Postural disturbance and vection when viewing visual stimulus oscillating in roll and fore-and-aft directions: effects of frequency and peak velocity

by

CHOW, Ho Chi Eric

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

October 2008, Hong Kong

Authorization

I hereby declare that I am the sole author of the thesis.

I authorize the Hong Kong University of Science and Technology to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I further authorize the Hong Kong University of Science and Technology to reproduce the thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

CHOW, Ho Chi Eric

3rd November, 2008

Postural disturbance and vection when viewing visual stimulus oscillating in roll and fore-and-aft directions: effects of frequency and peak velocity

by

CHOW, Ho Chi Eric

This is to certify that I have examined the above MPhil thesis
and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by
the thesis examination committee have been made.

Dr. Richard H.Y. So Supervisor

Professor Fugee Tsung Acting Head

Department of Industrial Engineering and Logistics Management

3rd November, 2008

Acknowledgments

I would like to express my gratitude to all those who gave me the possibility to complete this thesis. I want to thank my supervisor, Dr. Richard H. Y. So, whose help, stimulating suggestions and encouragement helped me throughout the research and writing of this thesis. I want to thank my colleagues from the Human Performance Lab and Manufacturing Systems Lab for all their help, support, interest and valuable suggestions. I also want to thank the administrative and technical staff of the Design and Manufacturing Services Facility and the Department of Industrial Engineering and Logistics Management for all their assistance.

I would like to give special thanks to my parents, Paul and Lavender, my brother Vincent, and my beloved Rita, whose support, patience, and love enabled me to complete this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Postural disturbance and vection when viewing visual stimulus oscillating in roll and fore-and-aft direction: the effects of frequency and peak velocity

By

CHOW, Ho Chi Eric

Department of Industrial Engineering and Logistics Management
The Hong Kong University of Science and Technology

Abstract

When a stationary human observer watches a moving visual stimulus, he or she may experience postural disturbance and illusion of self-motion (vection). While studies of postural disturbance of viewers watching scene oscillations of different frequencies in roll direction has led to important discoveries on the possible cause of motion sickness (Duh *et al.*, 2004), similar studies with scene oscillations in fore-and-aft direction are not found. This thesis examines the frequency response of postural disturbance and vection when viewing visual stimulus oscillating in roll direction and in fore-and-aft direction. The range of frequency investigated is from 0.05 to 0.8 Hz. Participants watching oscillating stimuli in both direction exhibited significantly higher postural disturbance and vection than watching stationary stimuli. Both the postural disturbance and vection reduce significantly with increasing scene oscillating frequency. Data obtained have been integrated with Duh *et al.* (2004)'s result to provide new insight in the possible cause of motion sickness. So far, both the author and Duh had manipulated the scene oscillation by varying oscillation amplitudes at a constant peak velocity of

70°/sec. A second study has been conducted to examine the effect of peak roll oscillation velocity on postural disturbance and vection. Frequency of visual stimulus oscillation was held constant at 0.05 Hz. Among the four peak velocities being tested (35, 70, 100 and 140°/sec), it was found that postural disturbance and vection at 35°/sec condition are significantly lower than other velocity conditions. Implications of the second study on Duh *et al.* (2004)'s work are discussed.

CHAPTER 1: INTRODUCTION

1.1 Summary

This chapter reviews the visual-vestibular crossover frequency hypothesis by Duh and his colleagues (2004). Research gaps concerning vection and postural disturbance as functions of visual motion in fore-and-aft and roll direction are identified. The chapter ends with the objectives of the thesis work.

1.2 Development of visual-vestibular crossover frequency hypothesis

Sensory conflict theory was first proposed by Reason (1978). The theory states that conflicts between visual and vestibular signals cause visually-induced motion sickness (VIMS). Such conflict can readily be experienced in virtual environment, in which a stationary human observer watches a moving visual scene. In this case, the lack of vestibular input and the presence of visual input cause visually-induced motion sickness.

On the basis of sensory conflict theory, Duh *et al.* (2004) proposed the visual-vestibular crossover frequency hypothesis: visually-induced motion sickness peaks around the frequency at which the summed response of the visual and vestibular self-motion system is at maximum. Duh *et al.* (2004) studied the visual self-motion system frequency response by measuring human postural disturbance in response to visual scene roll oscillation (0.8, 0.4, 0.2, 0.1, 0.05 Hz) with peak scene velocity held constant across frequencies at 70°/sec. Their results, illustrated in Figure 1.1, showed a low-pass filter characteristic response, which had a remarkably similar response pattern as those obtained by Berthoz *et al.* (1979) for linear perceived self-motion (i.e. vection).

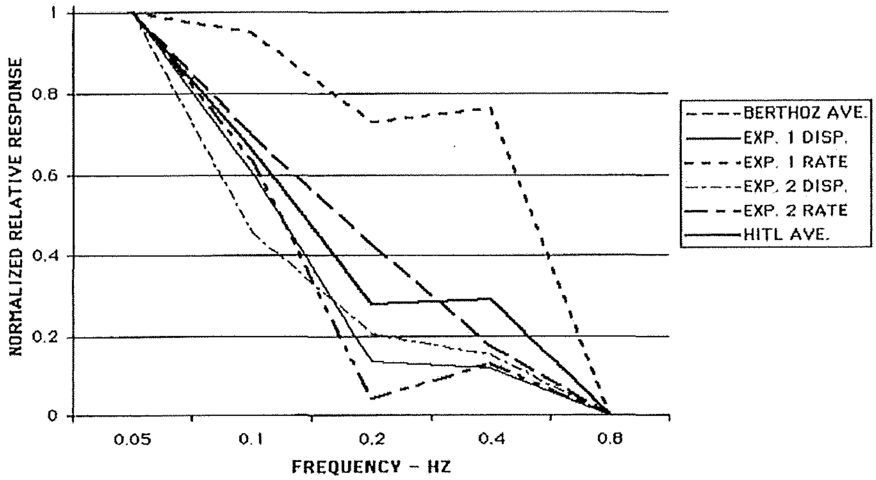


Figure 1.1 (cited from Duh *et al.*, 2004): Postural instability (Disp.) and perceived difficulty maintaining upright posture (Rate) as a function of visual stimulus frequency. Exp. 1 Disp.: center of balance dispersion from Experiment 1; Exp. 1 Rate: subjective difficulty rating from Experiment 1; Exp. 2 Disp.: dispersion from Experiment 2; Exp. 2 Rate: difficulty rating from Experiment 2. HITL Ave.: combined average dispersion and rating data from Experiments 1 and 2. Berthoz Ave.: combined average self-motion perception frequency responses from Berthoz (1979).

Duh *et al.* (2004) plotted an averaged low-pass curve (average of Berthoz's vection data with their own postural disturbance data) against a high-pass vestibular frequency response curve based on data from Jones & Milsum (1965). The frequency at the crossover point between the low-pass and high-pass curves was determined to be at around 0.06 Hz (see Figure 1.2). Duh *et al.* (2004) hypothesized that conflicting visual and vestibular self-motion cues at this frequency is most provocative, since, at this frequency, both systems has a relatively high gain.

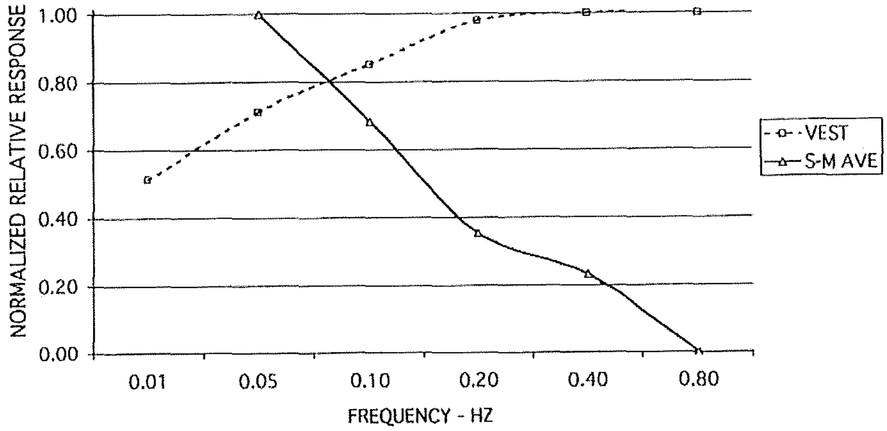


Figure 1.2 (cited from Duh *et al.* 2004): Visual-vestibular crossover. S-M Ave. (Self-Motion average): combined HITL Ave. and Berthoz Ave. Vest: vestibular frequency response. The crossover frequency, the frequency at which the summed gain from the visual and vestibular self-motion systems is maximum, appears to be about 0.06Hz.

