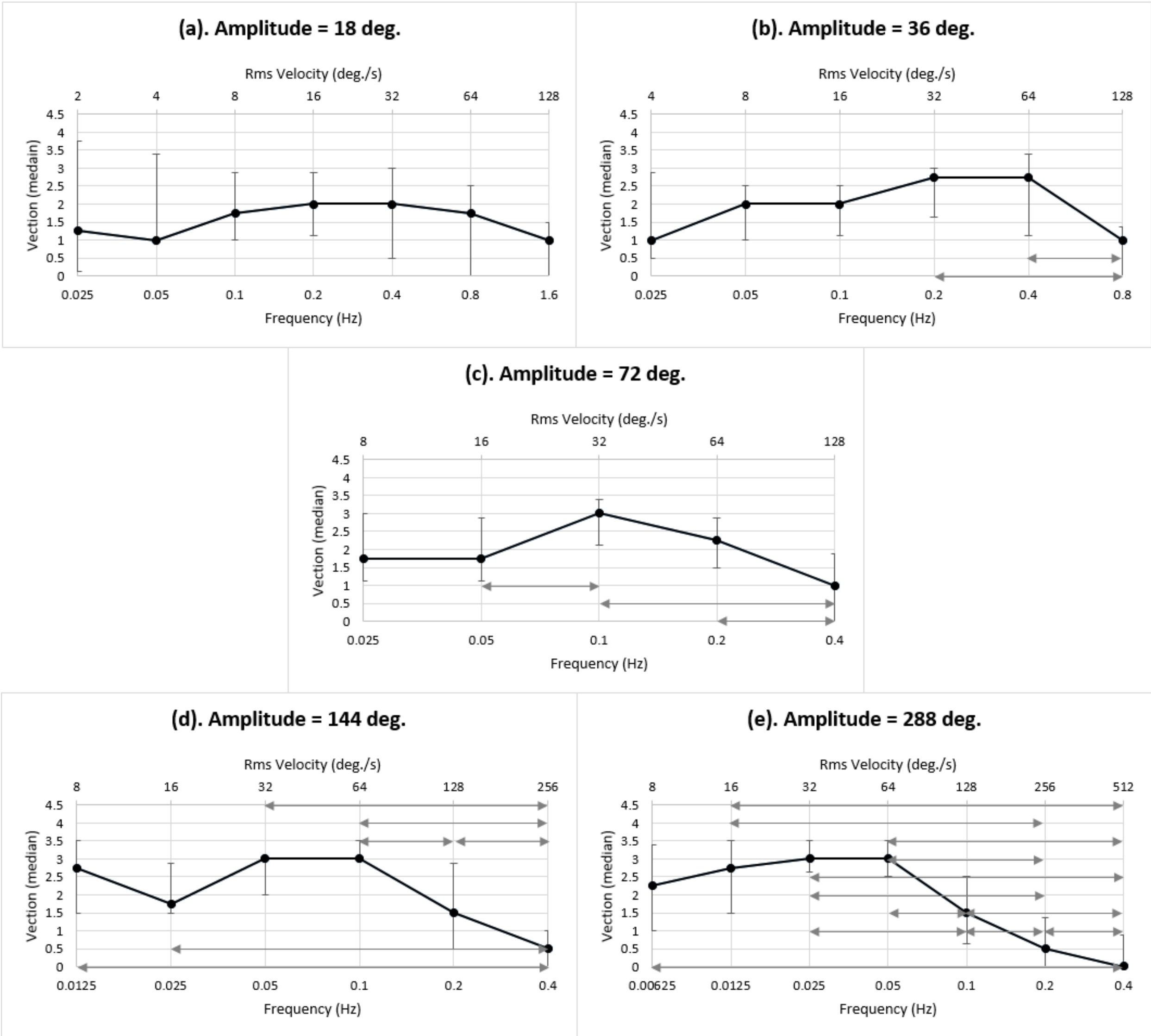

Figure 4.6 Medians of vection magnitude ratings under constant amplitude for five levels of amplitudes: (a). 18 degrees; (b). 36 degrees; (c). 72 degrees; (d). 144 degrees; (e). 288 degrees.

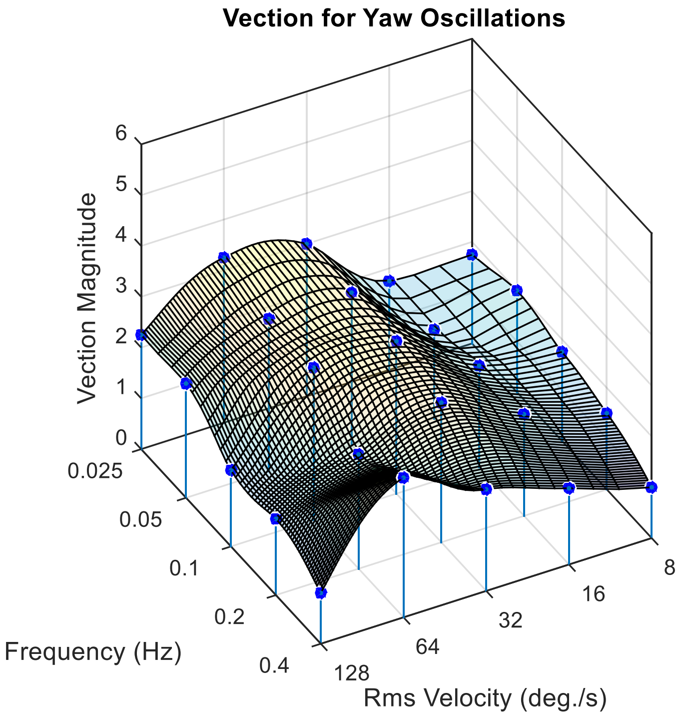

Figure 4.6.1 Medians of vection magnitude for conditions with different levels of rms velocity and frequency

Friedman tests find that vection ratings for conditions of the same amplitude are significantly different if the amplitude stays at 36 degrees (p=0.011), 144 degrees (p=0.001), and 288 degrees (p=0.000), which means that frequency (or rms velocity) has significant main effects on vection magnitude.

4.3.2.4 Vection magnitude under constant rms velocity

Under constant rms velocity, Figure 4.7 shows the medians of the vection magnitude ratings for five levels of rms velocities: (a). 8 deg./s, (b). 16 deg./s, (c). 32 deg./s, (d). 64 deg./s, and (e). 128 deg./s. The lower abscissa represents frequency, and the upper one represents amplitude. Error bars for each condition represent the first and third quartiles of the participants' ratings. The horizontal double sided arrows indicate significant differences in two conditions ($p<0.05$, Wilcoxon). The plots show that the median of vection decreases as the frequency increases (or the amplitude decreases). Results of Wilcoxon Signed Rank tests statistically support the trend.

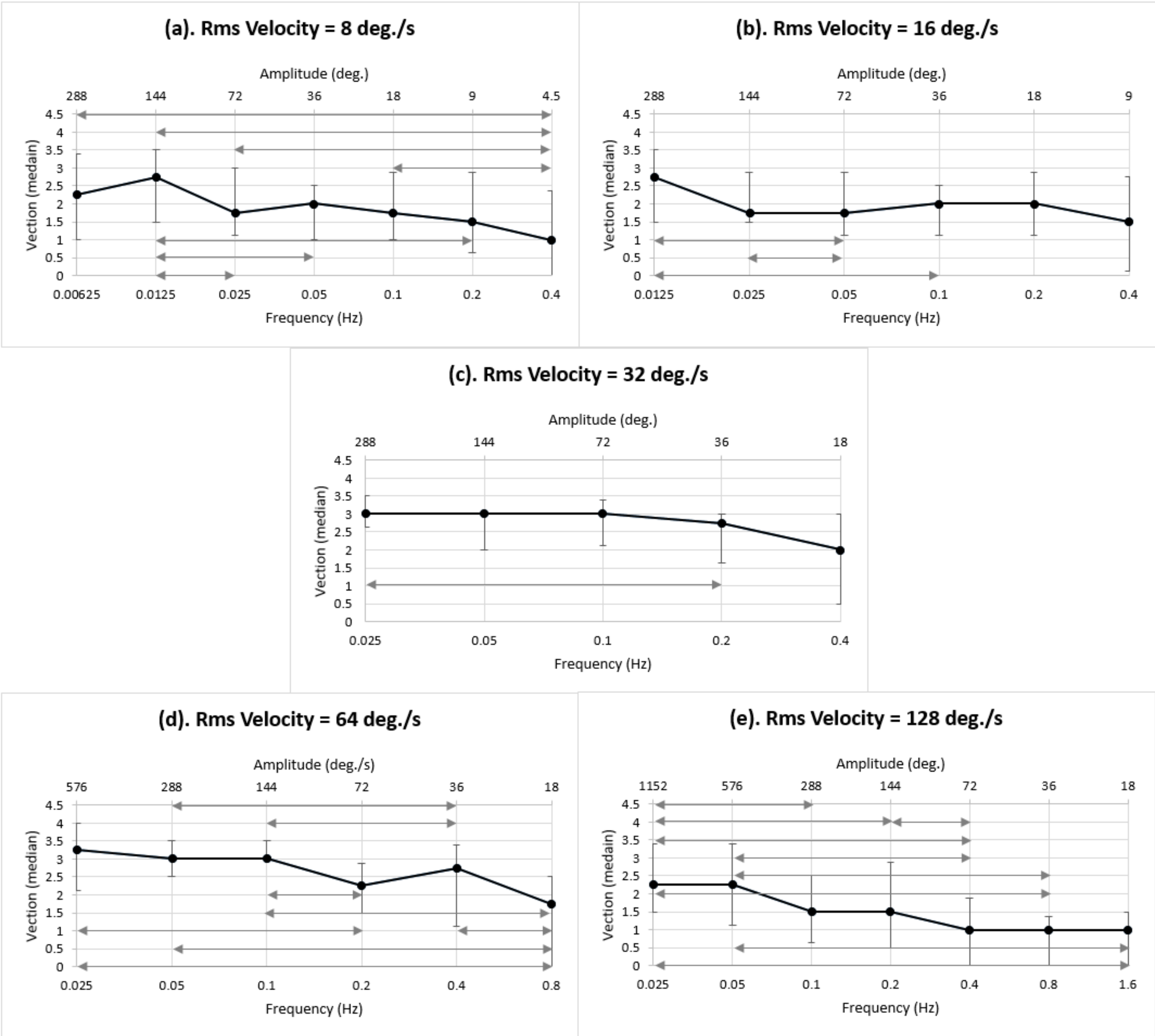

Figure 4.7 Medians of vection magnitude ratings under constant rms velocity for five levels of rms velocities: (a). 8 deg./s; (b). 16 deg./s; (c). 32 deg./s; (d). 64 deg./s; (e). 128 deg./s.

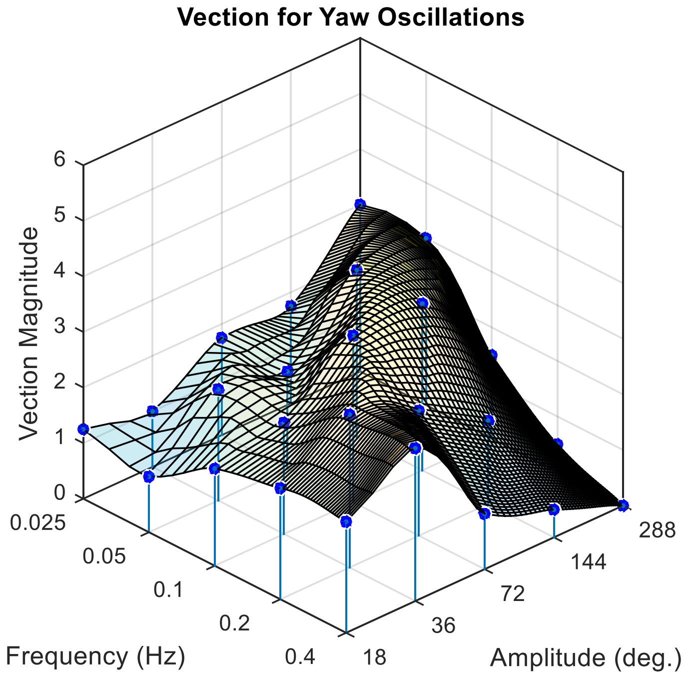

Figure 4.7.1 Medians of vection magnitude for conditions with different levels of frequency and amplitude

Conditions of the same rms velocity generate significant different vection magnitude when grouped by constant rms velocity 8 deg./s (p=0.001), 64 deg./s (p=0.001), and 128 deg./s (p=0.000).

4.3.2.5 Discussions

Comparing our results to previous relevant findings, similar profile patterns of frequency responses for yaw vection were found. In both Chen (2006)'s study, where frequency was manipulated by varying rms velocity and fixing amplitude (+-41 degrees), and our study (where amplitude was fixed at +-36 degrees), vection magnitude was lower when frequency was small. Chen (2006) found that vection magnitude was significantly lower when the frequency was 0.0375 Hz (experiment conditions with four level of frequencies: 0.0375, 0.1, 0.1875, 0.375 Hz). In our study, vection magnitude was smaller when frequency was 0.025 Hz than 0.05, 0.1, 0.2, and 0.4 Hz. Post et al. (1989) found that vection magnitude decreased as frequency increased (experiment conditions with six level of frequencies 0.125, 0.25, 0.5, 1, 2, 4 Hz), where amplitude was fixed at +-0.85 degrees and 3.4 degrees. In our study, there was a decreasing trend for vection magnitude when frequency increased from 0.2 Hz to 1.6 Hz when fixing amplitude.

Revisiting Chen (2014)'s proposition of two-frequency-response hypothesis, it was found that, for yaw vection, the hypothesis was supported. When frequency was manipulated by varying rms velocity and fixing amplitude, frequency response for vection magnitude presented an inverted U shape; and when frequency was manipulated by varying amplitude and fixing rms velocity, vection magnitude decreased as frequency increased.

It was also found that frequency responses were different if motion axis was changed. When amplitude remained constant and frequency was manipulated by varying rms velocity, Chen (2014) showed that vection magnitude increased as frequency increased in the fore-and-aft axis. While in our study vection magnitude increased first and then decreased with increasing frequency when motions were along the yaw axis. When rms velocity was kept constant, i.e., manipulating frequency by changing amplitude, frequency responses were similar in two directions. It indicates that the interaction effect of the three factors varies due to different oscillation directions.

In this study, we found that visual oscillations of the same frequency produced different levels of vection. When frequency remained unchanged, vection increased at first and then decreased as rms velocity (or amplitude) increased. It suggests that frequency alone should not be regarded as a sufficient predictor for perceived vection magnitude. This pattern can be interpreted by the effects of rms velocities and amplitudes on vection. Firstly, as rms velocity increased, vection ratings increased first then decreased (see Figure 4.6). It implied that vection was weak when rms velocity was too fast or too slow. Secondly, significant pairs of conditions in Figure 4.7 indicated that vection increased significantly as the amplitude increased if rms velocity was kept unchanged. Therefore, the increasing trend in Figure 4.5 benefits from both increasing velocity and increasing amplitude. And when the velocity becomes too fast, the vection ratings drop because the gain of vection from larger amplitude cannot make up the loss from faster velocity.

4.3.3 Correlation of vection magnitude and perceived speed accuracy

Perceived speed accuracy conveys more information about subjects' performance. Chen (2004) measured perceived speed accuracy by the 'perception bias', which was defined as follows:

$$\text{Perception Bias} = \log_2(\text{Perception speed}/\text{Actual speed})$$

Zero perception bias means a perfect perception; a positive bias means overestimation; and a negative bias means underestimation.

Descriptive statistics of perception bias grouped by the same level of vection magnitude are summarized in Table 4.4. From the table, it is found that perception bias decreases from a positive value to a negative value gradually as vection magnitude ranges from 0 to 6. And the correlation between the perception bias and vection ratings is significantly negative (Spearman, rho=-0.093, p=0.000). Therefore, larger vection magnitude is associated with a smaller perception bias. It indicates that the presence of vection produces lower perceived speed.

Table 4.4 Descriptive statistics of perception bias grouped by the same vection magnitude

Vection magnitude	**Perception Bias**							
	Number of observations	**Mean**	**Std. Deviation**	**Min**	**25 percentiles**	**Median**	**75 percentiles**	**Max**
0	592	.2703	.73	-2	0	0	1	3
1	383	.1070	.77	-2	0	0	1	2
2	323	.1393	.78	-2	0	0	1	2
3	439	.1116	.74	-2	0	0	1	3
4	218	.0963	.74	-2	0	0	1	2
5	78	-.0769	.88	-2	-1	0	0	2
6	39	-.0256	.93	-2	0	0	1	2

CHAPTER 5 : EFFECTS OF FREQUENCY, VELOCITY AND AMPLITUDE ON VECTION FOR ROLL VISUAL OSCILLATIONS

This chapter presents the work of Experiment 2, which studied effects of frequency, velocity, and amplitude of visual oscillations for roll vection. Frequency consists of five levels: 0.025, 0.05, 0.1, 0.2, and 0.4 Hz; rms velocity consists of five levels: 8, 16, 32, 64, and 128 degrees per second; and amplitude consists of five levels: 18, 36, 72, 144, and 288 degrees. The experiment consisted of four repeated sessions in separate days adopting a within subjects design. Fourteen subjects (7 males) participated in the experiment. They were exposed to radial checker-board pattern oscillating along the roll axis. Results found that visual oscillations of the same frequency produced different levels of vection. Analyses of the effects of amplitude indicated that the larger the amplitude, the stronger the vection. As for the effects of velocity, roll vection decreased as velocity increased. For the two-frequency-response hypothesis, only one frequency response, that vection dropped as frequency increased no matter whether rms velocity or amplitude was fixed, was observed here.

5.1 Research gaps and objectives

A detailed survey of literature in Chapter 2 showed that the effects of oscillation frequency, rms velocity, and amplitude on roll vection for oscillatory visual stimuli remained unclear. The effects of frequency on vection were confounded with effects of velocity and amplitude. Experiment 2 aimed to fill this research gap. In this study, it is hypothesized that vection is not dominated by oscillation frequency alone, but is affected by frequency, velocity, and amplitude interactively.

5.2 Methods

This experiment was approved by the Human Subject and Research Ethics Committee in Hong Kong University of Science and Technology. All of the subjects were asked to sign an informed consent form (see Appendix I). And they were compensated for the participation in the experiment at the rate of 50 HKD per hour.