Duh *et al.* (2004) conducted a follow-up experiment to test the crossover hypothesis. In their study, subjects were exposed to visual and inertial yaw oscillating stimulus simultaneously but at slightly different frequencies (beat frequency). The result confirmed that motion sickness was significantly higher at 0.06 Hz beat frequency than at 0.2 Hz. Lin *et al.* (2005) confirmed the crossover frequency hypothesis with an experiment in which oscillating roll visual stimulus (0.035, 0.08, 0.213 Hz) were presented to stationary human subjects. Visually-induced motion sickness was found to be highest at 0.08Hz, which was very close to the proposed crossover frequency obtained by Duh *et al.* (2004).

1.3 Frequency response of postural disturbance and vection

Clearly, frequency response of postural disturbance and vection has been the key foundation of the crossover frequency hypothesis. A review of related studies on both types of response when viewing oscillating visual stimulus is presented.

1.3.1 Postural disturbance when viewing oscillating visual stimulus

Postural disturbance due to oscillating visual stimulus was first studied in the "swinging room" experiment (Lee & Lishman, 1975), which demonstrated that displacement of the visual environment produces a compensatory postural response. Numerous studies have also shown that sinusoidal motion of the visual environment produces postural disturbance (Bardy *et al.*, 1996, 1999; Dijkstra, *et al.*, 1992, 1994; Van Asten et.al., 1988; Previc, 1993; Stoffregen, 1998; Duh *et al.*, 2004). Among these studies, Previc (1993) and Duh *et al.* (2004) studied the effects of frequency on the magnitude of postural disturbance. As discussed, Duh *et al.* (2004) showed a decreasing postural disturbance curve as a function of visual stimulus roll oscillation frequency (0.05, 0.1, 0.2, 0.4, 0.8 Hz), while holding peak velocity constant at 70°/sec. On the other hand, Previc (1993) showed that during exposure of visual roll oscillation (0.03, 0.06, 0.12, 0.25, 0.50 Hz) at a constant peak oscillation displacement of ±20°, postural disturbance magnitude peaked at 0.12 Hz.

1.3.2 Vection when viewing oscillating visual stimulus

Vection is a compelling illusion of self-motion, first described by Mach (1875), and was later termed vection by Fischer and Kornmuller (1930); Tschermak (1931). Vection due to oscillating fore-and-aft (linear) visual stimulus was studied by Berthoz *et al.* (1979). His results showed that vection magnitude decreased as a function of visual stimulus oscillation on 0.01 to 1.0 Hz frequency range. On the other hand, Diels (2008) showed that vection magnitude decreased as a function of fore-and-aft visual stimulus oscillation frequency on 0.2 – 1.0 Hz range, but *not* on 0.025 to 0.2 Hz range. Previc (1993) found that vection magnitude due to oscillating roll stimulus exposure (0.03, 0.06, 0.12, 0.25, 0.50 Hz) peaked at 0.25 Hz.

1.4 Research gaps

1.4.1 Frequency response in fore-and-aft vs. roll direction

Diels (2008) showed that visually induced motion sickness was at maximum when stationary subjects were presented with 0.2 Hz oscillating visual stimulus in fore-and-aft direction, which disagreed with Lin *et al.* (2005) results of 0.08 Hz in roll direction. From the view of crossover frequency hypothesis, one possible explanation for the discrepancy is that the frequency response between fore-and-aft and roll direction is fundamentally different. In particular, the frequency response in fore-and-aft direction may have a relatively larger magnitude, thereby crossing the vestibular response curve at a higher frequency. It is therefore possible that the crossover frequency for the response in fore-and-aft direction is higher than that of the roll direction.

However, frequency response of vection and postural disturbance are fundamentally two different types of responses. As well, Berthoz (1979) and Duh *et al.* (2004) study had different apparatus, subjects, display types, and contents of visual stimulus. Therefore, it is difficulty to compare the relative magnitude of these two responses obtained from two different studies on a same scale. No literature has been found in examining *both* vection and postural disturbance frequency response when viewing oscillating visual stimulus in roll *and* in fore-and-aft direction under a single study.

1.4.2 Motion profile of oscillating roll visual stimulus

Duh *et al.* (2004) varied the frequency of visual stimulus roll oscillation by holding peak velocity constant and varying oscillation peak displacement. On the other hand, Previc (1993) held oscillation peak displacement constant in his study. The two studies yielded two different frequency responses of postural disturbance and vection. In Duh *et al.* (2004) study, a low-pass filter characteristic curve was obtained. In Previc (1993) study, postural disturbance and vection frequency response peaked at 0.12 Hz and 0.25 Hz, respectively. The two studies differed fundamentally in their visual stimulus motion profile, in addition to the experimental setup (apparatus, subjects, visual contents, display types). Note that in Previc's (1993) study, the frequency and velocity of the oscillating visual stimulus were confounded (i.e. peak velocity also varied across frequency conditions by keeping peak displacement constant). Thus far, no study has been found in examining the effects of oscillating visual stimulus peak velocity of in the roll direction on postural disturbance and vection.

1.5 Objectives

Motivated by the two research gaps, this thesis attempts to achieve two objectives:

1. To study the frequency response of postural disturbance and vection due to oscillating visual stimulus in fore-and-aft and roll direction, and examine their relative magnitude to each other.

2. To study postural disturbance and vection due to oscillating visual roll stimulus by varying oscillation peak velocity, but holding oscillation frequency constant.

1.6 Hypotheses

H1a: the main effect of visual stimulus frequency (in roll and fore-and-aft direction) on postural disturbance and vection perception is significant

H1b: there is a significant difference in postural disturbance and vection perception magnitude between roll and fore-and-aft direction

H2: the main effect of roll visual stimulus velocity on postural disturbance and vection perception is significant

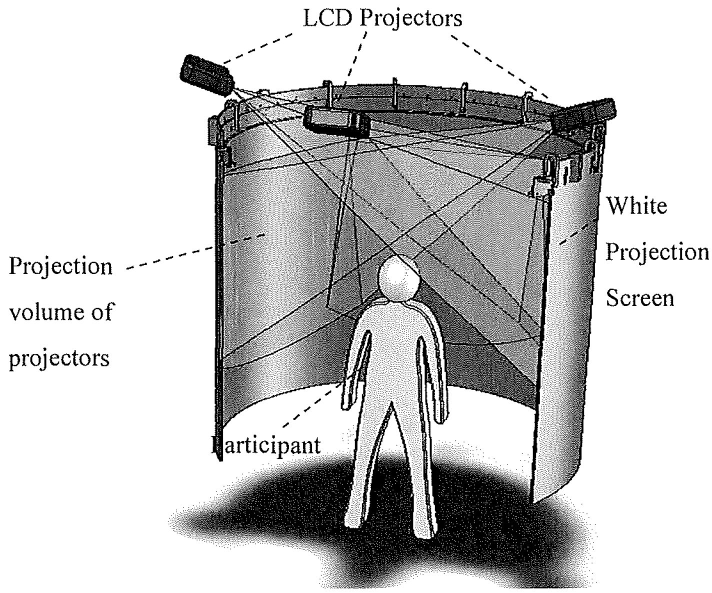
CHAPTER 2: OVERVIEW OF EXPERIMENTAL METHODOLOGY

2.1 Summary

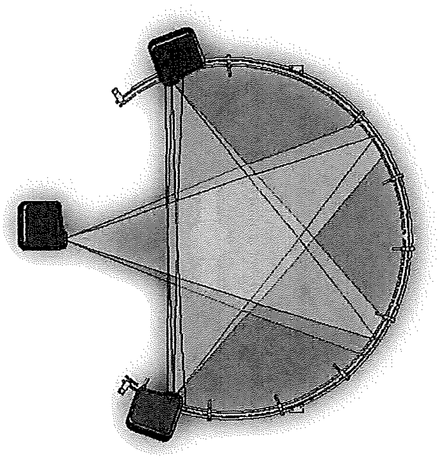
This chapter presents the methods used in the experiments described in the rest of this thesis. The experimental apparatus and visual stimulus will first be described. The methods of measuring postural disturbance and vection will then be presented.

2.2 Apparatus

Figure 2.1 shows the physical layout of the experiment setup located in the Virtual Reality Lab of The Hong Kong University of Science and Technology. Participants stood stationary in front of a cylindrically installed (Diameter: 2.2 meter) white projection screen (DaMatt, Da-Lite Screen Company, Inc., Indiana. Neutral gain: 1.0; Screen dimensions: width 4.6 x height 2.0 meter). The screen covered a wide FOV of 220° (horizontal) x 56° (vertical) at a viewing distance of 1.1 meter. Three NEC LT-380 LCD projectors (NEC, Corp. Maximum resolution: 1024 x 768 pixel, refresh rate: 60 Hz) simultaneously projected three images onto the projection screen.



(a)



(b)

Figure 2.1: (a) Layout of experiment setup, (b) Top view of experiment setup

Each projector was placed 2.5 meters away from the projection screen and 2.8 meters offset from the lab floor. The three projectors were positioned such that three projected images were located side-by-side with each other, with 60 pixels overlapping the adjacent projected image. Edge blending using software was implemented on the 60 pixels of overlapping areas of the visual stimulus image in order to remove any noticeable discontinuity between two adjacent projected images. In addition, the projectors were tilted by 15 degrees from horizontal in order to avoid occlusion of the projectors optics by the participant. Thus, appropriate scaling was performed using software to compensate for keystone distortion of the projected images.

A custom-made goggle which limited the visual field to approximately 200° x 50° was worn by the participants to occlude visual references (the floor, screen edges, etc.) when viewing visual stimulus during the experiments. The goggle has large enough interior space so that participants with corrected-to-normal vision can wear the goggle with glasses on (see Figure 2.2).

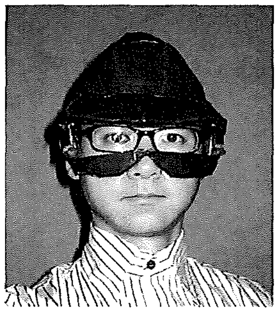


Figure 2.2: Viewing goggle which limits visual field to approximately 200° x 50°

2.3 Visual Stimulus

Visual stimulus was created and rendered using 3D Studio Max 6.0, and playback with Microsoft DirectDraw graphics programming library on a Pentium Core2Duo PC computer with an NVidia GeForce 7600 GT graphics card (NVidia Corporation, USA). The visual stimulus images were sent to a Triplehead2Go module (Matrox Electronic Systems, USA), which simultaneously output three 640 x 480 pixel VGA signals to the three LCD projectors at 60 Hz refresh rate. The visual stimulus was a perspective view inside a long circular tunnel (5 meter radius, 2,000 meter length) with black and white checkerboard patterned interior. For radial spacing there were 8 pairs of black-and-white units (Duh *et al.,* 2004). For linear spacing, there were 50 pairs of black-and-white units distributed evenly along the 2,000 meter tunnel. Figure 2.3 shows a sample frame of the visual stimulus.

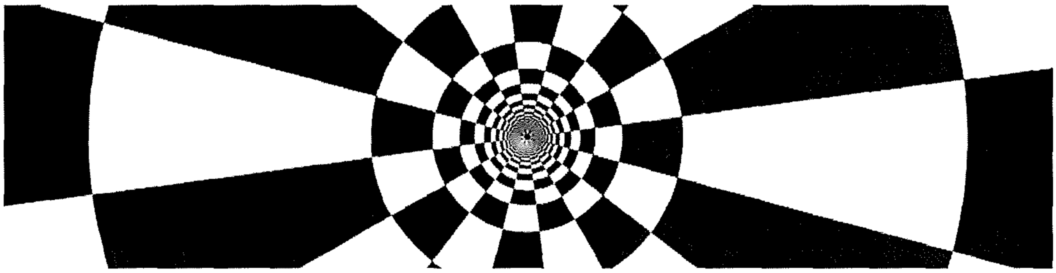


Figure 2.3: Sample frame of the checkerboard patterned tunnel visual stimulus

Due to physical limitation of the experiment setup, the projected image of the tunnel had its center offset by 15 cm above participants' line of sight. Luminance of the white units was 450 lm / m^2, and luminance of the black units was 15 lm / m^2, as measured by a RS 180-7133 light meter (RS Components Ltd., Hong Kong).

2.4 Measures

2.4.1 Postural measures

Postural sway data were collected in experiment using Polhemus 3 Space Fastrack system (Polhemus Inc., USA). The system consisted of two electromagnetic receivers. The first one was located at the crown of the participants' head (Musolino, 2006; Tanahashi, 2007), and was fixated onto a soft plastic swimming hat worn by the participants (see Figure 2.4). The second one was located on the back of the participants' waist (approximate height of center of balance; Mayagoitia, 2002), and was fixated on a belt worn by the participants (see Figure 2.5).

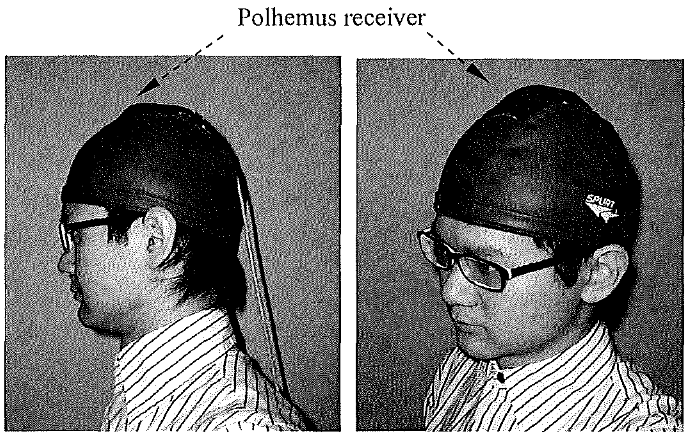


Figure 2.4: Polhemus receiver located on crown of head, fixated onto a soft plastic swimming hat

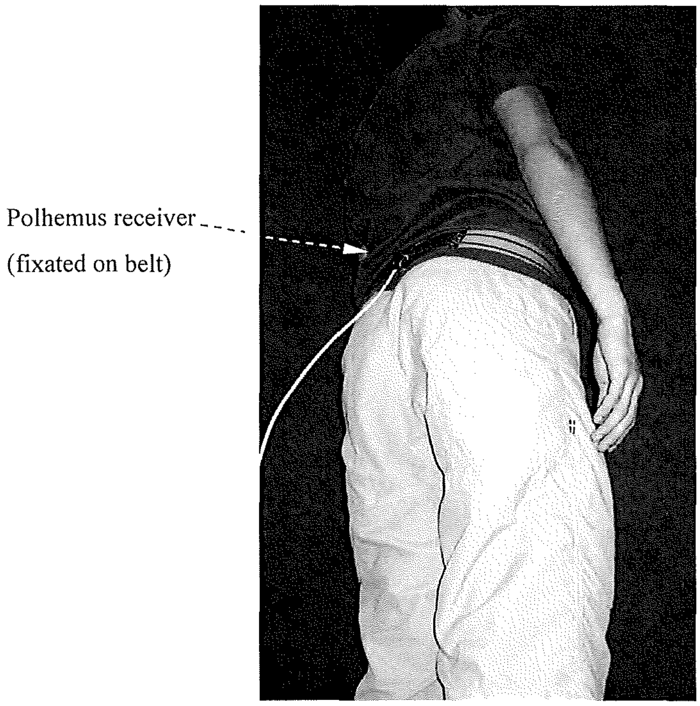


Figure 2.5: Polhemus receiver located on back of the waist, fixated on a belt

An electromagnetic transmitter was located approximately 50 cm from each receiver while the participants viewed the visual stimulus in an upright standing posture. 3-DOF position data of the two receivers were captured and recorded onto a PC at 30-Hz sampling rate and 0.15 degree (0.004 cm) spatial resolution for offline analysis.