5.2.1 Participants

There were 14 students or research assistants (7 males), from Hong Kong University of Science and Technology, completing all of the four sessions in Experiment 2. These 14 participants aged between 23 and 31 years with an average of 25.4 and a standard deviation of 2.2. All of them had normal or correct-to-normal visual acuity, and normal vestibule function. And none of them was under any medical treatment. The Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-Short) was filled by participants to find out how susceptible they were to motion sickness (Golding, 1998; Golding, 2006). An average percentile score of 46.46% indicated that the sample was slightly less susceptible.

5.2.2 Apparatus and stimulus

Apparatus and stimulus for Experiment 2 have been illustrated in detail in Chapter 3.

5.2.3 Experimental design

The framework of Chen (2014)'s experimental design was adopted. Similar to Experiment 1, in this experiment, three independent variables were designed. Since the mathematical relationship between rms velocity (v), frequency (f), and amplitude (A) ($v=\sqrt{2}\pi fA$), there were three ways to express independent variables: 1. repetition, frequency, and amplitude; or 2. repetition, frequency, and rms velocity; or 3. repetition, rms velocity, and amplitude. The levels of oscillation frequency, rms velocity, and amplitude were designed to be the same with Experiment 1 for purpose of comparison between yaw and roll vection. Frequency consists of five levels: 0.025, 0.05, 0.1, 0.2, and 0.4 Hz; rms velocity consists of five levels: 8, 16, 32, 64, and 128 degrees per second; and amplitude consists of five levels: 18, 36, 72, 144, and 288 degrees. The following Table 5.1 presents all the 37 conditions of different combinations of velocity, amplitude, and frequency.

Table 5.1 Design of Experiment 2: 37 conditions

Con #	freq (Hz)	rms v (deg./s)	amp (deg.)	Con #	freq (Hz)	rms v (deg./s)	amp (deg.)	Con #	freq (Hz)	rms v (deg./s)	amp (deg.)
1	.4	8	4.5	**14**	.2	32	36	**27**	.4	256	144
2	.2	8	9	**15**	.4	64	36	**28**	.00625	8	288
3	.4	16	9	**16**	.8	128	36	**29**	.0125	16	288
4	.025	2	18	**17**	.025	8	72	**30**	.025	32	288
5	.05	4	18	**18**	.05	16	72	**31**	.05	64	288
6	.1	8	18	**19**	.1	32	72	**32**	.1	128	288
7	.2	16	18	**20**	.2	64	72	**33**	.2	256	288
8	.4	32	18	**21**	.4	128	72	**34**	.4	512	288
9	.8	64	18	**22**	.0125	8	144	**35**	.025	64	576
10	1.6	128	18	**23**	.025	16	144	**36**	.05	128	576
11	.025	4	36	**24**	.05	32	144	**37**	.025	128	1152
12	.05	8	36	**25**	.1	64	144				
13	.1	16	36	**26**	.2	128	144				

Perceived vection magnitude and perceived speed were designed as dependent variables. Vection magnitude was measured by a 7-point Likert scale ranging from 0 to 6. Perceived speed was measured based on a ratio-scale method. The ratio of the average perceived speed of the signal condition relative to the reference condition was supposed to be estimated by subjects. Reference condition was the “middle one” (Con# 19) with frequency of 0.1 Hz (the middle of the frequency range), rms velocity of 32 deg./s (the middle of the rms velocity range), and amplitude of 72 degrees (the mddle of the amplitude range). The average speed of the reference was assigned as 1, and there were 9 choices of ratios provided: 1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, and 16. More details of these two measurements have been presented in Chapter 3.

The experiment used a within-subject design.

5.2.4 Experiment procedures

Before the experiment, visual acuity test and line length estimation test were conducted. Then in a training session, participants who passed these two tests would be instructed about their tasks and matters needing attention in the experiment. Instructions for Experiment 2 is attached in Appendix 5.1.

There were 4 repeated sessions for each subject. To reduce effects of habituation, the time interval, between two successive sessions, was at least 7 days (Regan, 1995).

In one session, each subject was exposed to all 37 conditions and each condition appeared once. Before each session, subjects filled the Pre-exposure Simulator Sickness Questionnaire (SSQ). If the pre-SSQ total score was larger than 7.48, subjects were required to rest for 5 minutes and filled the questionnaire again. If still larger than 7.48, subjects were asked to do the experiment on another day (Stanney et al., 2002). Then the formal session started. The 37 conditions in a session were separated into 4 groups randomly. Each group contained 9 or 10 conditions, and the order of the conditions was also random. In each group, subjects completed the 9 or 10 conditions successively. Between each group, there was a 10-minute rest at least until no symptoms is 'Moderate' in SSQ. At the end, subjects completed the post-SSQ.

For each condition in a group, Figure 5.1 shows the procedure. During the signal oscillation presenting, perceived speed and vection were orally reported by subjects. Subjects could have enough time to estimate. Then program will be switched to next condition.

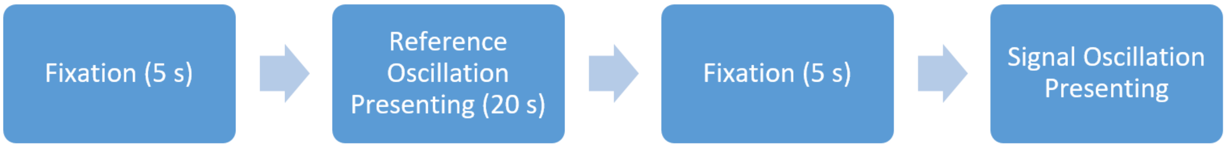

Figure 5.1 Experiment procedure for one condition

5.3 Results

Results of perceived speed and vection magnitude are shown respectively in the following. For each measurement, learning effects, effects of the three factors, and discussion on the results are presented. Correlation of vection and perceived speed accuracy is analyzed at last.

5.3.1 Perceived speed

5.3.1.1 Learning Effects

Table 5.2 shows the descriptive statistics for perceived speed in the four repetitions. Learning effects were tested first.

Table 5.2 Descriptive statistics for perceived speeds in 4 repetitions (deg./s)

	Mean	**Std. deviation**	**Minimum**	**25th percentile**	**Median**	**75th percentile**	**Maximum**
Repetition 1	72.35	109.97	2	8	32	64	512
Repetition 2	71.78	107.75	2	8	32	64	512
Repetition 3	74.03	111.57	2	8	32	64	512
Repetition 4	74.32	114.51	2	8	32	64	512

The perceived speeds were not normally distributed ($p<0.001$, Shapiro-Wilk). Thus, non-parametric tests were adopted here. Results showed that repetitions had a significant influence on perceived speed for 4 repetitions ($p=0.005$, Friedman). When the data from Repetition 1 were excluded, the effects of repetition did not exist ($p=0.16$, Friedman). When the data from Repetition 1 and 2 were excluded, learning effects were not significant ($p=0.47$, Friedman). Subjects' performance stabilized in the last three repetitions. The subsequent analysis is based on the average ratings of repetition 2, 3, and 4 of each participant for each condition.

5.3.1.2 Perceived speed under constant frequency

Conditions of the same frequency were grouped together to see how perceived speed is affected by amplitude and rms velocity. Figure 5.2 plots the medians of perceived speed for five levels of frequencies: (a). 0.025 Hz, (b). 0.05 Hz, (c). 0.1 Hz, (d). 0.2 Hz, and (e). 0.4 Hz. There are two abscissas in the figure. The lower one represents rms velocity, and the upper one represents amplitude. Error bars for each condition represent the first and third quartiles of the participants' ratings. Wilcoxon signed rank tests showed that perceived speed was significantly different for every pair of conditions under constant frequency ($p<0.05$).

As the figure shows, perceived speed increased with increasing rms velocity (or amplitude). This is to our expectations because perceived speed and rms velocity should be strongly linear correlated.

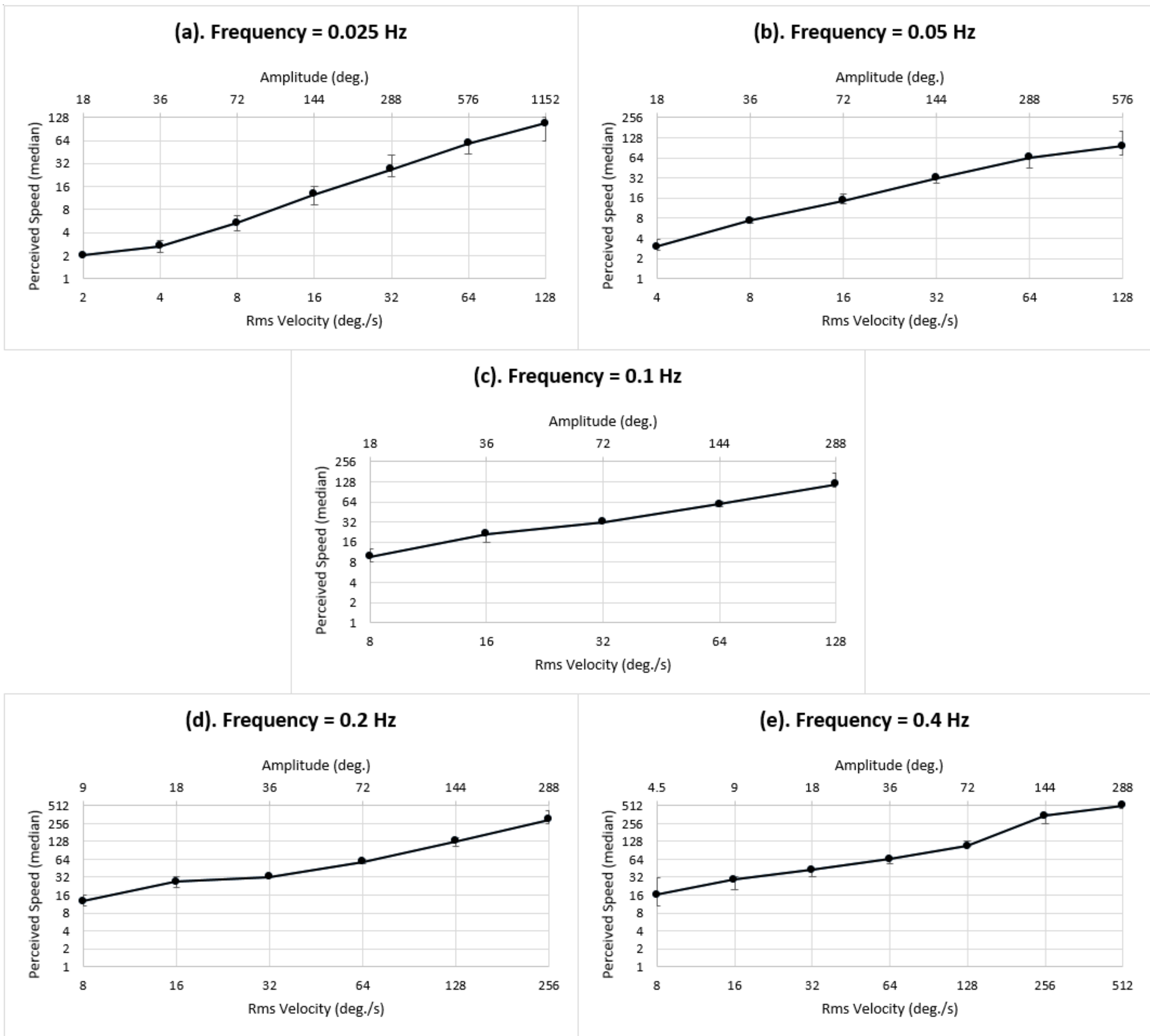

Figure 5.2 Medians of perceived speed under constant frequency for five levels of frequencies: (a). 0.025 Hz; (b). 0.05 Hz; (c). 0.1 Hz; (d). 0.2 Hz; (e). 0.4 Hz.

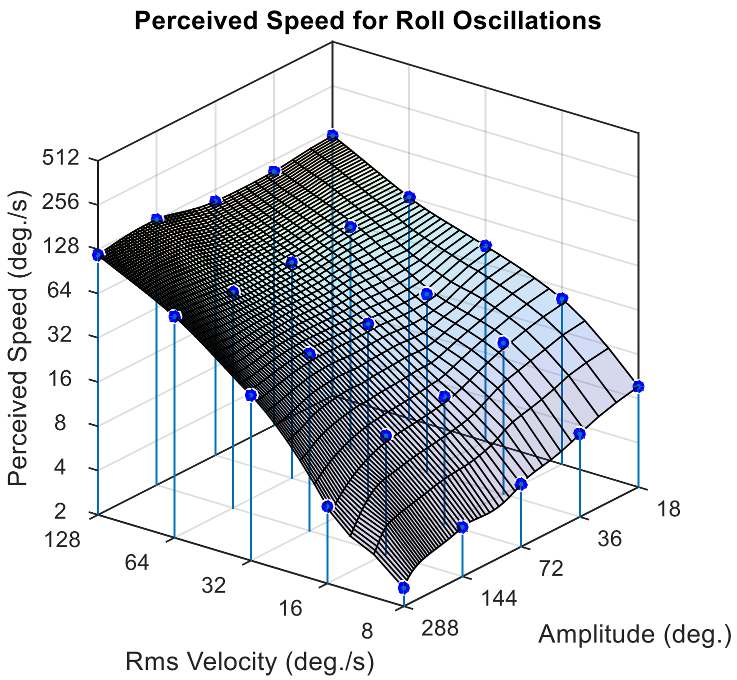

Figure 5.2.1 Medians of perceived speed for conditions with different levels of rms velocity and amplitude

5.3.1.3 Perceived speed under constant amplitude

Under constant amplitude, Figure 5.3 shows the medians of the perceived speed for five levels of amplitudes: (a). 18 degrees, (b). 36 degrees (c). 72 degrees, (d). 144 degrees, and (e). 288 degrees. The lower abscissa represents frequency, and the upper one represents rms velocity. Error bars for each condition represent the first and third quartiles of the participants' ratings. Wilcoxon signed rank tests showed that perceived speed was significantly different for every pair of conditions under constant frequency ($p<0.05$).

As the figure shows, perceived speed linearly increased with increasing frequency (or rms velocity). It is not surprising because perceived speed should change linearly with the visual oscillation rms velocity.

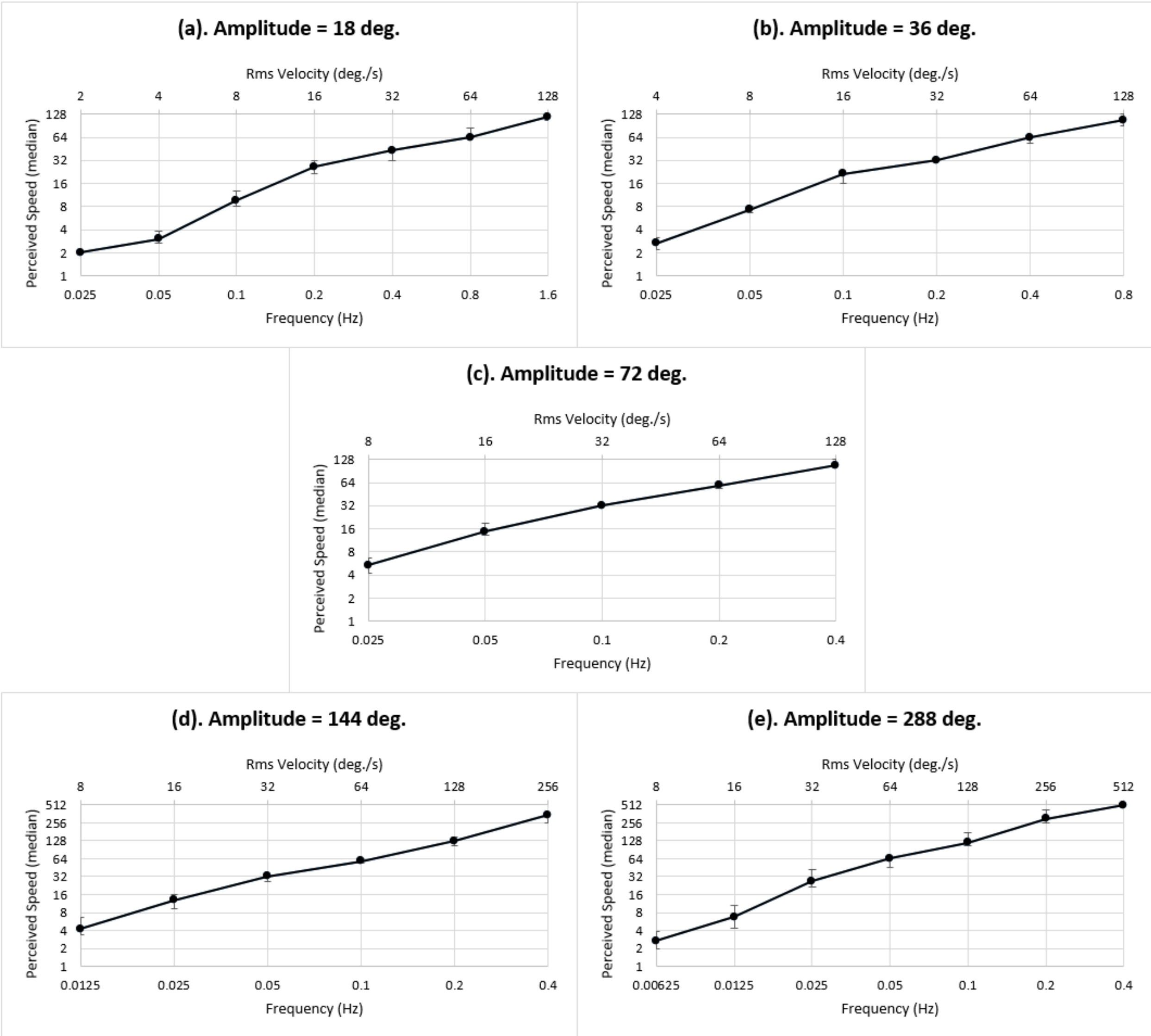

Figure 5.3 Medians of perceived speed under constant amplitude for five levels of amplitudes: (a). 18 degrees; (b). 36 degrees; (c). 72 degrees; (d). 144 degrees; (e). 288 degrees.

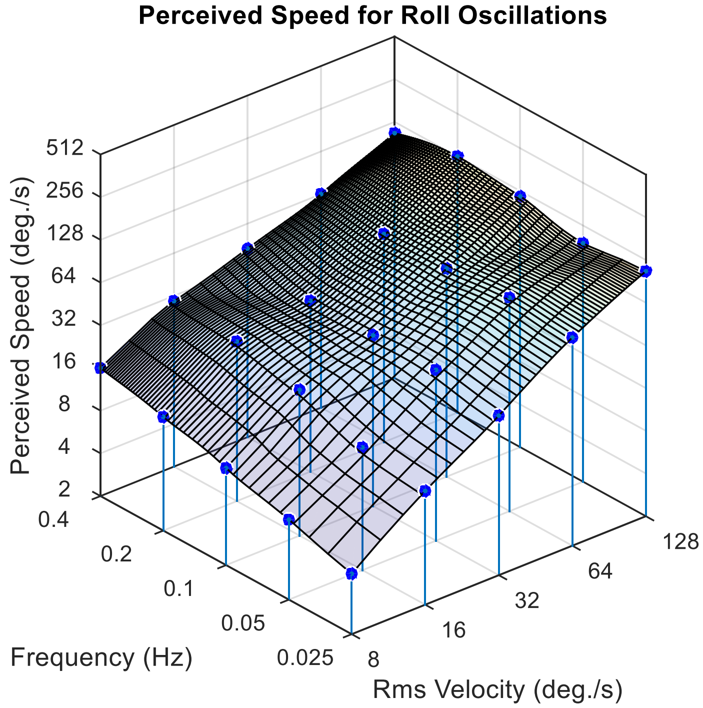

Figure 5.3.1 Medians of perceived speed for conditions with different levels of rms velocity and frequency

5.3.1.4 Perceived speed under constant rms velocity

Under constant rms velocity, Figure 5.4 shows the medians of the perceived speed for five levels of rms velocities: (a). 8 deg./s, (b). 16 deg./s, (c). 32 deg./s, (d). 64 deg./s, and (e). 128 deg./s. The lower abscissa represents frequency, and the upper one represents amplitude. Error bars for each condition represent the first and third quartiles of the participants' ratings. The horizontal double sided arrows indicate significant differences in two conditions ($p<0.05$, Wilcoxon).

These pairs of significantly different conditions show that perceived speed increased as frequency increased (or amplitude decreased). Especially when rms velocity was kept at 8 and 16 deg./s, the trend was apparent. It was also observed that, when rms velocity was fixed at 8 and 16 deg./s, perceived speed was underestimated if frequency was below around 0.05 Hz and overestimated if frequency was above around 0.05 Hz. Somehow, when rms velocity was fixed at 32, 64, and 128 deg./s, frequency response for perceived speed was flat.

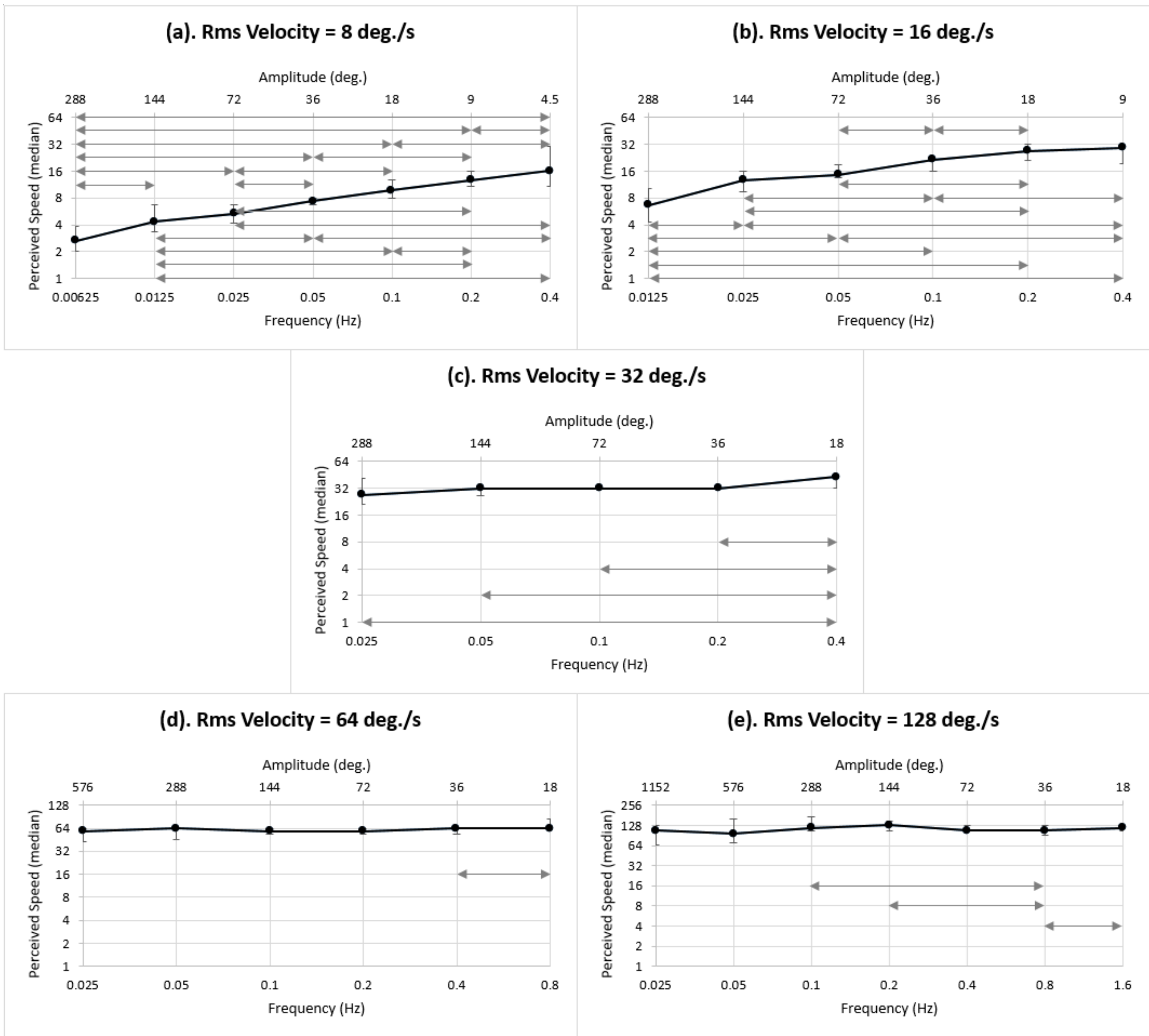

Figure 5.4 Medians of perceived speed under constant rms velocity for five levels of rms velocities: (a). 8 deg./s; (b). 16 deg./s; (c). 32 deg./s; (d). 64 deg./s; (e). 128 deg./s.

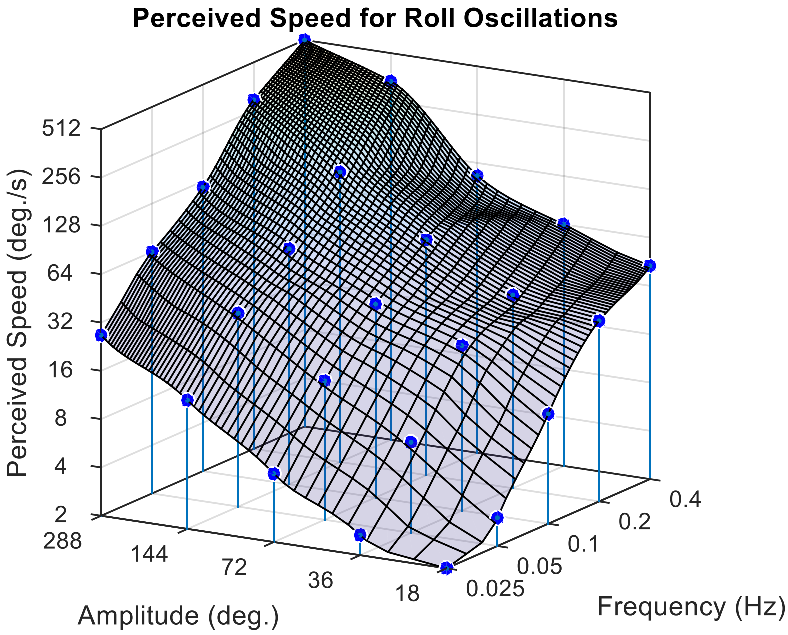

Figure 5.4.1 Medians of perceived speed for conditions with different levels of frequency and amplitude

5.3.1.5 Discussion

Chen (2014) found that there were two frequency responses for perceived speed when visual oscillations were along the fore-and-aft axis. In his study, he described the two patterns:

> *"One type of patterns is that when keeping the r.m.s. velocities of the stimuli constant, the frequency response curves are generally flat between 0.05 Hz to 1.6 Hz but they gradually take on an increase trend with increasing frequency for r.m.s. velocities at 22 m/s or below. For the other pattern, perceived speeds increase significantly with increasing frequency when the amplitudes of the oscillating stimuli are kept constant."*

In this dissertation, similar two-frequency-response was obtained when oscillations were along the roll axis: 1. When rms velocity was fixed, perceived speed increased as frequency increased if rms velocity was fixed at 8 and 16 deg./s; and perceived speed presented a flat frequency response if rms velocity was fixed at 32, 64, and 128 deg./s. 2. When amplitude was fixed, perceived speed increased as frequency increased.

5.3.2 Vection magnitude

5.3.2.1 Learning effects

Table 5.3 shows the descriptive statistics for vection magnitude in the four repetitions. It can be seen from the table that the average of vection magnitudes decreased as repetitions went on. Therefore, learning effects were tested first.

Table 5.3 Descriptive statistics for vection magnitudes in 4 repetitions

	Mean	**Std. deviation**	**Minimum**	**25^{th} percentile**	**Median**	**75^{th} percentile**	**Maximum**
Repetition 1	2.738	1.821	0	1	3	4	6
Repetition 2	2.608	1.826	0	1	3	4	6
Repetition 3	2.593	1.734	0	1	3	4	6
Repetition 4	2.521	1.750	0	1	3	4	6

The perceived vection magnitudes were not normally distributed ($p<0.001$, Shapiro-Wilk). Thus, non-parametric tests were adopted here. Results showed that repetitions had a significant influence on vection for 4 repetitions ($p=0.000$, Friedman). When the data from Repetition 1 were excluded, the effects of repetition still existed ($p=0.010$, Friedman). When the data from Repetition 1 and 2 were excluded, learning effects was still exit ($p=0.021$, Friedman). However, for Repetition 2 and 3, the effects of repetition was not significant ($p=0.181$, Friedman). A previous study in our lab found that, as repetitions went on, subjects were trained to be insensitive to feel vection. The drop of vection magnitude in Repetition 4 was supposed to be caused by the training effect. Subjects' performance in Repetition 2 and 3 was considered to be stabled. And the subsequent analysis is based on the average ratings of repetition 2 and 3 of each participant for each condition.

5.3.2.2 Vection magnitude under constant frequency

Conditions of the same frequency were grouped together to see how vection is affected by amplitude and rms velocity. Figure 5.5 plots the medians of the vection magnitude for five levels of frequencies: (a). 0.025 Hz, (b). 0.05 Hz, (c). 0.1 Hz, (d). 0.2 Hz, and (e). 0.4 Hz. There are two abscissas in the figure. The lower one represents rms velocity, and the upper one represents amplitude. When rms velocity doubles, amplitude doubles to maintain the same frequency. Error bars for each condition represent the first and third quartiles of the participants' ratings. The horizontal double sided arrows indicate significant differences in two conditions ($p<0.05$, Wilcoxon). These pairs of significantly different conditions show that when frequency is kept constant at 0.025 Hz, vection magnitude increases first and then decreases as rms velocity (or amplitude) increases. And when frequency is kept at 0.05 Hz, 0.1 Hz, 0.2 Hz, and 0.4 Hz, the vection magnitude decreases significantly as rms velocity (or amplitude) becomes larger.

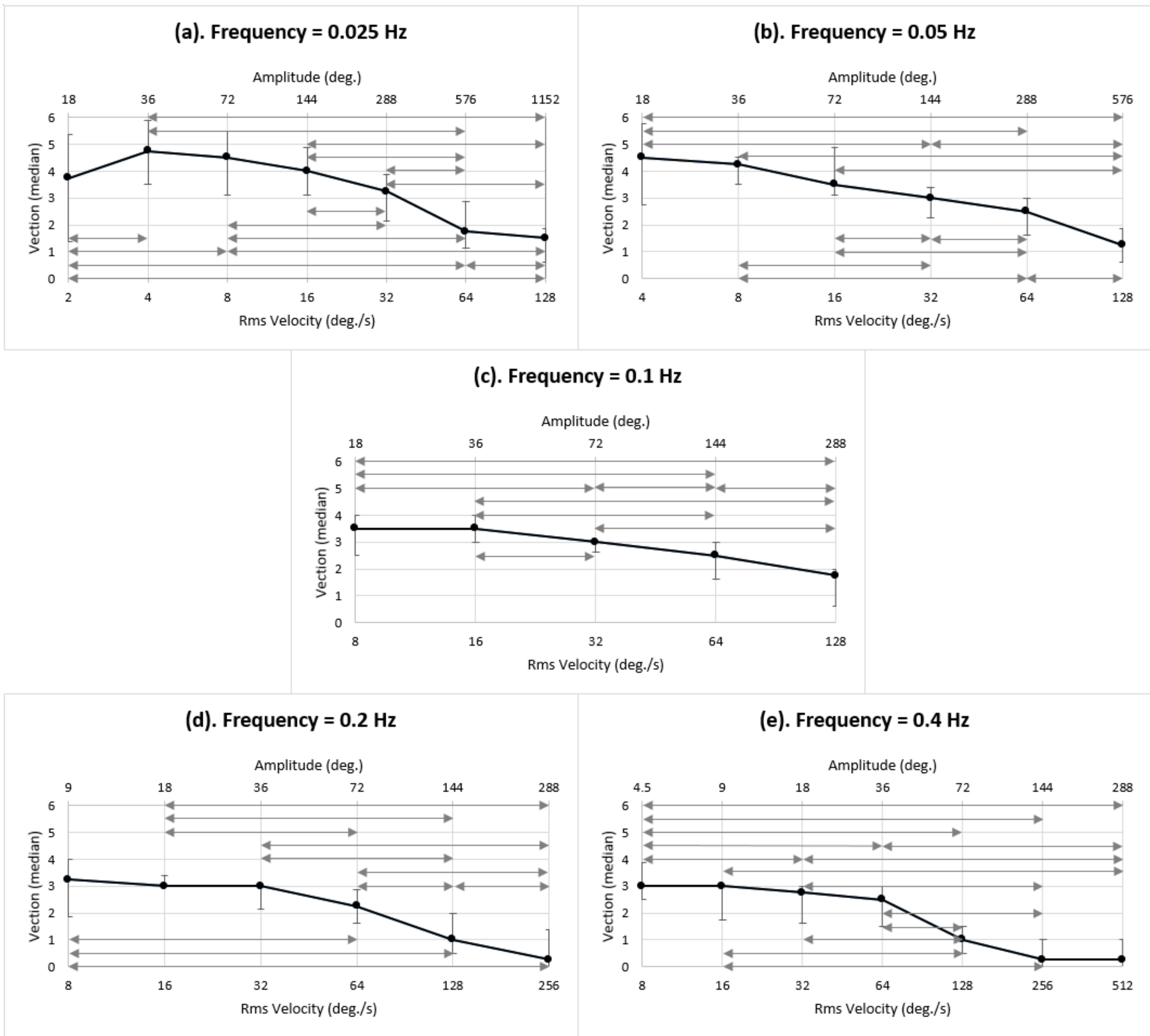

Figure 5.5 Medians of vection magnitude under constant frequency for five levels of frequencies: (a). 0.025 Hz; (b). 0.05 Hz; (c). 0.1 Hz; (d). 0.2 Hz; (e). 0.4 Hz.

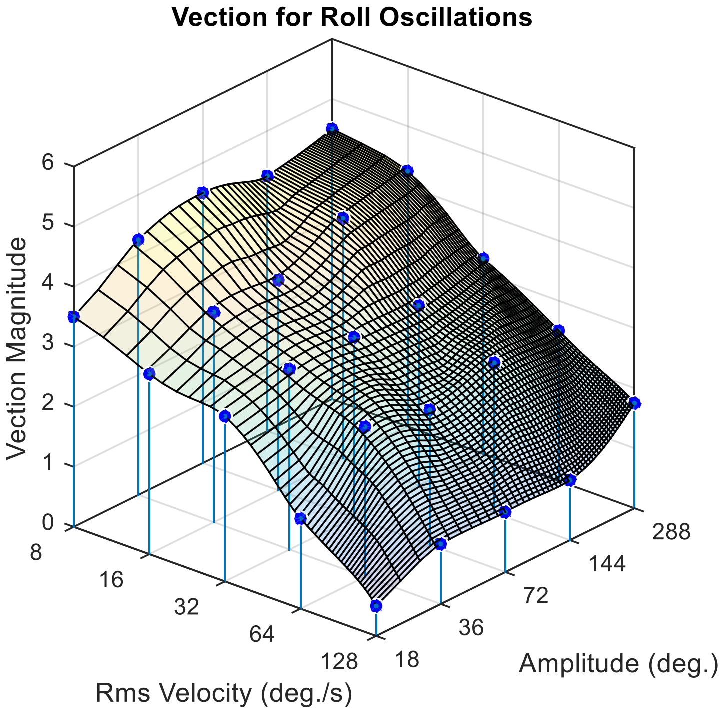

Figure 5.5.1 Medians of vection magnitude for conditions with different levels of rms velocity and amplitude

Friedman two-way analyses of variance show there are significant differences in vection magnitude ratings when the frequency is kept at 0.025 Hz (p=0.000), 0.05 Hz (p=0.000), 0.1 Hz (p=0.000), 0.2 Hz (p=0.000), and 0.4 Hz (p=0.000). It indicates significant effects of rms velocity (or amplitude) on vection magnitude.

5.3.2.3 Vection magnitude under constant amplitude

Under constant amplitude, Figure 5.6 shows the medians of the vection magnitude ratings for five levels of amplitudes: (a). 18 degrees, (b). 36 degrees (c). 72 degrees, (d). 144 degrees, and (e). 288 degrees. The lower abscissa represents frequency, and the upper one represents rms velocity. Error bars for each condition represent the first and third quartiles of the participants' ratings. The horizontal double sided arrows indicate significant differences in two conditions (p<0.05, Wilcoxon). Significantly different pairs show that, as frequency (or rms velocity) increases, vection magnitude drops significantly when amplitude is retained at 36, 72, 144, and 288 degrees. While amplitude is kept at 18 degrees, vection magnitude increases first then decreases with increasing frequency (or rms velocity).