Participants were also requested to perform the Sharpened Rhomberg stance (Hamilton and Magee, 1989; Kennedy, 1993; Regan and Price, 1994; Duh and Parker, 2004) immediately after each visual stimulus exposure trial. Participants reported subjective rating of difficulty in maintaining an upright, steady posture while performing the Sharpened Rhomberg on a 10-point scale adopted from Duh *et al.* (2004), as shown in Table 2.1.

Table 2.1: Subjective difficulty in maintaining an upright, stead posture while performing the Sharpened Rhomberg stance (Duh *et al.*, 2004)

1	2	3	4	5	6	7	8	9	10
Very Easy									Very Difficult

2.4.2 Vection measures

Time course of vection were recorded during visual stimulus exposure using a standard PC mouse held in the right hand of the participants. Participants were instructed to press the left mouse button whenever they experienced vection, and keep it pressed for as long as they experienced vection. The mouse sent a binary signal (1 = button pressed, 0 = button not pressed) to a PC, which captured and recorded the signal at 50 Hz sampling rate for offline analysis.

Magnitude of vection perception was measured after each visual stimulus trial.

Participants provided subjective rating on a 7-point scale (see Table 2.2), which was modified on the basis of Webb (2000) and Diels (2008) measure of vection perception.

Table 2.2: 7-point magnitude rating of vection perception

Vection (Perception of Self-Motion)	Rating
I perceive that the only thing oscillating is the visual stimulus and I remain stationary	1
	2
I perceive the visual stimulus to be oscillating, but also experience weak feeling of self-motion	3
	4
I perceive the visual stimulus to be oscillating, but also experience strong feeling of self-motion	5
	6
I perceive that the visual stimulus is stationary, and a strong feeling that I am oscillating	7

2.5 Experiment Design

2.5.1 Independent, dependent, and control variables

In Study 1, the independent variable was the visual scene oscillation frequency. In Study 2, the independent variable is the visual scene oscillation peak velocity. On the other hand, the dependent variables for both Study 1 and Study 2 were postural disturbance (in terms of RMS value of head and body position data; see section 3.4.2.1 for details), time to Sharpened Rhomberg stance break, subjective Sharpened Rhomberg stance difficulty rating, subjective vection perception rating, vection duration and vection onset time. The control variables were the viewing distance and field of view (FOV).

2.5.2 Design of Experiment

Both Study 1 and Study 2 are within-subject experiments. For each visual stimulus condition, there were four dependent repeats for better mean estimation of the dependent measures. In both studies, the order of visual stimulus conditions presentation followed balanced Latin Square design. Detailed procedure of each study will be presented in the respective chapters.

2.5.3 Internal, Construct, and External Validities

2.5.3.1 Internal Validity

Internal validity is necessary to ensure cause-effect relationship exists between the independent and dependent variables (McBurney, 1994). In the current study, internal validity was achieved in several ways. First, involuntary sway was measured during a baseline period during which participants viewed stationary visual stimulus. This was to ensure postural data measured during scene oscillation was indeed postural disturbance caused by the visual stimulus, but not involuntary body sway. As well, each participant was taught and understood the feeling of vection before the experiment began, to ensure that vection reported during the visual stimulus trail were valid.

Although it is acknowledged that there are co-founding factors, various measures were taken to minimize co-founding effect of these factors that may weaken the internal validity of the current study. The order of presentation were balanced Latin square to rid of any possible learning effect. All participants performed the experiment in the same lab. The lab was air-conditioned to the same temperature level for all participants. As well, the amount of background noise and lighting were consistent across all participants. The visual stimulus was adjusted to achieve consistent amount of offset above the subjects' line of sight. Since the experiments required participants to perform Sharpened Rhomberg stance, enough rest was provided for each and every participant to minimize the co-founding of feet tiredness. In addition, for each visual stimulus condition, four dependent repeats were performed for better mean estimation of Sharpened Rhomberg stance performance and to minimize the co-founding effect of accidental fall.

2.5.3.2 Construct Validity

Construct validity ensures that the results support the theory behind the current research (McBurney, 1994). Construct validity was achieved in the current study as part of Study 1 was repeating Duh *et al.* (2004) experiment which successfully showed that frequency of visual stimulus oscillation has a significant effect on postural disturbance. The rest of Study 1 and Study 2 were an extension of Duh *et al.* (2004)'s work..

2.5.3.3 External Validity

External validity states how well the findings of an experiment generalize to other situation or populations (McBurney, 1994). For the current study, participants were randomly recruited Hong Kong Chinese people. The scope of generalization was limited to the same geographic region and cultural background, which was also the case in Duh *et al.* (2004)'s study conducted in North America.

CHAPTER 3

STUDY 1 - FREQUENCY RESPONSE OF POSTURAL DISTURBANCE AND VECTION IN ROLL AND FORE-AND-AFT DIRECTION

3.1 Summary

This chapter describes an experiment in which the frequency response of postural disturbance and vection when viewing oscillating fore-and-aft and roll visual stimulus were investigated. Recent studies have showed evidence of disagreements between frequency responses to fore-and-aft and roll oscillating visual stimulus. The current experiment confirmed the low-pass characteristic of postural disturbance and vection frequency response with previous studies. The current study also showed that postural disturbance and vection frequency response magnitude do not significantly differ between roll and fore-and-aft visual stimulation.

3.2 Participants

Ten healthy Hong Kong Chinese participants (6 male and 4 female; mean age = 26.5) participated in the study. All participants were measured for their height and foot dimensions, and were tested for visual acuity by an Optec2000 Vision Tester (Stereo Optical Corp.) at far test distance (20 feet). All participants had normal or corrected-to-normal vision. Each participant was paid HK$50.0 per hour as compensation for his / her time for participating the experiment. In addition, all participants completed the Motion Sickness Susceptibility Survey (So *et al.*, 1999), as shown in Appendix C. See Appendix D for measurement records of all participants, and Appendix E for participants' responses of the Motion Sickness Susceptibility Survey.

3.3 Procedure

Prior to the experiment, all participants read the experimental procedure (see Appendix A) and signed a consent form (see Appendix B). Participants were requested to remove their shoes and put on a pair of cotton sport socks provided by the experimenter. All participants learnt and practiced the Sharpened Rhomberg stance (Hamilton and Magee, 1989; Kennedy, 1993; Regan and Price, 1994; Duh and Parker, 2004): standing upright, heel-to-toe, arm-folded, eyes-closed, and attempted to maintain a steady, upright posture. Learning and practice of the Sharpened Rhomberg stance was conducted systematically according to the flowchart shown in Figure 3.1.

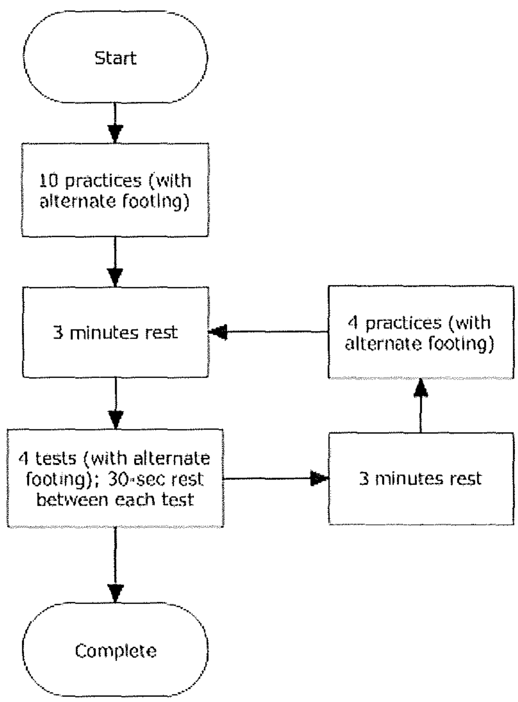


Figure 3.1: Learning and practice procedure of Sharpened Rhomberg stance flow chart

Participants also learnt and understood the sensation of vection by viewing continuously moving checkerboard patterned tunnel (described in Chapter 2) in roll (constant 30°/sec) and fore-and-aft (constant 27m/s) direction for one minute. Note that the velocity of visual stimulus in fore-and-aft and roll visual direction were designed to be consistent, in that there were same number of black-and-white contrast cycle passing thru a reference line per unit time. For roll velocity of 30°/sec, there were approximately 0.7 black-and-white contrasting cycles passing thru the projected image vertical per second. For fore-and-aft movement, linear velocity of 27 m/s also resulted in approximately 0.7 black-and-white contrast cycles passing thru the edges of the projected image per second.