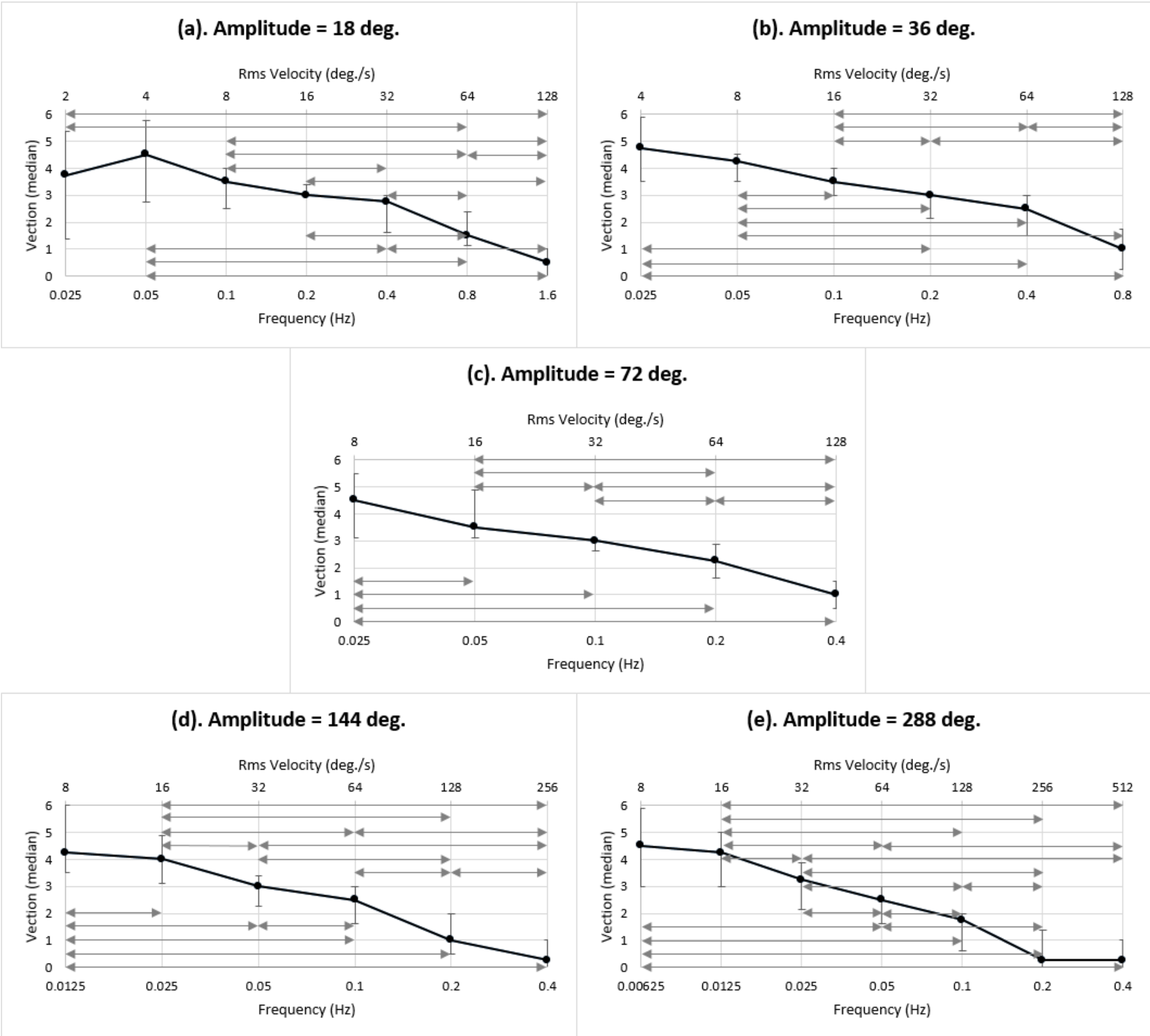

Figure 5.6 Medians of vection magnitude ratings under constant amplitude for five levels of amplitudes: (a). 18 degrees; (b). 36 degrees; (c). 72 degrees; (d). 144 degrees; (e). 288 degrees.

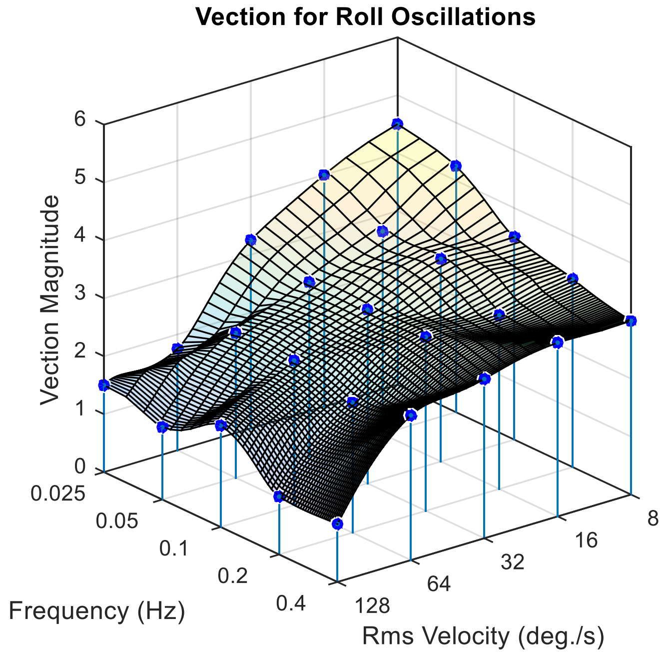

Figure 5.6.1 Medians of vection magnitude for conditions with different levels of rms velocity and frequency

Friedman tests find that vection ratings for conditions of the same amplitude are significantly different if the amplitude stays at 18 degrees (p=0.000), 36 degrees (p=0.000), 72 degrees (p=0.000), 144 degrees (p=0.000), and 288 degrees (p=0.000), which means that frequency (or rms velocity) has significant main effects on vection magnitude.

5.3.2.4 Vection magnitude under constant rms velocity

Under constant rms velocity, Figure 5.7 shows the medians of the vection magnitude ratings for five levels of rms velocities: (a). 8 deg./s, (b). 16 deg./s, (c). 32 deg./s, (d). 64 deg./s, and (e). 128 deg./s. The lower abscissa represents frequency, and the upper one represents amplitude. Error bars for each condition represent the first and third quartiles of the participants' ratings. The horizontal double sided arrows indicate significant differences in two conditions ($p<0.05$, Wilcoxon). Significantly different pairs of conditions show that the median of vection decreases as the frequency increases (or the amplitude decreases).

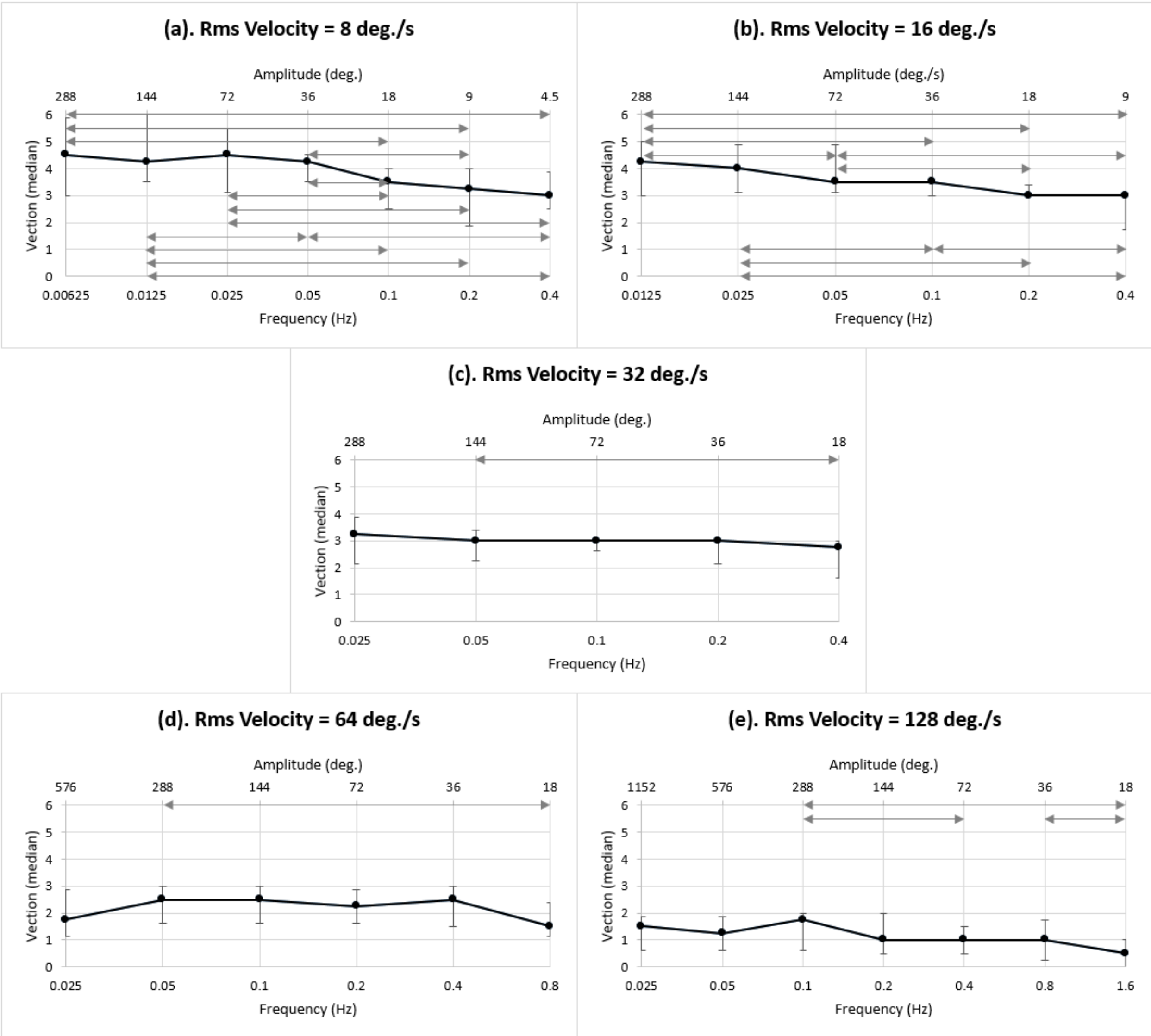

Figure 5.7 Medians of vection magnitude ratings under constant rms velocity for five levels of rms velocities: (a). 8 deg./s; (b). 16 deg./s; (c). 32 deg./s; (d). 64 deg./s; (e). 128 deg./s.

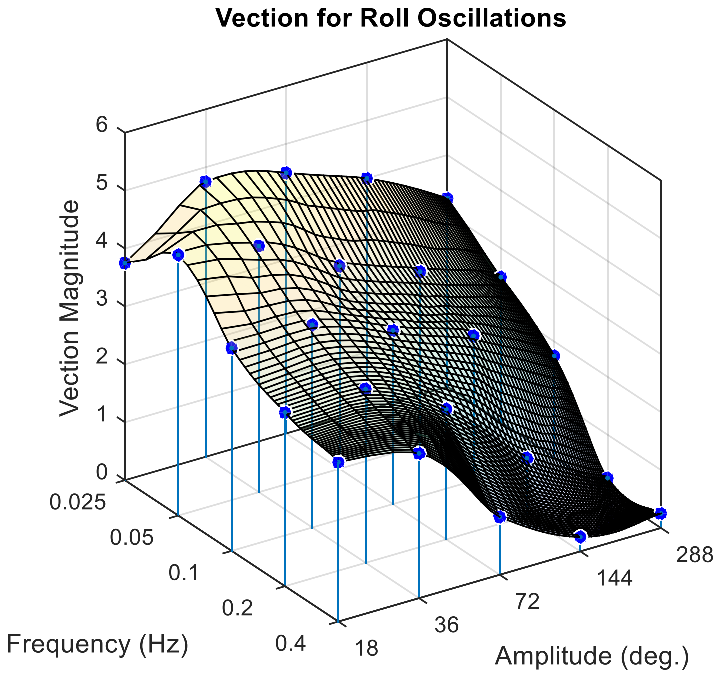

Figure 5.7.1 Medians of vection magnitude for conditions with different levels of frequency and amplitude

Conditions of the same rms velocity generate significant different vection magnitude when grouped by constant rms velocity 8 deg./s (p=0.000), 16 deg./s (p=0.000), and 128 deg./s (p=0.043).

5.3.2.5 Discussions

Comparing our results to previous relevant findings, frequency responses of roll vection were different. Babler and Ebenholtz (1989) found that roll vection peaked at 0.213 Hz, and Previc et al. (1993) found that roll vection peaked at 0.25 Hz. In their studies, they varied rms velocity and fixed amplitude to manipulate frequency (amplitude in Babler and Ebenholtz's study: +-15 degrees; amplitude in Previc et al.'s study: +-20 degrees). However, in our study, vection magnitude peaked at 0.05 Hz when frequency was manipulated by constant amplitude (+-18 degrees). There was a shift of the peak frequency comparing to their studies. Among these three studies, there were different control variables and experiment tasks. In Babler and Ebenholtz (1989)'s study, besides reporting vection, subjects were required to make prompt and continuous steering adjustments throughout the entire experiment session, which required attentional resources. Seno et al. (2011) observed that vection induction required attentional resources. In our study, subjects only needed to report vection and perceived speed. Differences in distribution of attentional resources may lead to the shift of peak frequency for vection. In addition, Babler and Ebenholtz used a real world stimulus rotating physically, while we projected the rotational movements onto a screen to elicit vection. Bodenheimer et al. (2016) reported that circular vection occurred more rapidly with a real world stimulus than a virtual one. In Previc et al. (1993)'s study, subject was instructed to maintain an erect stance, while in our study subjects maintained a sitting position, which may lead to different frequency responses of vection.

Similar results were obtained comparing with Chow (2008)'s study, in which frequency was manipulated by fixed rms velocity (49.5 deg./s). Chow observed that vection magnitude decreased as frequency increased from 0.05 Hz to 0.8 Hz. Our study found that vection magnitude was significantly smaller when frequency was 0.05 Hz than 0.8 Hz if rms velocity was fixed at 32 and 64 deg./s.

Revisiting Chen (2014)'s proposition of two-frequency-response hypothesis, it was found that, for roll vection, the hypothesis was not supported. Frequency responses for the two frequency manipulations are similar. When frequency was manipulated by varying rms velocity and fixing amplitude, vection magnitude decreased as frequency increased. Similarly, when frequency was manipulated by varying amplitude and fixing rms velocity, vection magnitude dropped with increasing frequency.

It was also found that frequency responses were different if motion axis was changed. When amplitude remained constant and frequency was manipulated by varying rms velocity, Chen (2014) showed that vection magnitude increased as frequency increased in the fore-and-aft axis. While in our study vection magnitude decreased with increasing frequency when motions were along the roll axis. When rms velocity was kept constant, i.e., manipulating frequency by changing amplitude, frequency responses were similar in two directions. It indicates that the interaction effect of the three factors varies due to different oscillation directions.

In this study, we found that visual oscillations of the same frequency produced different levels of vection. When frequency was kept at 0.025 Hz, vection magnitude presented an inverted U shape with increasing frequency; and when frequency was kept at 0.05, 0.1, 0.2, and 0.4 Hz, vection magnitude decreased as frequency increased. It suggests that frequency alone should not be regarded as a sufficient predictor for perceived vection magnitude. This pattern can be interpreted by the effects of rms velocities and amplitudes on vection. Firstly, as rms velocity increased, vection ratings decreased (see Figure 5.6). It implied that the larger the rms velocity, the weaker the vection. Secondly, significant pairs of conditions in Figure 5.7 indicated that vection increased significantly as the amplitude increased if rms velocity was kept unchanged. Therefore, in Figure 5.5, the vection ratings drop because the gain of vection from larger amplitude cannot make up the loss from faster velocity.

5.3.3 Correlation of vection magnitude and perceived speed accuracy

Perceived speed accuracy and perception bias have been defined in Chapter 4.

Descriptive statistics of perception bias grouped by the same level of vection magnitude are summarized in Table 5.4. From the table, it is found that perception bias decreases from a 0 to a negative value gradually as vection magnitude ranges from 0 to 6. And the correlation between the perception bias and vection ratings is significantly negative (Spearman, rho=-0.193, p=0.000). Therefore, larger vection magnitude is associated with a smaller perception bias. It indicates that the presence of vection produces lower perceived speed.

Table 5.4 Descriptive statistics of perception bias grouped by the same vection magnitude

Vection magnitude	Perception Bias							
	Number of observations	**Mean**	**Std. Deviation**	**Min**	**25 percentiles**	**Median**	**75 percentiles**	**Max**
0	319	0	0.79	-2	0	0	0	6
1	336	-.0208	0.87	-2	0	0	0	5
2	263	-.1103	0.77	-4	0	0	0	4
3	560	-.0375	0.85	-2	0	0	0	4
4	256	-.1992	1.02	-3	-1	0	0	3
5	176	-.5852	1.03	-4	-1	-1	0	2
6	162	-.8086	0.95	-4	-1	-1	0	1

CHAPTER 6 : DISSCUSION AND CONCLUSIONS

6.1 Effects of oscillation directions on vection

Effects of visual oscillation directions on vection are discussed in the following.

6.1.1 Effects of oscillation directions on vection magnitude

In this dissertation, vection along the yaw axis and roll axis was studied. As mentioned in Chapter 2, roll vection is associated with more sensory mismatch, and expected to be weaker than yaw vection. However, it is observed that roll visual oscillations will, in general, provoke stronger vection sensation.

The rotational movements around the yaw axis can indicate the change of viewing directions. Yaw visual oscillations naturally occurred in life when human beings turn their head around or shake their head. When human beings turn their head around or shake their head, they have a sensation of their head movement but do not have a sensation of their body movement. This adaptation may result that yaw visual oscillations are inhibited to generate sensation of body rotations. Thus, yaw vection is harder to be generated than roll vection.

6.1.2 Effects of oscillation directions on frequency responses of vection

In addition of Chen (2014)'s study, in which vection was along the fore-and-aft axis, vection of three different directions was compared in this section. In Experiment 1 for yaw vection, when frequency is fixed, vection magnitude presents an inverted U-shape pattern with increasing rms velocity (or amplitude) (see Figure 6.1). In Experiment 2 for roll vection, when frequency is fixed at 0.05, 0.1, 0.2, and 0.4 Hz, vection magnitude decreases as rms velocity (or amplitude) increases; and when frequency is fixed at 0.025 Hz, vection magnitude increases first and then decreases (see Figure 6.2). For roll vection, extending the rms velocity range, vection magnitude tends to drop with decreasing rms velocity, from evidence that vection is smaller with rms velocity of 2 deg./s than 4 deg./s when frequency is kept at 0.025 Hz. Thus, it is inferred that roll vection also presents an inverted U-shape pattern with increasing rms velocity under constant frequency. In both figures, the scale range of rms velocity (2 to 512 deg./s) and frequency (0.025 to 0.4 Hz) are the same. Results indicate, for different rotational vection, there is a horizontal shift of vection magnitude trend in response to increasing rms velocity (or magnitude) under constant frequency.