Finally, participants were allowed to rest on a chair for 5 minutes to rid of any feet fatigue (from Sharpened Rhomberg stance practice sessions) or aftereffect of vection.

The experiment was a within-subject design. Each participant viewed visual stimulus oscillating in two directions (roll and fore-and-aft), with five different frequencies for each direction. All participants viewed roll and fore-and-aft oscillating visual stimulus in two separate sessions in balanced order, with at least 24 hours between each session to limit any bias caused by habituation to the stimulus. Moreover, the two sessions took place at approximately the same time of day in order to avoid possible circadian rhythm effects. During each session, participants viewed sinusoidal-oscillating visual stimulus at five different frequencies: 0.05, 0.1, 0.2, 0.4, and 0.8 Hz (Duh *et al.*, 2004). Peak oscillation velocity of the oscillation was 70°/sec for roll visual stimulus (Duh *et al.*, 2004) and 63 m/s for fore-and-aft visual stimulus. Again, the velocity of visual stimulus in fore-and-aft and roll visual direction were designed to be consistent, in that there were same number of black-and-white contrast cycles passing thru a reference line on the projected image per oscillation period.

All participants completed the five conditions on a Latin square design that was balanced for possible immediate sequential learning effect (Bradley, 1958; Sharma, 1975). There were four repeated trials for each frequency condition, so that postural disturbance measures and vection scores were averaged for data analysis to obtain better estimations (Halmiton, 1989; Previc, 1993). Each trial lasted 60 seconds. Sequence of each 60-second trial is described in Table 3.1.

Table 3.1: Sequence of trial

	Duration	**Task**
Baseline	10 seconds	Viewing of stationary checkerboard patterned tunnel image in classic Rhomberg position (feet pressed together, hands on the side)
Exposure	20 seconds*	Viewing of oscillating checkerboard patterned tunnel in classic Rhomberg position
Sharpened Rhomberg (eyes closed)	30 seconds	Perform Sharpened Rhomberg stance, and attempt to maintain steady, upright posture; stop upon stance break (when either one foot moved) or at 30 second (Kennedy, 1993; Regan and Price, 1994)

*While Duh *et al.* (2004) used 10-second visual stimulus exposure time, the current study uses 20 seconds for two reasons. First, it provides enough time for at least one complete oscillation cycle for all frequency conditions. Second, in a pilot study, 50% subjects failed to perceive vection within 10 seconds when viewing 0.1, 0.2, and 0.4 Hz oscillating visual stimulus in both roll and fore-and-aft directions, but these subjects started to perceive vection between 10 to 20 seconds in about 70% of all trials.

A stop watch was used to time the number of seconds to reach Sharpened Rhomberg stance break (when either one foot moved). The feet position of the Sharpened Rhomberg stance (left-foot-front or right-foot-front) alternated on each trial, and the sequence of alternation balanced across subjects (Hamilton *et al.*, 1989). There was at least 60 seconds of separation between each trial. During this period, if participants reported feet fatigue or nausea, longer rest was allowed until both sensations disappeared.

3.4 Results

For all postural disturbance and vection measures, data which did not pass normality test were transformed using Box-Cox method. Data (either in its original form or after Box-Cox transformed) that passed the normality test were analyzed using ANOVA for main effects. SNK grouping of frequency conditions was also performed on these data. In contrast, data that could not pass the normality test after Box-Cox transformation were analyzed using Friedman test, Kruskal-Wallis test, and Wilcoxon non-parametric test. In addition to visual stimulus frequency, the possible effect of gender was also examined, as Chen (2006)'s work showed that gender is a significant effect on vection perception under VR exposure. All data analysis was performed using SAS 8.0 and SPSS 10.0.

Four repetitions were performed for each and every frequency condition to obtain a better mean estimate of postural disturbance and vection measures. Thus, the effect of repetition was not analyzed.

3.4.1 Order Effect

To determine whether order effect was present, Pearson correlation test between the visual stimulus presentation order and all postural and vection measures were performed. A summary of test statistics of Pearson correlation test is shown on Table 3.2. Clearly, there was no apparent correlation between the presentation order and any of the postural and vection measure. Hence, presentation order effect was not present.

Table 3.2: Summary of Pearson Correlation Coefficient between visual stimulus presentation order and all postural and vection measure for (a) Roll visual stimulus session, and (b) Fore-and-aft visual stimulus session

(a) Roll visual stimulus session

Measure	Pearson Correlation Coefficient (p-value)
RMS value of head position data	-0.08895 (p=0.5390)
RMS value of body position data	-0.01995 (p=0.8906)
Balance difficulty score	0.06107 (p=0.6735)
Time to SR stance break	-0.09989 (p=0.4901)
Vection perception magnitude	0.11219 (p=0.4379)
Vection duration	-0.01020 (p=0.9440)
Vection onset time	0.03455 (p=0.8117)

(b) Fore-and-aft visual stimulus session

Measure	Pearson Correlation Coefficient (p-value)
RMS value of head position data	-0.18478 (p=0.1989)
RMS value of body position data	-0.12874 (p=0.3729)
Balance difficulty score	0.08489 (p=0.5578)
Time to SR stance break	-0.20690 (p=0.1494)
Vection perception magnitude	-0.01743 (p=0.9044)
Vection duration	-0.14885 (p=0.3022)
Vection onset time	0.02184 (p=0.8804)

3.4.2 Postural disturbance measures

All trajectory plots of head and body displacement are shown in Appendix F. Figure 3.2 shows an example trajectory plot of head displacement (Subject XYU) when viewing (a) oscillating roll visual stimulus and (b) fore-and-aft visual stimulus.

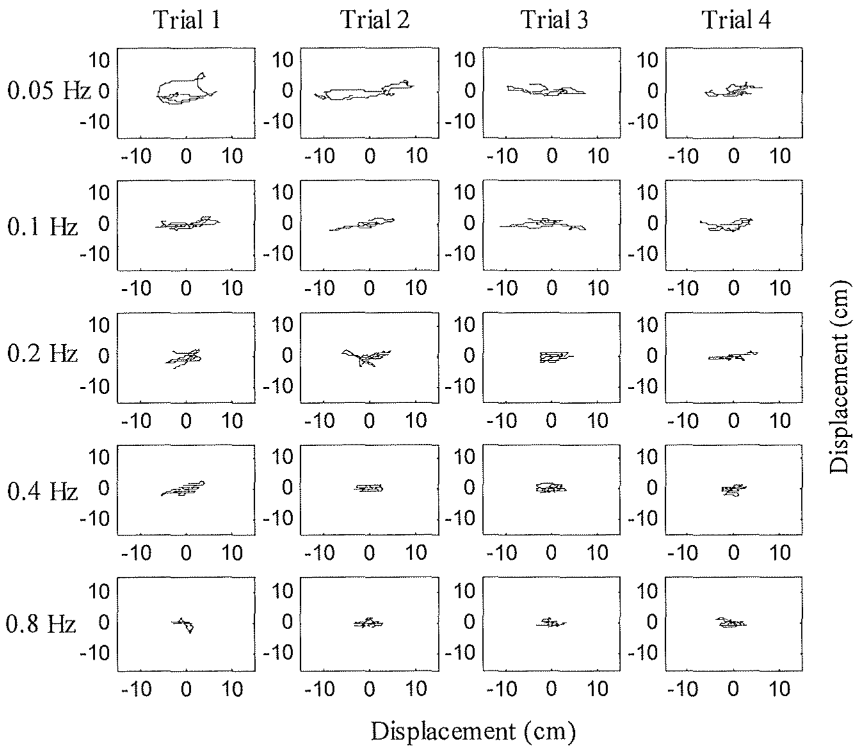


Figure 3.2 (a) Head displacement trajectory plots (Subject XYU; roll stimulus)