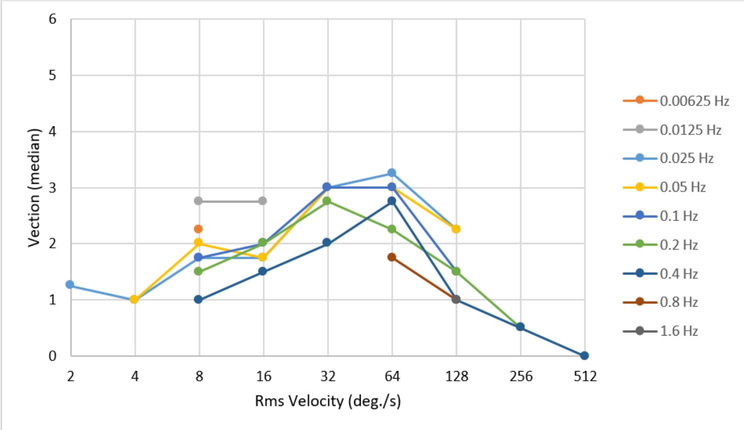

Figure 6.1 Vection magnitude under constant frequency for yaw vection

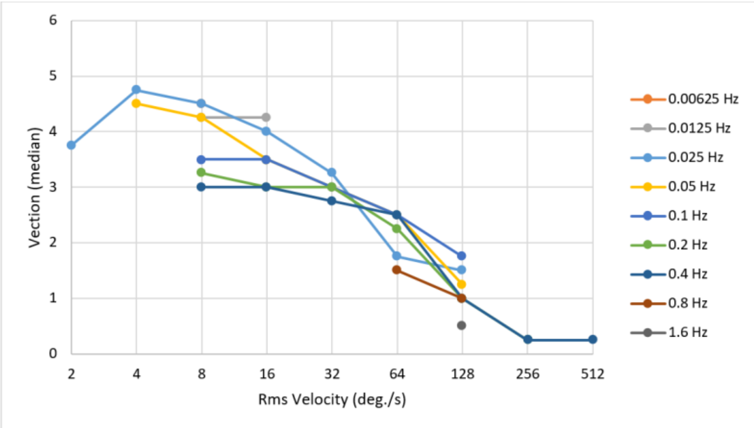

Figure 6.2 Vection magnitude under constant frequency for roll vection

For yaw, roll, and fore-and-aft directions, vection magnitude decreases as frequency increases (or amplitude decreases) under constant rms velocity (see Figure 6.3, 6.4, and 6.5). Results of Wilcoxon signed rank test statistically support this decreasing trend pattern. Within the ranges of the frequency, rms velocity, and amplitude studied in this dissertation and Chen (2014)'s study, it is found that different oscillation directions do not result in different frequency response for vection under constant rms velocity.

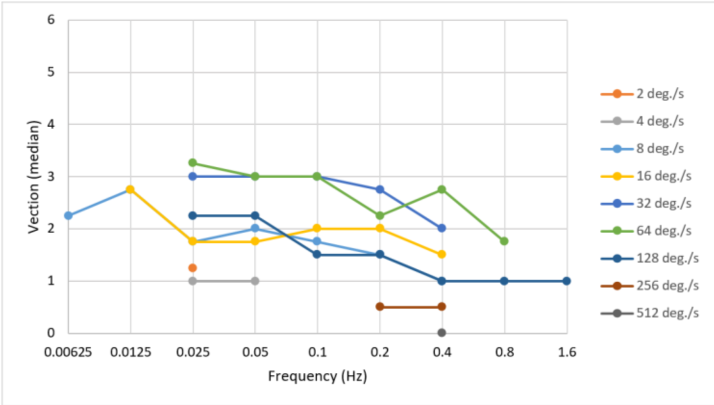

Figure 6.3 Vection magnitude under constant rms velocity for yaw vection

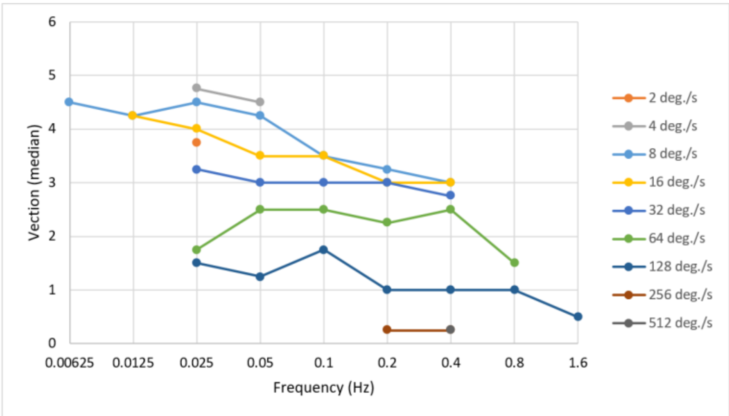

Figure 6.4 Vection magnitude under constant rms velocity for roll vection

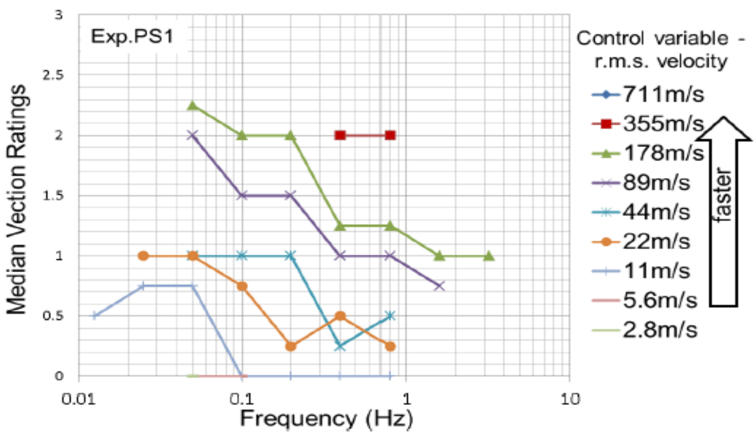

Figure 6.5 Vection magnitude under constant rms velocity for fore-and-aft vection (Chen, 2014)

Frequency responses under constant amplitude are different for vection along the yaw axis, roll axis, and fore-and-aft axis. For yaw vection, frequency response for vection presents an inverted U-shape pattern with increasing frequency (see Figure 6.6). For roll vection, vection magnitude decreases as frequency increases under constant amplitude (see Figure 6.7). For vection along the fore-and-aft axis, vection magnitude increases as frequency increases (see Figure 6.8). In summary, different oscillation directions result in different frequency response for vection under constant amplitude. It indicates there may be different motion perception mechanisms for visual system along different directions.

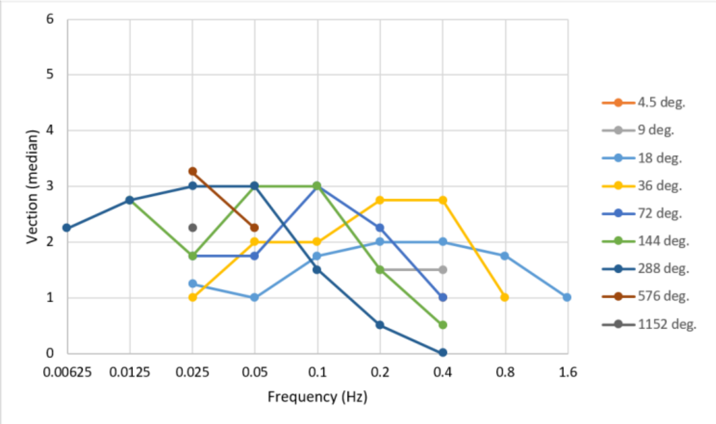

Figure 6.6 Vection magnitude under constant amplitude for yaw vection

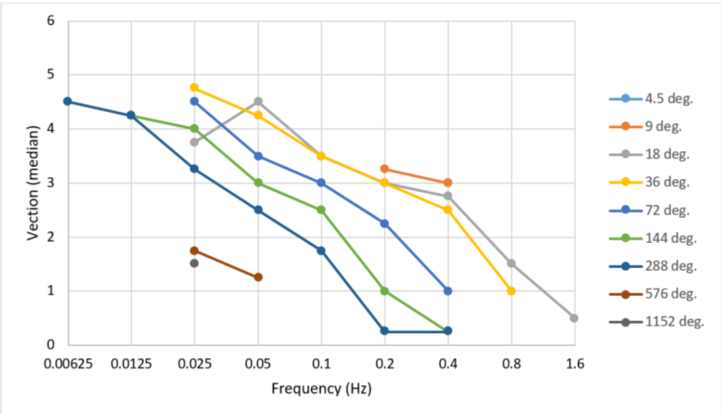

Figure 6.7 Vection magnitude under constant amplitude for roll vection

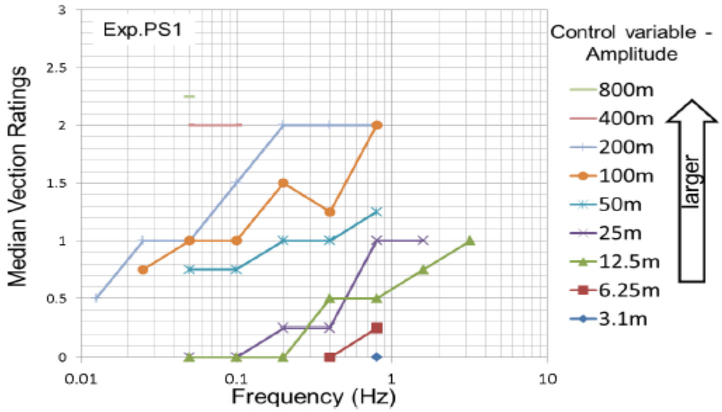

Figure 6.8 Vection magnitude under constant amplitude for fore-and-aft vection (Chen,2014)

6.2 Effects of rms velocity on vection induced by visual oscillations

From Figure 4.5 to Figure 4.7, and Figure 5.5 to Figure 5.7, it is observed that plots for fixed rms velocity (Figure 4.7 and Figure 5.7) are relatively flatter than plots for fixed frequency or fixed amplitude. It indicates that rms velocity of the visual oscillations has a relatively stronger influence on vection than frequency and amplitude. In a view of neurophysiology, studies found that neurons in the cortical areas V1 and Middle Temporal (MT) were velocity tuned during the perception of visual motions (Burr and Thompson, 2011). Therefore, perception pathways of visual motions are dominated by some velocity-tuned neural circuits, which may lead to stronger influence of rms velocity on vection.

6.3 Conclusions, implications and limitations

In summary, this thesis concludes:

- Frequency response for yaw vection supported the two-frequency-response hypothesis. Results showed that under constant rms velocity, yaw vection decreased as frequency increased; and under constant amplitude, yaw vection presented an inverted U-shape with increasing frequency.
- As for roll vection, vection dropped as frequency increased no matter whether rms velocity or amplitude was fixed. In other word, the two-frequency-response hypothesis was not supported. This indicated that the two-frequency-response hypothesis is axis dependent.
- It was also found that visual oscillations of the same frequency but different amplitudes and velocities generated different vection magnitudes for both yaw and roll vection. Findings suggested that frequency alone should not be regarded as a sufficient predictor for perceived vection magnitude.
- Analyses of the effects of amplitude indicated that the larger the amplitude, the stronger the vection for yaw and roll vection.
- As for the effects of velocity, yaw vection presented an inverted U-shape with increasing velocity; while roll vection decreased as velocity increased.
- Comparing vection along the three different directions, three different frequency responses under constant amplitude were found. It indicated there may be different motion perception mechanisms for visual system along different directions.

This study implies that frequency alone should not be regarded as a sufficient predictor for perceived vection magnitude, since frequency, amplitude, and rms velocity affect vection interactively. And the significant effects of oscillation directions on vection implies that there may be different motion perception mechanisms for visual system along different directions.

Although important findings were obtained in this study, there are limitations worth mentioned:

- Only abstract visual stimuli were adopted. Normally, vection is utilized to simulate self-motion in real settings. Studied found that natural visual-field features enhanced vection (Bubka and Bonato, 2010). The findings in this study are not sufficient to be directly applied to design oscillation parameters in real settings.
- Only yaw and roll vection were investigated. Two frequency responses for vection along the lateral axis, vertical axis and pitch axis have not been studied yet.
- Only young participants (age between 18 to 35) were included in the current study. Since it has been suggested that VIMS severity can be affected by the ages of individuals, the current results may not generalize to other populations, such as older people or children.

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APPENDIX 3.1: MOTION SICKNESS SUSCEPTIBILITY QUESTIONNAIRE SHORT-FORM (MSSQ-SHORT) AND THE SCORING METHOD

Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-Short)

1. Please State Your **Age** .... Years. *2.* Please State Your Sex (tick box) **Male** [ ] 1 **Female** [ ] 2

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

3. **As a CHILD (before age 12),** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

4. **Over the LAST 10 YEARS,** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	**Never Felt Sick**	**Rarely Felt Sick**	**Sometimes Felt Sick**	**Frequently Felt Sick**
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Scoring the MSSQ- Short

Section A (Child) (Question 3)

Score the number of types of transportation not experienced (i.e., total the number of ticks in the 't' column, maximum is 9).

Total the sickness scores for each mode of transportation, i.e. the nine types from 'cars' to 'big dippers' (use the 0-3 number score key at bottom, those scores in the 't' column count as zeroes).

MSA = (total sickness score child) x (9) / (9 - number of types not experienced as a child)

Note 1. Where a subject has not experienced any forms of transport a division by zero error occurs. It is not possible to estimate this subject's motion sickness susceptibility in the absence of any relevant motion exposure.
Note 2. The Section A (Child) score can be used as a pre-morbid indicator of motion sickness susceptibility in patients with vestibular disease.

Section B (Adult) (Question 4)

Repeat as for section A but using the data from section B.

MSB = (total sickness score adult) x (9) / (9 - number of types not experienced as an adult)

Raw Score MSSQ-Short

Total the section A (Child) MSA score and the section B (Adult) MSB score to give the MSSQ-Short raw score (possible range from minimum 0 to maximum 54, the maximum being unlikely)

MSSQ raw score = MSA + MSB

Percentile Score MSSQ-Short

The raw to percentile conversions are given below in the Table of Statistics & Figure, use interpolation where necessary.

Alternatively a close approximation is given by the fitted polynomial where y is percentile; x is raw score
$y = a.x + b.x^2 + c.x^3 + d.x^4$
a = 5.1160923 b = -0.055169904
c = -0.00067784495 d = 1.0714752e-005

Table of Means and Percentile Conversion Statistics for the MSSQ-Short (n=257)

Percentiles Conversion	Raw Scores MSSQ-Short		
	Child Section A	Adult Section B	Total A+B
0	0	0	0
10	.0	.0	.8
20	2.0	1.0	3.0
30	4.0	1.3	7.0
40	5.6	2.6	9.0
50	7.0	3.7	11.3
60	9.0	6.0	14.1
70	11.0	7.0	17.9
80	13.0	9.0	21.6
90	16.0	12.0	25.9
95	20.0	15.0	30.4
100	23.6	21.0	44.6
Mean	7.75	5.11	12.90
Std. Deviation	5.94	4.84	9.90

Table note: numbers are rounded

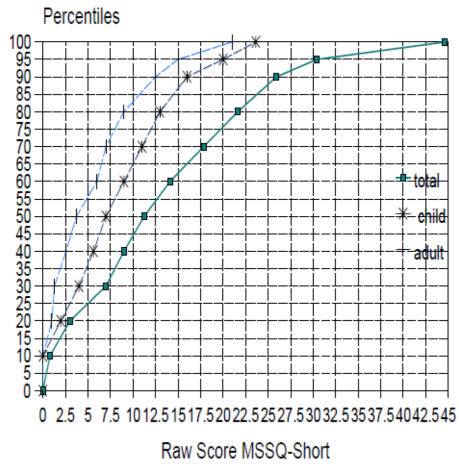


Figure: Cumulative distribution Percentiles of the Raw Scores of the MSSQ-Short (n=257 subjects).

Reference Note

For more background information and references to the original Reason & Brand MSSQ and to its revised version the 'MSSQ-Long', see:
Golding JF. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. **Brain Research Bulletin**, 1998; 47: 507-516.
Golding JF. (2006) Predicting Individual Differences in Motion Sickness Susceptibility by Questionnaire. **Personality and Individual differences, 41:** 237-248.