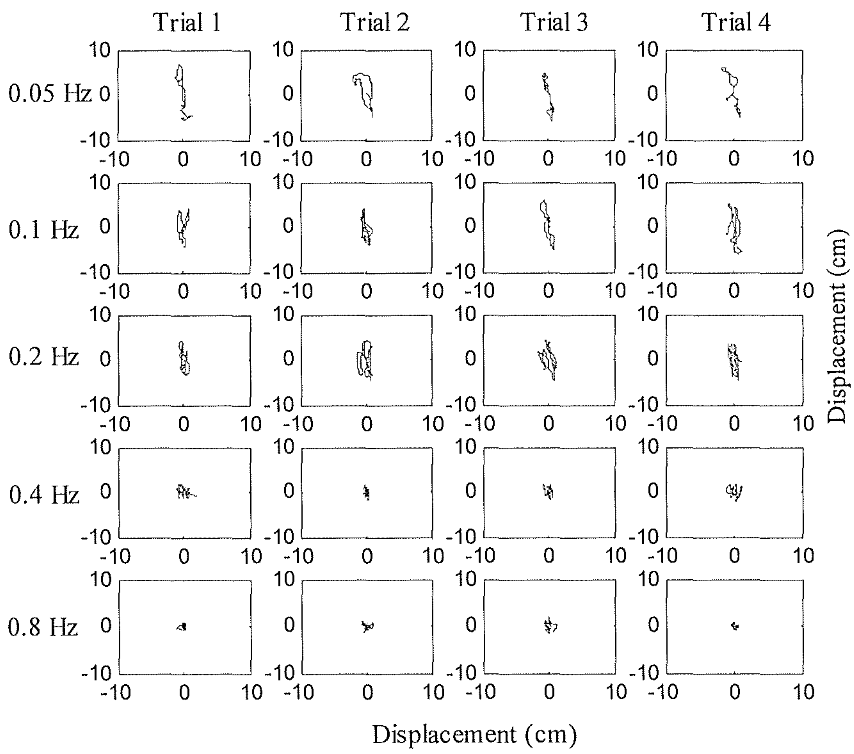


Figure 3.2 (b) Head displacement trajectory plots (Subject XYU; fore-and-aft stimulus)

3.4.2.1 RMS value of head position data

For each electromagnetic receiver, time series of position data in anterior-posterior (AP) and medial-lateral (ML) directions were first filtered with a 4th order Butterworth low-pass filter (cutoff frequency at 5.0Hz) using MATLAB 7.0. Postural disturbance measure was then determined by computing the RMS value of the sway time series (Prieto *et al.*, 1996; Previc, 2003) using equation (1) to (4).

$$\overline{AP} = \frac{1}{N}\sum AP_o[n], \quad \overline{ML} = \frac{1}{N}\sum ML_o[n] \qquad (1)$$

$$AP[n] = AP_o[n] - \overline{AP}, \quad ML[n] = ML_o[n] - \overline{ML} \qquad (2)$$

$$RD[n] = \sqrt{AP[n]^2 + ML[n]^2} \qquad \text{n} = 1,\ldots,\text{N} \qquad (3)$$

$$RDIST = \sqrt{\frac{1}{N}\sum RD[n]^2} \qquad (4)$$

First, $AP_o[n]$ and $ML_o[n]$ were the filtered time series data. Time series mean, $\overline{AP}$ and $\overline{ML}$, were computed from the filtered sway time series with equations (1). Then, $AP_o[n]$ and $ML_o[n]$ were referenced to the time series mean using equations (2). The resultant distance time series $RD[n]$ (equation 3) is the vector distance from the time series mean to each pair of N points in the $AP_o[n]$ and $ML_o[n]$ time series. Finally, the rms distance (*RDIST*) value of the time series was computed by equation (4).

RMS value of the time series for exposure period and baseline period were computed separately. Due to large inter- and intra-participant variability, RMS values were normalized for each trial: RMS value of exposure period was divided by RMS value of the baseline period. The normalized RMS values obtained from four trials were averaged for each and every frequency condition.

Normalized RMS values of head position time series data for 10 participants are plotted in Figure 3.3 and Figure 3.4 for roll and fore-and-aft visual stimulus session, respectively. Mean normalized RMS values of ten participants did not pass Shapiro-Wilk normality test ($p < .0001$) for both roll and fore-and-aft visual stimulus session. The data were transformed using Box-Cox method (λ = -0.75 for roll session and -1.0 for fore-and-aft session data), and achieved data normality (p = 0.1303 for roll session and p = 0.1701 for fore-and-aft session).

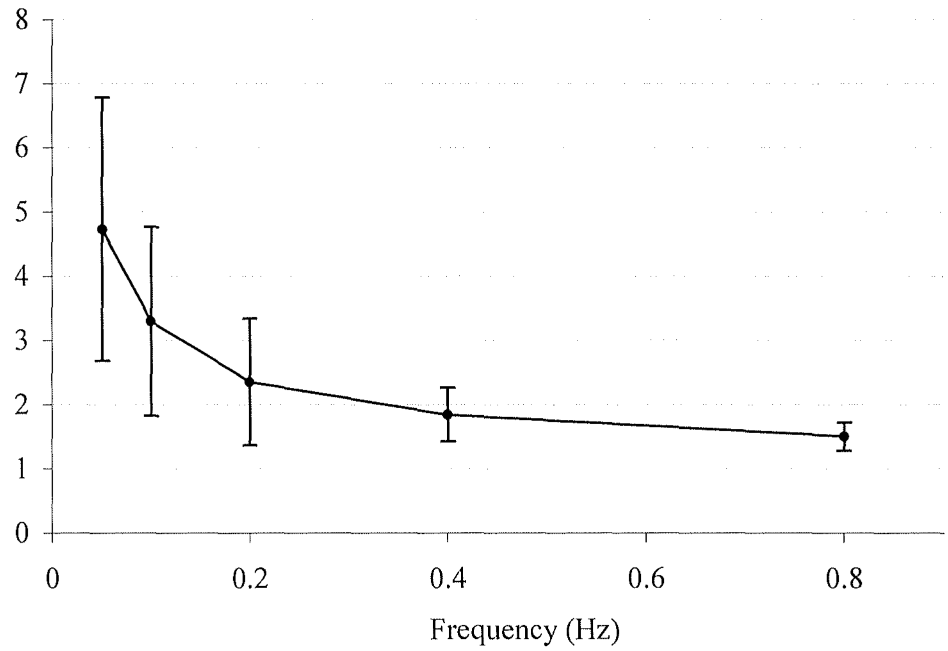


Figure 3.3: Mean (±S.D.) normalized RMS value of head position time series data as a function of roll visual stimulus frequency

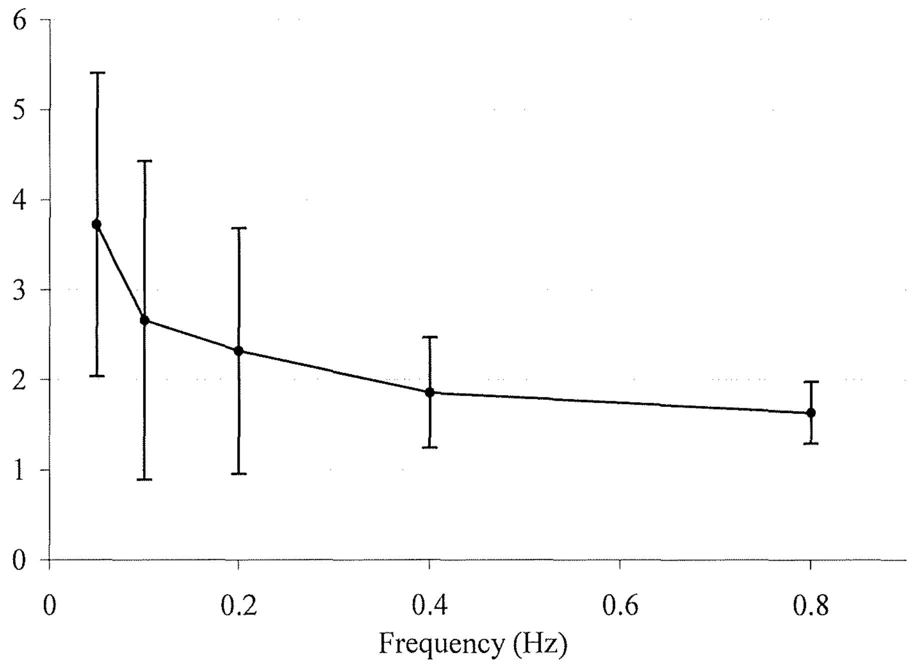


Figure 3.4: Mean (±S.D.) normalized RMS value of head position time series data as a function of fore-and-aft visual stimulus frequency

ANOVA (Table 3.3 and Table 3.4) performed on the Box-Cox transformed data showed significant main effect of visual stimulus frequency for roll session ($F_{4,40} = 15.37$, $p < .0001$), and fore-and-aft session ($F_{4,40} = 4.25$, $p = 0.006$). On the other hand, gender and its interaction term were not significant main effect.