APPENDIX 3.2: PRE-EXPOSURE AND POST-EXPOSURE SIMULATOR SICKNESS QUESTIONNAIRES (SSQ)

Pre-exposure Simulator Sickness Questionnaire

SYMPTOM CHECKLIST (Pre-exposure)

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

一般不適	1. General discomfort	None	Slight		Moderate	Severe	
疲 倦	2. Fatigue	None	Slight		Moderate	Severe	
沉 悶	3. Boredom	None	Slight		Moderate	Severe	
想 睡	4. Drowsiness	None	Slight		Moderate	Severe	
頭 痛	5. Headache	None	Slight		Moderate	Severe	
眼 痛	6. Eyestrain	None	Slight		Moderate	Severe	
很難集中視力	7. Difficulty focusing	None	Slight		Moderate	Severe	
口水分秘增加	8. Salivation increase	None	Slight		Moderate	Severe	
口水分秘減少	Salivation decrease	None	Slight		Moderate	Severe	
出 汗	9. Sweating	None	Slight		Moderate	Severe	
作 嘔	10. Nausea	None	Slight		Moderate	Severe	
很難集中精神	11. Difficulty concentrating	None	Slight		Moderate	Severe	
精神的壓抑	12. Mental depression		No	Yes (	Slight	Moderate	Severe)
頭 脹	13. "Fullness of the head"		No	Yes (	Slight	Moderate	Severe)
視野模糊	14. Blurred vision		No	Yes (	Slight	Moderate	Severe)
眼 花 (開)	15. Dizziness eyes open		No	Yes (	Slight	Moderate	Severe)
眼 花 (合)	Dizziness eyes close		No	Yes (	Slight	Moderate	Severe)
眩 暈	16. Vertigo		No	Yes (	Slight	Moderate	Severe)
幻 覺	17. Visual flashbacks*		No	Yes (	Slight	Moderate	Severe)
昏 厥	18. Faintness		No	Yes (	Slight	Moderate	Severe)
呼 吸 異 樣	19. Aware of breathing		No	Yes (	Slight	Moderate	Severe)
胃感覺異樣	20. Stomach awareness		No	Yes (	Slight	Moderate	Severe)
沒 有 胃 口	21. Loss of appetite		No	Yes (	Slight	Moderate	Severe)
胃 口 增 加	22. Increased appetite		No	Yes (	Slight	Moderate	Severe)
想去洗手間	23. Desire to move bowels		No	Yes (	Slight	Moderate	Severe)
迷 惘	24. Confusion		No	Yes (	Slight	Moderate	Severe)
打 嗝	25. Burping		No	Yes (	Slight	Moderate	Severe)
嘔 吐	26. Vomiting		No	Yes (	Slight	Moderate	Severe)
其 他	27. Other		No	Yes (	Slight	Moderate	Severe)

Post-exposure Simulator Sickness Questionnaire

SYMPTOM CHECKLIST (Post-exposure)

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

一般不適	1.	General discomfort	None	Slight		Moderate	Severe
疲 倦	2.	Fatigue	None	Slight		Moderate	Severe
沉 悶	3.	Boredom	None	Slight		Moderate	Severe
想 睡	4.	Drowsiness	None	Slight		Moderate	Severe
頭 痛	5.	Headache	None	Slight		Moderate	Severe
眼 痛	6.	Eyestrain	None	Slight		Moderate	Severe
很難集中視力	7.	Difficulty focusing	None	Slight		Moderate	Severe
口水分秘增加	8.	Salivation increase	None	Slight		Moderate	Severe
口水分秘減少		Salivation decrease	None	Slight		Moderate	Severe
出 汗	9.	Sweating	None	Slight		Moderate	Severe
作 嘔	10.	Nausea	None	Slight		Moderate	Severe
很難集中精神	11.	Difficulty concentrating	None	Slight		Moderate	Severe
精神的壓抑	12.	Mental depression		No	Yes (Slight	Moderate	Severe)
頭 脹	13.	"Fullness of the head"		No	Yes (Slight	Moderate	Severe)
視野模糊	14.	Blurred vision		No	Yes (Slight	Moderate	Severe)
眼 花 (開)	15.	Dizziness eyes open		No	Yes (Slight	Moderate	Severe)
眼 花 (合)		Dizziness eyes close		No	Yes (Slight	Moderate	Severe)
眩 暈	16.	Vertigo		No	Yes (Slight	Moderate	Severe)
幻 覺	17.	Visual flashbacks*		No	Yes (Slight	Moderate	Severe)
昏 厥	18.	Faintness		No	Yes (Slight	Moderate	Severe)
呼 吸 異 樣	19.	Aware of breathing		No	Yes (Slight	Moderate	Severe)
胃感覺異樣	20.	Stomach awareness		No	Yes (Slight	Moderate	Severe)
沒 有 胃 口	21.	Loss of appetite		No	Yes (Slight	Moderate	Severe)
胃 口 增 加	22.	Increased appetite		No	Yes (Slight	Moderate	Severe)
想去洗手間	23.	Desire to move bowels		No	Yes (Slight	Moderate	Severe)
迷 惘	24.	Confusion		No	Yes (Slight	Moderate	Severe)
打 嗝	25.	Burping		No	Yes (Slight	Moderate	Severe)
嘔 吐	26.	Vomiting		No	Yes (Slight	Moderate	Severe)
其 他	27.	Other		No	Yes (Slight	Moderate	Severe)

APPENDIX 4.1: INSTRUCTIONS FOR EXPERIMENT 1

Training Instructions

Dear participant,
Thank you for participation in this experiment.
Now we will spend 5-10min to help you get familiar with the task and formal experiment procedures.

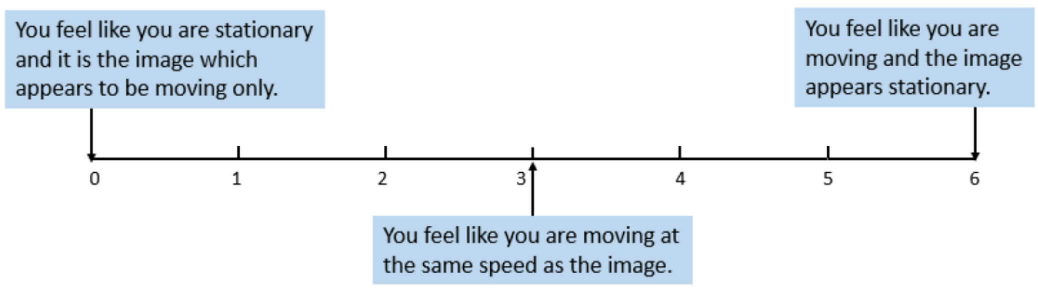
There are 2 concepts you need to learn: **vection** and **perceived speed**.

Vection:

Vection is an illusion of self-motion.

Sometimes, what we see can cheat on us. For example, when we sit on train, look out of the window and find another train next to us moving, we may feel that our train is moving forward even though we do not move at all. And this is an illusion of self-motion.
有时候我们看到的东西会让我们产生错觉，比如当我们坐在静止的火车上，有时旁边的另外一辆火车开出车站时，虽然所搭乘的列车并没有动，但我们有时会产生我们在缓慢地往相反方向运动的错觉。而这就是一种自我运动的错觉。
In the experiment, when you stare strips patterns moving for a while, you may feel the moving of strips gradually slow down and this is a sign that you are starting to generate an illusion of self-motion.
实验中，当您观看条纹运动时，您有时会觉得条纹的运动速度在渐渐变慢，这就是您开始产生自我运动的错觉的标志之一。
Then, you may gradually start to feel your body is rotating toward the opposite direction which the strips are moving.
随后，您可能会渐渐感觉到自己的身体开始向条纹运动的相反方向旋转。
However, different individuals may have slight different feelings, and take different time to initiate the illusion of self-motion feelings. So take your time and there is no need to worry if you do not see the illusive self-motion in the beginning.
不过，每个人的感觉都会各有不同，而不同人需要产生这种感觉的时间长短也不同；这跟人的视觉特点有关并没有好坏之分，所以请放轻松，如果一开始您没有任何感觉，也完全不必担心。

Throughout this experiment, you will be reporting this feeling of illusive self-motion (i.e. **vection**). Please ensure that you understand this feeling. The vection will be measured using the following scale:

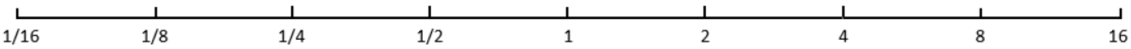


Perceived Speed:

Another figure you need to report is **perceived speed**. The definition of perceived speed is "**how fast you are feeling the patterns are travelling relative to you**". It's important to know that perceived speed is **not** "the number of cycles of oscillations completed by the moving patterns per unit time".

In each condition of the experiment, you will be first present with a **reference oscillation** for 20 seconds, then a **signal oscillation**. You are required to compare the **average perceived speed** between the reference and the signal.

The average speed of the reference is assigned as 1, and **you need to report the ratio** of the average perceived speed of the signal relative to the reference. 9 choices of ratios are provided:

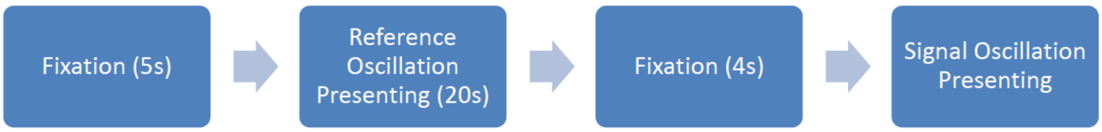


You are required to choose one out of the nine ratios closest to your perception.

Experiment procedure

In this experiment, there are 4 groups of conditions. Each group contains about 10 conditions. Between groups, you have 5 to 10 minutes to rest. The first 4 conditions of Group 1 are for practice to help you get familiar with the experiment. The experimenter will remind you when the formal experiment starts.

In one group, there are 5 seconds between 2 consecutive conditions for you to prepare. In each condition, the procedure is:



During the signal oscillation presenting, you need to report **perceived speed**, and then is the **vection** orally to the experimenter. **Please try to be accurate as possible**. After your reporting, the program will be switched to next condition.

Matters need attention

1). Please fix your eyes on the center **RED CROSS** during the experiment.

2). Please keep your eyes open during the experiment (you can have normal blinking).

2). Please rest your head on the chin-rest during the experiment and hold the chin-rest with your both hands.

APPENDIX 5.1: INSTRUCTIONS FOR EXPERIMENT 2

Training Instructions

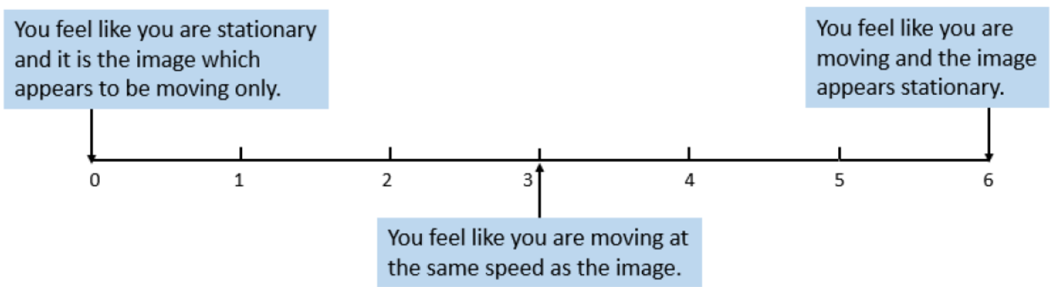
Dear participant,
Thank you for participation in this experiment.
Now we will spend 5-10min to help you get familiar with the task and formal experiment procedures.

There are 2 concepts you need to learn: **vection** and **perceived speed**.

Vection:
Vection is an illusion of self-motion.

Sometimes, what we see can cheat on us. For example, when we sit on train, look out of the window and find another train next to us moving, we may feel that our train is moving forward even though we do not move at all. And this is an illusion of self-motion.
有时候我们看到的东西会让我们产生错觉，比如当我们坐在静止的火车上，有时旁边的另外一辆火车开出车站时，虽然所搭乘的列车并没有动，但我们有时会产生我们在缓慢地往相反方向运动的错觉。而这就是一种自我运动的错觉。
In the experiment, when you stare checkerboard patterns moving for a while, you may feel the moving of patterns gradually slow down and this is a sign that you are starting to generate an illusion of self-motion.
实验中，当您观看棋盘格旋转运动时，您有时会觉得棋盘格的运动速度在渐渐变慢，这就是您开始产生自我运动的错觉的标志之一。
Then, you may gradually start to feel your body is rotating toward the opposite direction which the patterns are rotating.
随后，您可能会渐渐感觉到自己的身体开始向棋盘格运动的相反方向旋转。
However, different individuals may have slight different feelings, and take different time to initiate the illusion of self-motion feelings. So take your time and there is no need to worry if you do not see the illusive self-motion in the beginning.
不过，每个人的感觉都会各有不同，而不同人需要产生这种感觉的时间长短也不同；这跟人的视觉特点有关并没有好坏之分，所以请放轻松，如果一开始您没有任何感觉，也完全不必担心。

Throughout this experiment, you will be reporting this feeling of illusive self-motion (i.e. **vection**). Please ensure that you understand this feeling. The vection will be measured using the following scale:

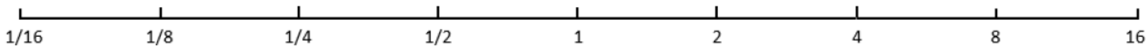


Perceived Speed:

Another figure you need to report is **perceived speed**. The definition of perceived speed is "**how fast you are feeling the patterns are travelling relative to you**". It's important to know that perceived speed is **not** "the number of cycles of oscillations completed by the moving patterns per unit time".

In each condition of the experiment, you will be first present with a **reference oscillation** for 20 seconds, then a **signal oscillation**. You are required to compare the **average perceived speed** between the reference and the signal.

The average speed of the reference is assigned as 1, and **you need to report the ratio** of the average perceived speed of the signal relative to the reference. 9 choices of ratios are provided:

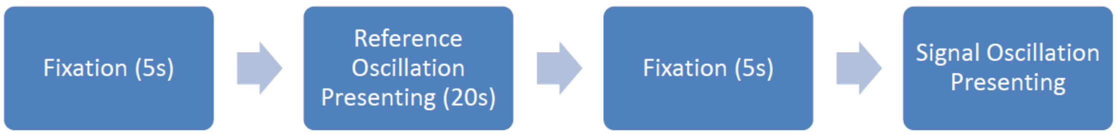


You are required to choose one out of the nine ratios closest to your perception.

Experiment procedure

In this experiment, there are 4 groups of conditions. Each group contains about 10 conditions. Between groups, you have 5 to 10 minutes to rest. The first 4 conditions of Group 1 are for practice to help you get familiar with the experiment. The experimenter will remind you when the formal experiment starts.

In one group, there are 5 seconds between 2 consecutive conditions for you to prepare. In each condition, the procedure is:



During the signal oscillation presenting, you need to report **vection**, and then is the **perceived speed** orally to the experimenter. **Please try to be accurate as possible**. After your reporting, the program will be switched to next condition.

Matters need attention

1). Please fix your eyes on the center **RED CROSS** during the experiment.

2). Please keep your eyes open during the experiment (you can have normal blinking).

3). Please rest your head on the chin-rest during the experiment and hold the chin-rest with your both hands.

APPENDIX I: CONSENT FORM FOR HUMAN FACTORS EXPERIMENT PARTICIPATION

Consent Form For Human Factors Experiment Participation

1. Name ____________________________ Age _________________________
2. Are you feeling ill in any way? Yes/No
3. Do you suffer from diabetics (糖尿病), epilepsy (癲癇症) or other neurological diseases? Yes/No
4. Are you under medical treatment? Yes/No
5. Have you had any intake of alcohol (飲酒) during past 24 hours? Yes / No
6. Have you had injuries or over-exercises during the past 24 hours that will affect your postural stability or perception? Yes / No

If your answer is "Yes" to question (2) to (6), please give details to the Experimenter.

DECLARATION

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

I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdraw declared above.

I undertake to obey the regulations of the laboratory and instructions of the experimenter regarding safety only to my right to withdraw declared above.

The purpose and methods of the experiment have been explained to me and I have had the opportunity to ask questions.

I know I will get **50HKD/h** for compensation of participation.

Signature of Subject ___________________ Date ________________________

This experiment conforms to the requirement of the University Research Ethic Committee.

Signature of Experimenter _________________ Date ________________________

Starting time ______________________ Finish time _________________________

APPENDIX II: RESULTS OF ANOVA ANALYSES FOR EXPERIMENT 1: YAW VECTION

Three-way repeated measures ANOVA

Independent variables: amplitude, rms velocity, repetition

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
repeat	.071	31.079	5	.000	.446	.478	.333
velocity	.020	44.789	9	.000	.421	.477	.250
amplitude	.112	25.042	9	.003	.545	.659	.250
repeat * velocity	.000	102.369	77	.083	.396	.653	.083
repeat * amplitude	.000	125.371	77	.002	.365	.575	.083
velocity * amplitude	.000	.	135	.	.324	.565	.063
repeat * velocity * amplitude	.000	.	1175	.	.174	.512	.021

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: repeat + velocity + amplitude + repeat * velocity + repeat * amplitude + velocity * amplitude + repeat * velocity * amplitude

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
repeat	Sphericity Assumed	35.551	3	11.850	1.588	.208
	Greenhouse-Geisser	35.551	1.337	26.588	1.588	.230
	Huynh-Feldt	35.551	1.434	24.799	1.588	.230
	Lower-bound	35.551	1.000	35.551	1.588	.230
Error(repeat)	Sphericity Assumed	291.129	39	7.465		
	Greenhouse-Geisser	291.129	17.383	16.748		
	Huynh-Feldt	291.129	18.637	15.621		
	Lower-bound	291.129	13.000	22.395		
velocity	Sphericity Assumed	157.304	4	39.326	3.017	.026
	Greenhouse-Geisser	157.304	1.685	93.366	3.017	.077
	Huynh-Feldt	157.304	1.908	82.452	3.017	.069
	Lower-bound	157.304	1.000	157.304	3.017	.106
Error(velocity)	Sphericity Assumed	677.876	52	13.036		
	Greenhouse-Geisser	677.876	21.903	30.950		
	Huynh-Feldt	677.876	24.802	27.332		
	Lower-bound	677.876	13.000	52.144		
amplitude	Sphericity Assumed	141.340	4	35.335	11.367	.000
	Greenhouse-Geisser	141.340	2.180	64.848	11.367	.000
	Huynh-Feldt	141.340	2.635	53.636	11.367	.000
	Lower-bound	141.340	1.000	141.340	11.367	.005
Error(amplitude)	Sphericity Assumed	161.640	52	3.108		
	Greenhouse-Geisser	161.640	28.334	5.705		
	Huynh-Feldt	161.640	34.257	4.718		
	Lower-bound	161.640	13.000	12.434		
repeat * velocity	Sphericity Assumed	45.999	12	3.833	2.914	.001
	Greenhouse-Geisser	45.999	4.755	9.674	2.914	.022
	Huynh-Feldt	45.999	7.831	5.874	2.914	.006
	Lower-bound	45.999	1.000	45.999	2.914	.112
Error(repeat*velocity)	Sphericity Assumed	205.221	156	1.316		
	Greenhouse-Geisser	205.221	61.812	3.320		
	Huynh-Feldt	205.221	101.801	2.016		
	Lower-bound	205.221	13.000	15.786		
repeat * amplitude	Sphericity Assumed	15.677	12	1.306	1.480	.137
	Greenhouse-Geisser	15.677	4.385	3.575	1.480	.217
	Huynh-Feldt	15.677	6.894	2.274	1.480	.186
	Lower-bound	15.677	1.000	15.677	1.480	.245
Error(repeat*amplitude)	Sphericity Assumed	137.743	156	.883		
	Greenhouse-Geisser	137.743	57.007	2.416		
	Huynh-Feldt	137.743	89.623	1.537		
	Lower-bound	137.743	13.000	10.596		
velocity * amplitude	Sphericity Assumed	28.810	16	1.801	1.513	.097
	Greenhouse-Geisser	28.810	5.188	5.553	1.513	.195
	Huynh-Feldt	28.810	9.042	3.186	1.513	.151
	Lower-bound	28.810	1.000	28.810	1.513	.240
Error(velocity*amplitude)	Sphericity Assumed	247.510	208	1.190		
	Greenhouse-Geisser	247.510	67.446	3.670		
	Huynh-Feldt	247.510	117.546	2.106		
	Lower-bound	247.510	13.000	19.039		
repeat * velocity * amplitude	Sphericity Assumed	31.487	48	.656	.752	.890
	Greenhouse-Geisser	31.487	8.331	3.779	.752	.651
	Huynh-Feldt	31.487	24.553	1.282	.752	.798
	Lower-bound	31.487	1.000	31.487	.752	.402
Error (repeat*velocity*amplitude)	Sphericity Assumed	544.193	624	.872		
	Greenhouse-Geisser	544.193	108.304	5.025		
	Huynh-Feldt	544.193	319.183	1.705		
	Lower-bound	544.193	13.000	41.861		

- There was a significant main effect of amplitude, F(2.18, 28.334)=11.367, p=0.000.
- There was a significant interaction between repeat and velocity, F(4.755, 61.812)=2.914, p=0.022.