Table 3.3: ANOVA on RMS value of head position data (Box-Cox transformed) analyzing the effect of roll visual stimulus frequency and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Frequency	4	0.9802	0.2451	15.37	<.0001
Gender	1	0.0594	0.0594	3.73	0.061
Frequency*Gender	4	0.0197	0.0049	0.31	0.870
Error	40	0.6375	0.0159		
Total	49	1.6969			

Table 3.4: ANOVA on RMS value of head position data (Box-Cox transformed) analyzing the effect of fore-and-aft visual stimulus frequency and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Frequency	4	0.5663	0.1416	4.25	0.006
Gender	1	0.0600	0.0597	1.79	0.188
Frequency*Gender	4	0.0430	0.0108	0.32	0.861
Error	40	1.3338	0.0333		
Total	49	2.0029			

Grouping and ordering of the frequency conditions for roll and fore-and-aft visual stimulus session data revealed by Student-Newman-Keuls test are shown in Table 3.5 and Table 3.6.

Table 3.5: SNK tests indicating the effect of roll visual stimulus frequency on RMS value of head position data (Box-Cox transformed)

SNK Grouping		Mean	N	Frequency
	A	0.3473	10	0.05
B	A	0.4609	10	0.1
B	C	0.5728	10	0.2
D	C	0.6506	10	0.4
D		0.7462	10	0.8

Table 3.6: SNK tests indicating the effect of fore-and-aft visual stimulus frequency on RMS value of head position data (Box-Cox transformed)

SNK Grouping		Mean	N	Frequency
	A	0.3262	10	0.05
B	A	0.5025	10	0.1
B	A	0.5180	10	0.2
B		0.5853	10	0.4
B		0.6410	10	0.8

3.4.2.2 RMS value of body position data

Normalized RMS values of body position time series data for 10 participants are plotted in Figure 3.5 and Figure 3.6 for roll and fore-and-aft visual stimulus session, respectively.

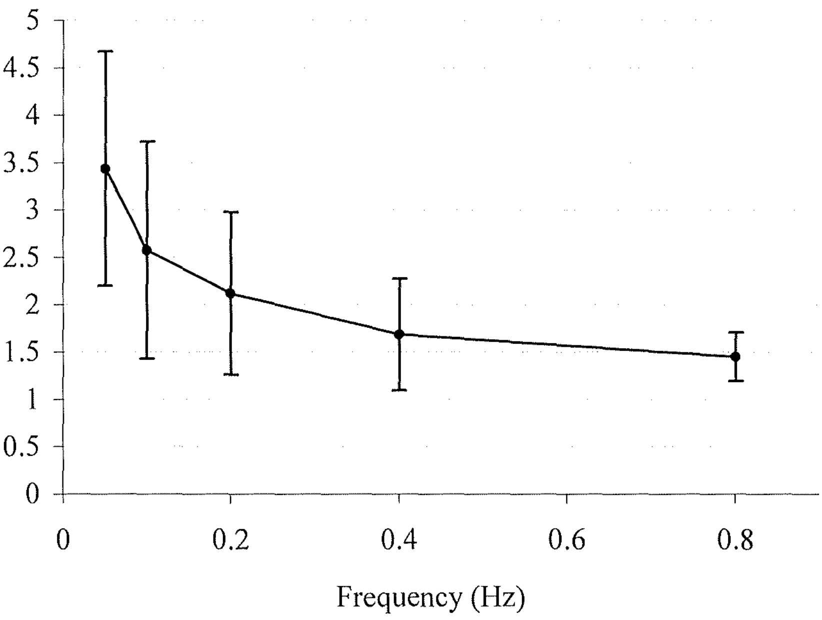


Figure 3.5: Mean (±S.D.) normalized RMS value of body position time series data as a function of roll visual stimulus frequency

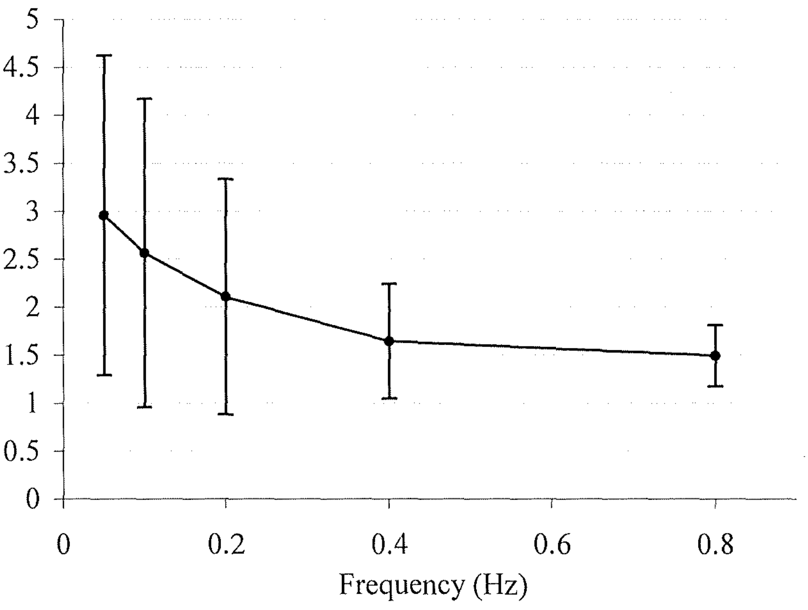


Figure 3.6: Mean (±S.D.) normalized RMS value of body position time series data as a function of fore-and-aft visual stimulus frequency

Data for both sessions did not pass Shapiro-Wilk test of normality, and were transformed using Box-Cox method (λ = -1.0 for both roll and fore-and-aft session data), and achieved data normality (Shapiro-Wilk test: p = 0.0717 for roll session, and p = 0.1347 for fore-and-aft session)..

ANOVA (Table 3.7 and Table 3.8) performed on the Box-Cox transformed data showed significant main effect of visual stimulus frequency for roll session ($F_{4,40} = 9.42$, $p < .0001$), but not for fore-and-aft session ($F_{4,40} = 2.03$, $p = 0.1085$). Gender and its interaction term were not significant main effect.

Table 3.7: ANOVA on RMS value of body position data (Box-Cox transformed) analyzing the effect of roll visual stimulus frequency and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Frequency	4	0.9006	0.2251	9.42	<.0001
Gender	1	0.0562	0.0562	2.35	0.1330
Frequency*Gender	4	0.0723	0.0181	0.76	0.5601
Error	40	0.9565	0.0239		
Total	49	1.9857			

Table 3.8: ANOVA on RMS value of body position data (Box-Cox transformed) analyzing the effect of fore-and-aft visual stimulus frequency and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Frequency	4	0.4147	0.1037	2.03	0.1085
Gender	1	0.0982	0.0982	1.92	0.1731
Frequency*Gender	4	0.0264	0.0066	0.13	0.9708
Error	40	2.0420	0.0511		
Total	49	2.5814			

Grouping and ordering of the frequency conditions for roll visual stimulus session data revealed by Student-Newman-Keuls test are shown in Table 3.9.

Table 3.9: SNK tests indicating the effect of roll visual stimulus frequency on RMS value of body position data (Box-Cox transformed)

SNK Grouping		Mean	N	Frequency
	A	0.3473	10	0.05
B	A	0.4609	10	0.1
B	C	0.5728	10	0.2
D	C	0.6506	10	0.4
D		0.7462	10	0.8

Table 3.10 shows the Wilcoxon Signed Rank test (p-values) on postural disturbance (RMS value of body movement data) for each and every frequency condition for fore-and-aft visual stimulus session.