Independent variables: frequency, rms velocity, repetition

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
repeat	.105	26.461	5	.000	.463	.501	.333
velocity	.021	44.304	9	.000	.414	.466	.250
frequency	.034	38.502	9	.000	.436	.498	.250
repeat * velocity	.000	98.717	77	.131	.410	.691	.083
repeat * frequency	.000	116.823	77	.009	.430	.746	.083
velocity * frequency	.000	.	135	.	.365	.696	.063
repeat * velocity * frequency	.000	.	1175	.	.166	.455	.021

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: repeat + velocity + frequency + repeat * velocity + repeat * frequency + velocity * frequency + repeat * velocity * frequency

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
repeat	Sphericity Assumed	34.749	3	11.583	1.914	.143
	Greenhouse-Geisser	34.749	1.389	25.016	1.914	.183
	Huynh-Feldt	34.749	1.503	23.125	1.914	.180
	Lower-bound	34.749	1.000	34.749	1.914	.190
Error(repeat)	Sphericity Assumed	236.031	39	6.052		
	Greenhouse-Geisser	236.031	18.058	13.071		
	Huynh-Feldt	236.031	19.534	12.083		
	Lower-bound	236.031	13.000	18.156		
velocity	Sphericity Assumed	232.000	4	58.000	5.258	.001
	Greenhouse-Geisser	232.000	1.654	140.250	5.258	.018
	Huynh-Feldt	232.000	1.865	124.405	5.258	.014
	Lower-bound	232.000	1.000	232.000	5.258	.039
Error(velocity)	Sphericity Assumed	573.580	52	11.030		
	Greenhouse-Geisser	573.580	21.504	26.673		
	Huynh-Feldt	573.580	24.243	23.659		
	Lower-bound	573.580	13.000	44.122		
frequency	Sphericity Assumed	148.557	4	37.139	8.797	.000
	Greenhouse-Geisser	148.557	1.746	85.105	8.797	.002
	Huynh-Feldt	148.557	1.994	74.513	8.797	.001
	Lower-bound	148.557	1.000	148.557	8.797	.011
Error(frequency)	Sphericity Assumed	219.523	52	4.222		
	Greenhouse-Geisser	219.523	22.692	9.674		
	Huynh-Feldt	219.523	25.918	8.470		
	Lower-bound	219.523	13.000	16.886		
repeat * velocity	Sphericity Assumed	38.709	12	3.226	2.664	.003
	Greenhouse-Geisser	38.709	4.923	7.862	2.664	.031
	Huynh-Feldt	38.709	8.287	4.671	2.664	.010
	Lower-bound	38.709	1.000	38.709	2.664	.127
Error(repeat*velocity)	Sphericity Assumed	188.911	156	1.211		
	Greenhouse-Geisser	188.911	64.005	2.951		
	Huynh-Feldt	188.911	107.729	1.754		
	Lower-bound	188.911	13.000	14.532		
repeat * frequency	Sphericity Assumed	4.923	12	.410	.332	.982
	Greenhouse-Geisser	4.923	5.156	.955	.332	.897
	Huynh-Feldt	4.923	8.949	.550	.332	.962
	Lower-bound	4.923	1.000	4.923	.332	.575
Error(repeat*frequency)	Sphericity Assumed	192.997	156	1.237		
	Greenhouse-Geisser	192.997	67.034	2.879		
	Huynh-Feldt	192.997	116.335	1.659		
	Lower-bound	192.997	13.000	14.846		
velocity * frequency	Sphericity Assumed	18.121	16	1.133	1.086	.370
	Greenhouse-Geisser	18.121	5.840	3.103	1.086	.378
	Huynh-Feldt	18.121	11.139	1.627	1.086	.376
	Lower-bound	18.121	1.000	18.121	1.086	.316
Error(velocity*frequency)	Sphericity Assumed	216.899	208	1.043		
	Greenhouse-Geisser	216.899	75.918	2.857		
	Huynh-Feldt	216.899	144.808	1.498		
	Lower-bound	216.899	13.000	16.685		
repeat * velocity * frequency	Sphericity Assumed	42.799	48	.892	1.092	.315
	Greenhouse-Geisser	42.799	7.981	5.363	1.092	.375
	Huynh-Feldt	42.799	21.863	1.958	1.092	.354
	Lower-bound	42.799	1.000	42.799	1.092	.315
Error (repeat*velocity*frequency)	Sphericity Assumed	509.381	624	.816		
	Greenhouse-Geisser	509.381	103.752	4.910		
	Huynh-Feldt	509.381	284.224	1.792		
	Lower-bound	509.381	13.000	39.183		

- There was a significant main effect of velocity, F(1.654, 21.504)=5.258, p=0.018.
- There was a significant main effect of frequency, F(1.746, 22.692)=8.797, p=0.002.
- There was a significant interaction between repeat and velocity, F(4.923, 64.005)=2.664, p=0.031.

Independent variables: amplitude, frequency, repetition

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
repeat	.062	32.545	5	.000	.440	.470	.333
frequency	.018	45.929	9	.000	.382	.423	.250
amplitude	.009	54.037	9	.000	.321	.341	.250
repeat * frequency	.000	164.648	77	.000	.399	.659	.083
repeat * amplitude	.000	119.797	77	.006	.403	.671	.083
frequency * amplitude	.000	.	135	.	.238	.348	.063
repeat * frequency * amplitude	.000	.	1175	.	.183	.594	.021

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: repeat + frequency + amplitude + repeat * frequency + repeat * amplitude + frequency * amplitude + repeat * frequency * amplitude

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
repeat	Sphericity Assumed	28.574	3	9.525	1.414	.253
	Greenhouse-Geisser	28.574	1.320	21.653	1.414	.261
	Huynh-Feldt	28.574	1.411	20.258	1.414	.261
	Lower-bound	28.574	1.000	28.574	1.414	.256
Error(repeat)	Sphericity Assumed	262.686	39	6.736		
	Greenhouse-Geisser	262.686	17.156	15.312		
	Huynh-Feldt	262.686	18.337	14.326		
	Lower-bound	262.686	13.000	20.207		
frequency	Sphericity Assumed	106.354	4	26.589	3.585	.012
	Greenhouse-Geisser	106.354	1.528	69.593	3.585	.057
	Huynh-Feldt	106.354	1.691	62.906	3.585	.052
	Lower-bound	106.354	1.000	106.354	3.585	.081
Error(frequency)	Sphericity Assumed	385.686	52	7.417		
	Greenhouse-Geisser	385.686	19.867	19.413		
	Huynh-Feldt	385.686	21.979	17.548		
	Lower-bound	385.686	13.000	29.668		
amplitude	Sphericity Assumed	15.169	4	3.792	.488	.744
	Greenhouse-Geisser	15.169	1.286	11.797	.488	.541
	Huynh-Feldt	15.169	1.366	11.105	.488	.551
	Lower-bound	15.169	1.000	15.169	.488	.497
Error(amplitude)	Sphericity Assumed	403.871	52	7.767		
	Greenhouse-Geisser	403.871	16.715	24.162		
	Huynh-Feldt	403.871	17.758	22.744		
	Lower-bound	403.871	13.000	31.067		
repeat * frequency	Sphericity Assumed	15.440	12	1.287	.861	.587
	Greenhouse-Geisser	15.440	4.784	3.227	.861	.508
	Huynh-Feldt	15.440	7.910	1.952	.861	.551
	Lower-bound	15.440	1.000	15.440	.861	.370
Error(repeat*frequency)	Sphericity Assumed	233.000	156	1.494		
	Greenhouse-Geisser	233.000	62.198	3.746		
	Huynh-Feldt	233.000	102.827	2.266		
	Lower-bound	233.000	13.000	17.923		
repeat * amplitude	Sphericity Assumed	38.397	12	3.200	3.979	.000
	Greenhouse-Geisser	38.397	4.839	7.936	3.979	.004
	Huynh-Feldt	38.397	8.055	4.767	3.979	.000
	Lower-bound	38.397	1.000	38.397	3.979	.067
Error(repeat*amplitude)	Sphericity Assumed	125.443	156	.804		
	Greenhouse-Geisser	125.443	62.901	1.994		
	Huynh-Feldt	125.443	104.713	1.198		
	Lower-bound	125.443	13.000	9.649		
frequency * amplitude	Sphericity Assumed	292.760	16	18.298	9.177	.000
	Greenhouse-Geisser	292.760	3.800	77.041	9.177	.000
	Huynh-Feldt	292.760	5.565	52.604	9.177	.000
	Lower-bound	292.760	1.000	292.760	9.177	.010
Error (frequency*amplitude)	Sphericity Assumed	414.700	208	1.994		
	Greenhouse-Geisser	414.700	49.401	8.395		
	Huynh-Feldt	414.700	72.350	5.732		
	Lower-bound	414.700	13.000	31.900		
repeat * frequency * amplitude	Sphericity Assumed	45.589	48	.950	1.269	.110
	Greenhouse-Geisser	45.589	8.766	5.201	1.269	.262
	Huynh-Feldt	45.589	28.509	1.599	1.269	.165
	Lower-bound	45.589	1.000	45.589	1.269	.280
Error (repeat*frequency*amplitude)	Sphericity Assumed	466.871	624	.748		
	Greenhouse-Geisser	466.871	113.953	4.097		
	Huynh-Feldt	466.871	370.616	1.260		
	Lower-bound	466.871	13.000	35.913		

- There was a significant interaction between repeat and amplitude, F(4.839, 62.901)=3.979, p=0.004.
- There was a significant interaction between frequency and amplitude, F(3.8, 49.401)=9.177, p=0.000.

Two-way repeated measures ANOVA

Independent variables: amplitude, rms velocity

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
velocity	.478	8.427	9	.496	.753	1.000	.250
amplitude	.758	3.167	9	.958	.874	1.000	.250
velocity * amplitude	.000	.	135	.	.356	.666	.063

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: velocity + amplitude + velocity * amplitude

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
velocity	Sphericity Assumed	11.293	4	2.823	1.618	.184
	Greenhouse-Geisser	11.293	3.014	3.747	1.618	.201
	Huynh-Feldt	11.293	4.000	2.823	1.618	.184
	Lower-bound	11.293	1.000	11.293	1.618	.226
Error(velocity)	Sphericity Assumed	90.747	52	1.745		
	Greenhouse-Geisser	90.747	39.176	2.316		
	Huynh-Feldt	90.747	52.000	1.745		
	Lower-bound	90.747	13.000	6.981		
amplitude	Sphericity Assumed	68.629	4	17.157	17.153	.000
	Greenhouse-Geisser	68.629	3.496	19.632	17.153	.000
	Huynh-Feldt	68.629	4.000	17.157	17.153	.000
	Lower-bound	68.629	1.000	68.629	17.153	.001
Error(amplitude)	Sphericity Assumed	52.011	52	1.000		
	Greenhouse-Geisser	52.011	45.444	1.145		
	Huynh-Feldt	52.011	52.000	1.000		
	Lower-bound	52.011	13.000	4.001		
velocity * amplitude	Sphericity Assumed	104.507	16	6.532	3.822	.000
	Greenhouse-Geisser	104.507	5.700	18.334	3.822	.003
	Huynh-Feldt	104.507	10.658	9.806	3.822	.000
	Lower-bound	104.507	1.000	104.507	3.822	.072
Error(velocity*amplitude)	Sphericity Assumed	355.453	208	1.709		
	Greenhouse-Geisser	355.453	74.102	4.797		
	Huynh-Feldt	355.453	138.553	2.565		
	Lower-bound	355.453	13.000	27.343		

- There was a significant main effect of amplitude, $F(4, 52)=17.153$, $p=0.000$.
- There was a significant interaction between amplitude and velocity, $F(5.7, 74.1)=3.822$, $p=0.003$.

Independent variables: frequency, rms velocity

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
velocity	.019	45.053	9	.000	.384	.425	.250
frequency	.065	31.197	9	.000	.405	.455	.250
velocity * frequency	.000	.	135	.	.386	.775	.063

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: velocity + frequency + velocity * frequency

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
velocity	Sphericity Assumed	56.933	4	14.233	4.310	.004
	Greenhouse-Geisser	56.933	1.534	37.106	4.310	.036
	Huynh-Feldt	56.933	1.699	33.509	4.310	.031
	Lower-bound	56.933	1.000	56.933	4.310	.058
Error(velocity)	Sphericity Assumed	171.727	52	3.302		
	Greenhouse-Geisser	171.727	19.946	8.609		
	Huynh-Feldt	171.727	22.088	7.775		
	Lower-bound	171.727	13.000	13.210		
frequency	Sphericity Assumed	34.061	4	8.515	5.453	.001
	Greenhouse-Geisser	34.061	1.622	21.004	5.453	.017
	Huynh-Feldt	34.061	1.820	18.720	5.453	.013
	Lower-bound	34.061	1.000	34.061	5.453	.036
Error(frequency)	Sphericity Assumed	81.199	52	1.562		
	Greenhouse-Geisser	81.199	21.082	3.852		
	Huynh-Feldt	81.199	23.654	3.433		
	Lower-bound	81.199	13.000	6.246		
velocity * frequency	Sphericity Assumed	9.589	16	.599	1.300	.199
	Greenhouse-Geisser	9.589	6.181	1.551	1.300	.266
	Huynh-Feldt	9.589	12.397	.773	1.300	.221
	Lower-bound	9.589	1.000	9.589	1.300	.275
Error(velocity*frequency)	Sphericity Assumed	95.851	208	.461		
	Greenhouse-Geisser	95.851	80.352	1.193		
	Huynh-Feldt	95.851	161.156	.595		
	Lower-bound	95.851	13.000	7.373		

- There was a significant main effect of velocity, F(1.534, 19.946)=4.31, p=0.036.
- There was a significant main effect of frequency, F(1.622, 21.082)=5.453, p=0.017.

Independent variables: amplitude, frequency

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
frequency	.015	48.226	9	.000	.366	.401	.250
amplitude	.003	64.826	9	.000	.303	.318	.250
frequency * amplitude	.000	.	135	.	.312	.529	.063

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: frequency + amplitude + frequency * amplitude

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
frequency	Sphericity Assumed	41.229	4	10.307	3.970	.007
	Greenhouse-Geisser	41.229	1.465	28.152	3.970	.047
	Huynh-Feldt	41.229	1.604	25.703	3.970	.042
	Lower-bound	41.229	1.000	41.229	3.970	.068
Error(frequency)	Sphericity Assumed	135.011	52	2.596		
	Greenhouse-Geisser	135.011	19.039	7.091		
	Huynh-Feldt	135.011	20.852	6.475		
	Lower-bound	135.011	13.000	10.385		
amplitude	Sphericity Assumed	3.321	4	.830	.396	.811
	Greenhouse-Geisser	3.321	1.214	2.737	.396	.578
	Huynh-Feldt	3.321	1.272	2.612	.396	.587
	Lower-bound	3.321	1.000	3.321	.396	.540
Error(amplitude)	Sphericity Assumed	109.119	52	2.098		
	Greenhouse-Geisser	109.119	15.776	6.917		
	Huynh-Feldt	109.119	16.532	6.600		
	Lower-bound	109.119	13.000	8.394		
frequency * amplitude	Sphericity Assumed	93.557	16	5.847	8.687	.000
	Greenhouse-Geisser	93.557	4.990	18.751	8.687	.000
	Huynh-Feldt	93.557	8.471	11.045	8.687	.000
	Lower-bound	93.557	1.000	93.557	8.687	.011
Error (frequency*amplitude)	Sphericity Assumed	140.003	208	.673		
	Greenhouse-Geisser	140.003	64.864	2.158		
	Huynh-Feldt	140.003	110.118	1.271		
	Lower-bound	140.003	13.000	10.769		

- There was a significant main effect of frequency, $F(1.465, 19.039)=3.97$, $p=0.047$.
- There was a significant interaction between amplitude and frequency, $F(4.99, 64.864)=8.687$, $p=0.000$.

APPENDIX III: RESULTS OF ANOVA ANALYSES FOR EXPERIMENT 2: ROLL VECTION

Three-way repeated measures ANOVA

Independent variables: amplitude, rms velocity, repetition

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
repeat	.402	10.678	5	.059	.638	.745	.333
velocity	.032	39.253	9	.000	.410	.462	.250
amplitude	.079	28.982	9	.001	.421	.476	.250
repeat * velocity	.000	122.320	77	.003	.298	.424	.083
repeat * amplitude	.000	109.459	77	.031	.361	.563	.083
velocity * amplitude	.000	.	135	.	.364	.693	.063
repeat * velocity * amplitude	.000	.	1175	.	.165	.446	.021

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: repeat + velocity + amplitude + repeat * velocity + repeat * amplitude + velocity * amplitude + repeat * velocity * amplitude

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
repeat	Sphericity Assumed	8.105	3	2.702	1.442	.245
	Greenhouse-Geisser	8.105	1.913	4.237	1.442	.255
	Huynh-Feldt	8.105	2.235	3.627	1.442	.253
	Lower-bound	8.105	1.000	8.105	1.442	.251
Error(repeat)	Sphericity Assumed	73.045	39	1.873		
	Greenhouse-Geisser	73.045	24.865	2.938		
	Huynh-Feldt	73.045	29.053	2.514		
	Lower-bound	73.045	13.000	5.619		
velocity	Sphericity Assumed	1420.990	4	355.248	42.893	.000
	Greenhouse-Geisser	1420.990	1.642	865.585	42.893	.000
	Huynh-Feldt	1420.990	1.847	769.194	42.893	.000
	Lower-bound	1420.990	1.000	1420.990	42.893	.000
Error(velocity)	Sphericity Assumed	430.670	52	8.282		
	Greenhouse-Geisser	430.670	21.341	20.180		
	Huynh-Feldt	430.670	24.016	17.933		
	Lower-bound	430.670	13.000	33.128		
amplitude	Sphericity Assumed	105.947	4	26.487	15.050	.000
	Greenhouse-Geisser	105.947	1.682	62.978	15.050	.000
	Huynh-Feldt	105.947	1.904	55.636	15.050	.000
	Lower-bound	105.947	1.000	105.947	15.050	.002
Error(amplitude)	Sphericity Assumed	91.513	52	1.760		
	Greenhouse-Geisser	91.513	21.870	4.184		
	Huynh-Feldt	91.513	24.756	3.697		
	Lower-bound	91.513	13.000	7.039		
repeat * velocity	Sphericity Assumed	14.084	12	1.174	1.095	.368
	Greenhouse-Geisser	14.084	3.572	3.944	1.095	.367
	Huynh-Feldt	14.084	5.091	2.766	1.095	.372
	Lower-bound	14.084	1.000	14.084	1.095	.314
Error(repeat*velocity)	Sphericity Assumed	167.216	156	1.072		
	Greenhouse-Geisser	167.216	46.430	3.601		
	Huynh-Feldt	167.216	66.184	2.527		
	Lower-bound	167.216	13.000	12.863		
repeat * amplitude	Sphericity Assumed	5.813	12	.484	.638	.808
	Greenhouse-Geisser	5.813	4.329	1.343	.638	.650
	Huynh-Feldt	5.813	6.758	.860	.638	.718
	Lower-bound	5.813	1.000	5.813	.638	.439
Error(repeat*amplitude)	Sphericity Assumed	118.487	156	.760		
	Greenhouse-Geisser	118.487	56.271	2.106		
	Huynh-Feldt	118.487	87.850	1.349		
	Lower-bound	118.487	13.000	9.114		
velocity * amplitude	Sphericity Assumed	19.274	16	1.205	1.247	.234
	Greenhouse-Geisser	19.274	5.826	3.308	1.247	.293
	Huynh-Feldt	19.274	11.090	1.738	1.247	.261
	Lower-bound	19.274	1.000	19.274	1.247	.284
Error(velocity*amplitude)	Sphericity Assumed	200.866	208	.966		
	Greenhouse-Geisser	200.866	75.734	2.652		
	Huynh-Feldt	200.866	144.164	1.393		
	Lower-bound	200.866	13.000	15.451		
repeat * velocity * amplitude	Sphericity Assumed	32.909	48	.686	1.092	.315
	Greenhouse-Geisser	32.909	7.917	4.156	1.092	.374
	Huynh-Feldt	32.909	21.415	1.537	1.092	.355
	Lower-bound	32.909	1.000	32.909	1.092	.315
Error (repeat*velocity*amplitude)	Sphericity Assumed	391.591	624	.628		
	Greenhouse-Geisser	391.591	102.927	3.805		
	Huynh-Feldt	391.591	278.401	1.407		
	Lower-bound	391.591	13.000	30.122		

- There was a significant main effect of velocity, F(1.642, 21.341)=42.893, p=0.000.
- There was a significant main effect of amplitude, F(1.682, 21.870)=15.05, p=0.000.

Independent variables: frequency, rms velocity, repetition

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
repeat	.398	10.801	5	.056	.747	.910	.333
velocity	.067	30.855	9	.000	.464	.537	.250
frequency	.117	24.464	9	.004	.468	.543	.250
repeat * velocity	.000	130.309	77	.001	.371	.588	.083
repeat * frequency	.000	119.885	77	.005	.385	.622	.083
velocity * frequency	.000	.	135	.	.377	.738	.063
repeat * velocity * frequency	.000	.	1175	.	.168	.467	.021

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: repeat + velocity + frequency + repeat * velocity + repeat * frequency + velocity * frequency + repeat * velocity * frequency

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
repeat	Sphericity Assumed	15.100	3	5.033	2.429	.080
	Greenhouse-Geisser	15.100	2.242	6.736	2.429	.100
	Huynh-Feldt	15.100	2.731	5.529	2.429	.086
	Lower-bound	15.100	1.000	15.100	2.429	.143
Error(repeat)	Sphericity Assumed	80.800	39	2.072		
	Greenhouse-Geisser	80.800	29.141	2.773		
	Huynh-Feldt	80.800	35.504	2.276		
	Lower-bound	80.800	13.000	6.215		
velocity	Sphericity Assumed	828.040	4	207.010	29.958	.000
	Greenhouse-Geisser	828.040	1.854	446.576	29.958	.000
	Huynh-Feldt	828.040	2.150	385.210	29.958	.000
	Lower-bound	828.040	1.000	828.040	29.958	.000
Error(velocity)	Sphericity Assumed	359.320	52	6.910		
	Greenhouse-Geisser	359.320	24.105	14.907		
	Huynh-Feldt	359.320	27.945	12.858		
	Lower-bound	359.320	13.000	27.640		
frequency	Sphericity Assumed	110.504	4	27.626	7.852	.000
	Greenhouse-Geisser	110.504	1.870	59.088	7.852	.003
	Huynh-Feldt	110.504	2.173	50.859	7.852	.002
	Lower-bound	110.504	1.000	110.504	7.852	.015
Error(frequency)	Sphericity Assumed	182.956	52	3.518		
	Greenhouse-Geisser	182.956	24.312	7.525		
	Huynh-Feldt	182.956	28.246	6.477		
	Lower-bound	182.956	13.000	14.074		
repeat * velocity	Sphericity Assumed	9.514	12	.793	.678	.771
	Greenhouse-Geisser	9.514	4.450	2.138	.678	.625
	Huynh-Feldt	9.514	7.053	1.349	.678	.691
	Lower-bound	9.514	1.000	9.514	.678	.425
Error(repeat*velocity)	Sphericity Assumed	182.486	156	1.170		
	Greenhouse-Geisser	182.486	57.851	3.154		
	Huynh-Feldt	182.486	91.688	1.990		
	Lower-bound	182.486	13.000	14.037		
repeat * frequency	Sphericity Assumed	8.964	12	.747	.864	.585
	Greenhouse-Geisser	8.964	4.616	1.942	.864	.504
	Huynh-Feldt	8.964	7.468	1.200	.864	.544
	Lower-bound	8.964	1.000	8.964	.864	.370
Error(repeat*frequency)	Sphericity Assumed	134.936	156	.865		
	Greenhouse-Geisser	134.936	60.002	2.249		
	Huynh-Feldt	134.936	97.089	1.390		
	Lower-bound	134.936	13.000	10.380		
velocity * frequency	Sphericity Assumed	52.439	16	3.277	3.806	.000
	Greenhouse-Geisser	52.439	6.026	8.702	3.806	.002
	Huynh-Feldt	52.439	11.811	4.440	3.806	.000
	Lower-bound	52.439	1.000	52.439	3.806	.073
Error(velocity*frequency)	Sphericity Assumed	179.101	208	.861		
	Greenhouse-Geisser	179.101	78.341	2.286		
	Huynh-Feldt	179.101	153.543	1.166		
	Lower-bound	179.101	13.000	13.777		
repeat * velocity * frequency	Sphericity Assumed	32.207	48	.671	.955	.562
	Greenhouse-Geisser	32.207	8.060	3.996	.955	.476
	Huynh-Feldt	32.207	22.440	1.435	.955	.523
	Lower-bound	32.207	1.000	32.207	.955	.346
Error (repeat*velocity*frequency)	Sphericity Assumed	438.493	624	.703		
	Greenhouse-Geisser	438.493	104.784	4.185		
	Huynh-Feldt	438.493	291.717	1.503		
	Lower-bound	438.493	13.000	33.730		

- There was a significant main effect of velocity, F(1.854, 24.105)=29.958, p=0.000.
- There was a significant main effect of frequency, F(1.87, 24.312)=7.852, p=0.003.
- There was a significant interaction between frequency and velocity, F(6.026, 78.341)=3.806, p=0.002.

Independent variables: amplitude, frequency, repetition

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
repeat	.429	9.927	5	.078	.651	.765	.333
frequency	.012	50.934	9	.000	.339	.365	.250
amplitude	.001	75.881	9	.000	.298	.311	.250
repeat * frequency	.000	149.349	77	.000	.322	.475	.083
repeat * amplitude	.000	159.439	77	.000	.356	.552	.083
frequency * amplitude	.000	.	135	.	.239	.351	.063
repeat * frequency * amplitude	.000	.	1175	.	.167	.464	.021

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: repeat + frequency + amplitude + repeat * frequency + repeat * amplitude + frequency * amplitude + repeat * frequency * amplitude

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
repeat	Sphericity Assumed	21.208	3	7.069	4.119	.012
	Greenhouse-Geisser	21.208	1.954	10.855	4.119	.029
	Huynh-Feldt	21.208	2.295	9.241	4.119	.022
	Lower-bound	21.208	1.000	21.208	4.119	.063
Error(repeat)	Sphericity Assumed	66.942	39	1.716		
	Greenhouse-Geisser	66.942	25.397	2.636		
	Huynh-Feldt	66.942	29.835	2.244		
	Lower-bound	66.942	13.000	5.149		
frequency	Sphericity Assumed	1062.554	4	265.639	39.940	.000
	Greenhouse-Geisser	1062.554	1.356	783.607	39.940	.000
	Huynh-Feldt	1062.554	1.459	728.488	39.940	.000
	Lower-bound	1062.554	1.000	1062.554	39.940	.000
Error(frequency)	Sphericity Assumed	345.846	52	6.651		
	Greenhouse-Geisser	345.846	17.628	19.619		
	Huynh-Feldt	345.846	18.961	18.239		
	Lower-bound	345.846	13.000	26.604		
amplitude	Sphericity Assumed	525.890	4	131.473	23.213	.000
	Greenhouse-Geisser	525.890	1.193	440.738	23.213	.000
	Huynh-Feldt	525.890	1.245	422.247	23.213	.000
	Lower-bound	525.890	1.000	525.890	23.213	.000
Error(amplitude)	Sphericity Assumed	294.510	52	5.664		
	Greenhouse-Geisser	294.510	15.512	18.986		
	Huynh-Feldt	294.510	16.191	18.190		
	Lower-bound	294.510	13.000	22.655		
repeat * frequency	Sphericity Assumed	6.903	12	.575	.494	.916
	Greenhouse-Geisser	6.903	3.865	1.786	.494	.734
	Huynh-Feldt	6.903	5.704	1.210	.494	.802
	Lower-bound	6.903	1.000	6.903	.494	.494
Error(repeat*frequency)	Sphericity Assumed	181.497	156	1.163		
	Greenhouse-Geisser	181.497	50.242	3.612		
	Huynh-Feldt	181.497	74.151	2.448		
	Lower-bound	181.497	13.000	13.961		
repeat * amplitude	Sphericity Assumed	6.939	12	.578	.613	.829
	Greenhouse-Geisser	6.939	4.274	1.624	.613	.665
	Huynh-Feldt	6.939	6.627	1.047	.613	.735
	Lower-bound	6.939	1.000	6.939	.613	.448
Error(repeat*amplitude)	Sphericity Assumed	147.061	156	.943		
	Greenhouse-Geisser	147.061	55.559	2.647		
	Huynh-Feldt	147.061	86.157	1.707		
	Lower-bound	147.061	13.000	11.312		
frequency * amplitude	Sphericity Assumed	116.367	16	7.273	4.784	.000
	Greenhouse-Geisser	116.367	3.821	30.453	4.784	.003
	Huynh-Feldt	116.367	5.610	20.741	4.784	.000
	Lower-bound	116.367	1.000	116.367	4.784	.048
Error (frequency*amplitude)	Sphericity Assumed	316.233	208	1.520		
	Greenhouse-Geisser	316.233	49.676	6.366		
	Huynh-Feldt	316.233	72.935	4.336		
	Lower-bound	316.233	13.000	24.326		
repeat * frequency * amplitude	Sphericity Assumed	30.576	48	.637	.938	.594
	Greenhouse-Geisser	30.576	8.039	3.803	.938	.489
	Huynh-Feldt	30.576	22.286	1.372	.938	.545
	Lower-bound	30.576	1.000	30.576	.938	.350
Error (repeat*frequency*amplitude)	Sphericity Assumed	423.624	624	.679		
	Greenhouse-Geisser	423.624	104.512	4.053		
	Huynh-Feldt	423.624	289.718	1.462		
	Lower-bound	423.624	13.000	32.586		

- There was a significant main effect of repeat, F(1.954, 25.397)=4.119, p=0.029.
- There was a significant main effect of frequency, F(1.356, 17.628)=39.94, p=0.000.
- There was a significant main effect of amplitude, F(1.193, 15.512)=23.213, p=0.000.
- There was a significant interaction between frequency and amplitude, F(3.821, 49.676)=4.784, p=0.003.

Two-way repeated measures ANOVA

Independent variables: amplitude, rms velocity

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
velocity	.039	37.173	9	.000	.449	.516	.250
amplitude	.150	21.695	9	.011	.525	.629	.250
velocity * amplitude	.000	.	135	.	.338	.607	.063

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: velocity + amplitude + velocity * amplitude

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
velocity	Sphericity Assumed	372.647	4	93.162	45.499	.000
	Greenhouse-Geisser	372.647	1.794	207.700	45.499	.000
	Huynh-Feldt	372.647	2.063	180.629	45.499	.000
	Lower-bound	372.647	1.000	372.647	45.499	.000
Error(velocity)	Sphericity Assumed	106.473	52	2.048		
	Greenhouse-Geisser	106.473	23.324	4.565		
	Huynh-Feldt	106.473	26.820	3.970		
	Lower-bound	106.473	13.000	8.190		
amplitude	Sphericity Assumed	26.319	4	6.580	13.417	.000
	Greenhouse-Geisser	26.319	2.101	12.526	13.417	.000
	Huynh-Feldt	26.319	2.515	10.463	13.417	.000
	Lower-bound	26.319	1.000	26.319	13.417	.003
Error(amplitude)	Sphericity Assumed	25.501	52	.490		
	Greenhouse-Geisser	25.501	27.314	.934		
	Huynh-Feldt	25.501	32.699	.780		
	Lower-bound	25.501	13.000	1.962		
velocity * amplitude	Sphericity Assumed	6.781	16	.424	1.095	.361
	Greenhouse-Geisser	6.781	5.409	1.254	1.095	.372
	Huynh-Feldt	6.781	9.712	.698	1.095	.371
	Lower-bound	6.781	1.000	6.781	1.095	.314
Error(velocity*amplitude)	Sphericity Assumed	80.499	208	.387		
	Greenhouse-Geisser	80.499	70.316	1.145		
	Huynh-Feldt	80.499	126.257	.638		
	Lower-bound	80.499	13.000	6.192		

- There was a significant main effect of velocity, $F(1.794, 23.324)=45.499$, $p=0.000$.
- There was a significant main effect of amplitude, $F(2.101, 27.314)=13.417$, $p=0.000$.

Independent variables: frequency, rms velocity

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
velocity	.094	27.032	9	.002	.547	.663	.250
frequency	.149	21.736	9	.010	.638	.807	.250
velocity * frequency	.000	.	135	.	.386	.774	.063

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: velocity + frequency + velocity * frequency

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
velocity	Sphericity Assumed	222.646	4	55.661	33.279	.000
	Greenhouse-Geisser	222.646	2.190	101.682	33.279	.000
	Huynh-Feldt	222.646	2.651	83.996	33.279	.000
	Lower-bound	222.646	1.000	222.646	33.279	.000
Error(velocity)	Sphericity Assumed	86.974	52	1.673		
	Greenhouse-Geisser	86.974	28.465	3.055		
	Huynh-Feldt	86.974	34.459	2.524		
	Lower-bound	86.974	13.000	6.690		
frequency	Sphericity Assumed	26.924	4	6.731	6.411	.000
	Greenhouse-Geisser	26.924	2.552	10.549	6.411	.002
	Huynh-Feldt	26.924	3.229	8.339	6.411	.001
	Lower-bound	26.924	1.000	26.924	6.411	.025
Error(frequency)	Sphericity Assumed	54.596	52	1.050		
	Greenhouse-Geisser	54.596	33.179	1.645		
	Huynh-Feldt	54.596	41.972	1.301		
	Lower-bound	54.596	13.000	4.200		
velocity * frequency	Sphericity Assumed	13.283	16	.830	2.356	.003
	Greenhouse-Geisser	13.283	6.177	2.150	2.356	.037
	Huynh-Feldt	13.283	12.383	1.073	2.356	.008
	Lower-bound	13.283	1.000	13.283	2.356	.149
Error(velocity*frequency)	Sphericity Assumed	73.297	208	.352		
	Greenhouse-Geisser	73.297	80.307	.913		
	Huynh-Feldt	73.297	160.982	.455		
	Lower-bound	73.297	13.000	5.638		

- There was a significant main effect of velocity, F(2.19, 28.465)=33.279, p=0.000.
- There was a significant main effect of frequency, F(2.552, 33.179)=6.411, p=0.002.
- There was a significant interaction between frequency and velocity, F(6.177, 80.307)=2.356, p=0.037.

Independent variables: amplitude, frequency

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
frequency	.022	43.645	9	.000	.375	.413	.250
amplitude	.004	63.006	9	.000	.303	.318	.250
frequency * amplitude	.000	.	135	.	.271	.425	.063

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: frequency + amplitude + frequency * amplitude

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
frequency	Sphericity Assumed	265.717	4	66.429	30.841	.000
	Greenhouse-Geisser	265.717	1.500	177.114	30.841	.000
	Huynh-Feldt	265.717	1.653	160.794	30.841	.000
	Lower-bound	265.717	1.000	265.717	30.841	.000
Error(frequency)	Sphericity Assumed	112.003	52	2.154		
	Greenhouse-Geisser	112.003	19.503	5.743		
	Huynh-Feldt	112.003	21.483	5.214		
	Lower-bound	112.003	13.000	8.616		
amplitude	Sphericity Assumed	123.089	4	30.772	20.454	.000
	Greenhouse-Geisser	123.089	1.213	101.507	20.454	.000
	Huynh-Feldt	123.089	1.271	96.877	20.454	.000
	Lower-bound	123.089	1.000	123.089	20.454	.001
Error(amplitude)	Sphericity Assumed	78.231	52	1.504		
	Greenhouse-Geisser	78.231	15.764	4.963		
	Huynh-Feldt	78.231	16.517	4.736		
	Lower-bound	78.231	13.000	6.018		
frequency * amplitude	Sphericity Assumed	34.704	16	2.169	3.850	.000
	Greenhouse-Geisser	34.704	4.343	7.991	3.850	.006
	Huynh-Feldt	34.704	6.793	5.109	3.850	.001
	Lower-bound	34.704	1.000	34.704	3.850	.072
Error (frequency*amplitude)	Sphericity Assumed	117.176	208	.563		
	Greenhouse-Geisser	117.176	56.460	2.075		
	Huynh-Feldt	117.176	88.304	1.327		
	Lower-bound	117.176	13.000	9.014		

- There was a significant main effect of frequency, $F(1.5, 19.503)=30.841$, $p=0.000$.
- There was a significant main effect of amplitude, $F(1.213, 15.764)=20.454$, $p=0.000$.
- There was a significant interaction between frequency and amplitude, $F(4.343, 56.46)=3.85$, $p=0.006$.