Table 3.10: Summary of Wilcoxon Signed Rank test (*p*-values) on postural disturbance (RMS value of body movement data) for all fore-and-aft visual stimulus frequency conditions

Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
0.05	x				
0.1	*p*=0.2754	x			
0.2	0.0195*	0.0273*	X		
0.4	0.0059*	0.0098*	0.0840	x	
0.8	0.0098*	0.0488*	0.0840	0.6953	x

*significant at the 0.05 level

It is clear from Table 3.10 and Figure 3.6 that both 0.05 and 0.1 Hz frequency conditions have significantly higher postural disturbance than that of all other frequency conditions (0.2 to 0.8 Hz). Difference between all other frequency conditions did not reach the level of significance.

3.4.2.3 Sharpened Rhomberg stance performance

Sharpened Rhomberg stance performance was measured by the number of seconds a participant was able to maintain the stance without moving his / her feet in each trial (Hamilton *et al.*, 1989; Kennedy *et al.* 1996), with a maximum of 30 seconds. Sharpened Rhomberg stance performance obtained from four trials were averaged for each and every frequency condition. Performance of 10 participants are plotted in Figure 3.7 (roll visual stimulus session) and Figure 3.8 (fore-and-aft visual stimulus session) as a function of visual stimulus oscillation frequency.

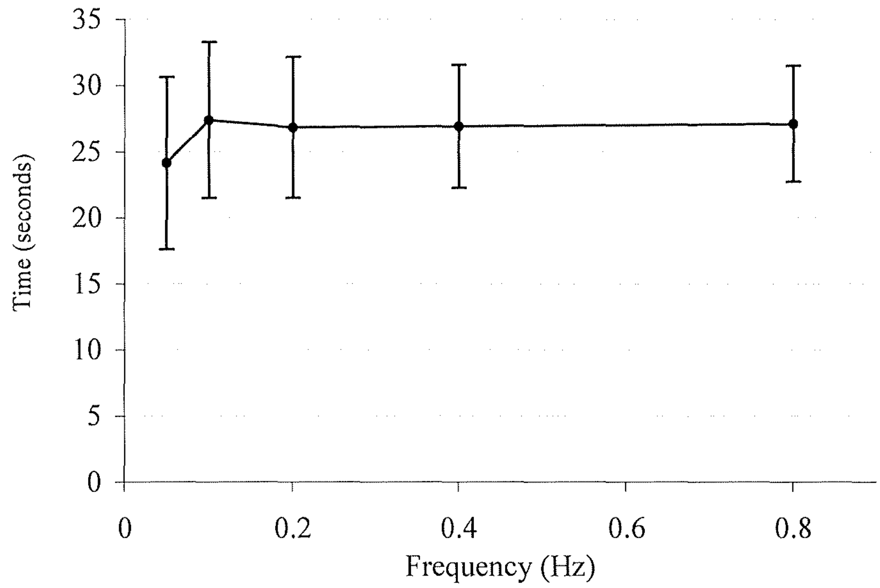


Figure 3.7: Mean (±S.D.) time to Sharpened Rhomberg stance break as a function of roll visual stimulus frequency

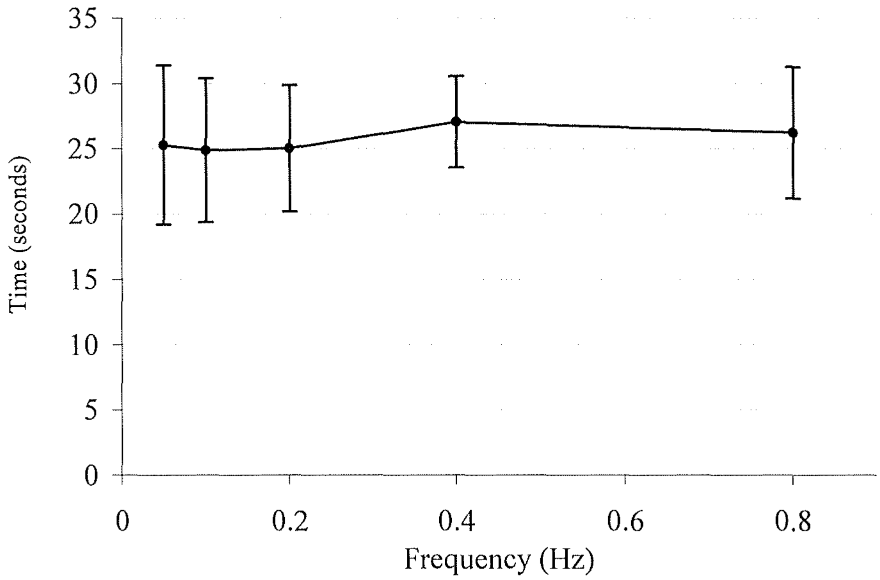


Figure 3.8: Mean (±S.D.) time to Sharpened Rhomberg stance break as a function of fore-and-aft visual stimulus frequency

The data for both roll and fore-and-aft visual stimulus session did not pass the Shapiro-Wilk normality test ($p < 0.0001$). Box-Cox transformation was performed on the data but did not achieve normality ($p < 0.0001$).

Friedman's non-parametric rank test was applied on the original data and confirmed the lack of significant effect of visual stimulus frequency for both roll ($F = 9.073$, *d.f.* = 4, $p = 0.060$) and fore-and-aft ($F = 3.473$, *d.f.* = 4, $p = 0.482$) visual stimulus sessions. In addition, Kruskal-Wallis test failed to show difference in mean time to Sharpened Rhomberg stance break between the two gender groups for both roll (Chi-square =2.286, *d.f.* = 1, $p = 0.131$) and fore-and-aft (Chi-square = 1.798, *d.f.* = 1, $p = 0.180$) session.

Table 3.11 and Table 3.12 shows the rank scores of all frequency condition resulted from Wilcoxon Signed Rank test (*p*-values) and Friedman's ranking on all frequency conditions.

Table 3.11: Time to Sharpened Rhomberg stance break rank scores and summary of Wilcoxon Signed Rank test (*p*-values) for roll visual stimulus frequency conditions

Sum of ranks (Friedman)	Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
19.0	0.05	x				
34.5	0.1	p=0.0078*	x			
33.0	0.2	0.1484	1.0000	x		
31.5	0.4	0.2500	0.8438	1.0000	x	
32.0	0.8	0.2422	0.6875	0.8125	0.8438	x

*significant at the 0.05 level

Table 3.12: Time to Sharpened Rhomberg stance break rank scores and summary of Wilcoxon Signed Rank test (*p*-values) for fore-and-aft visual stimulus frequency conditions

Sum of ranks (Friedman)	Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
31.0	0.05	x				
27.5	0.1	p=0.8438	x			
24.0	0.2	0.9219	0.9102	x		
34.5	0.4	0.4688	0.0781	0.1875	x	
33.0	0.8	0.7188	0.5781	0.2422	0.6094	x

For roll visual stimulus session, time to Sharpened Rhomberg stance break for 0.05 Hz condition (average 24.12 seconds) is significantly lower than that of 0.1 Hz condition (average 27.39 seconds). For all other conditions, none of the differences reached the required statistical significance. For fore-and-aft visual stimulus session, the differences between all frequency conditions were not statistically significant.

A possible explanation for the lack of significant result in Sharpened Rhomberg stance break time is that this measure was traditionally used for testing balance disturbance after prolonged period of visual stimulus exposure. For example, Hamilton (1989)'s experiment had 6 minutes of simulator exposure, and Kennedy (1996)'s experiment had two hours of simulator exposure. In the current study, the amount of postural disturbance subjects experienced *after* 10 seconds of visual stimulus exposure might not always be able to cause enough balance disturbances for subjects to break the Sharpened Rhomberg stance. Nevertheless, the postural disturbance measured *during* the 20 seconds of visual stimulus exposure, as we saw in previous sections, is significantly different across frequency conditions.

3.4.2.4 Balance difficulty rating of Sharpened Rhomberg stance

Subjective ratings of balance difficulty in performing the Sharpened Rhomberg stance obtained from four trials were averaged for each and every frequency condition. Mean balance difficulty rating of 10 participants are plotted in Figure 3.9 (roll visual stimulus session) and Figure 3.10 (fore-and-aft visual stimulus session) as a function of oscillation frequency.

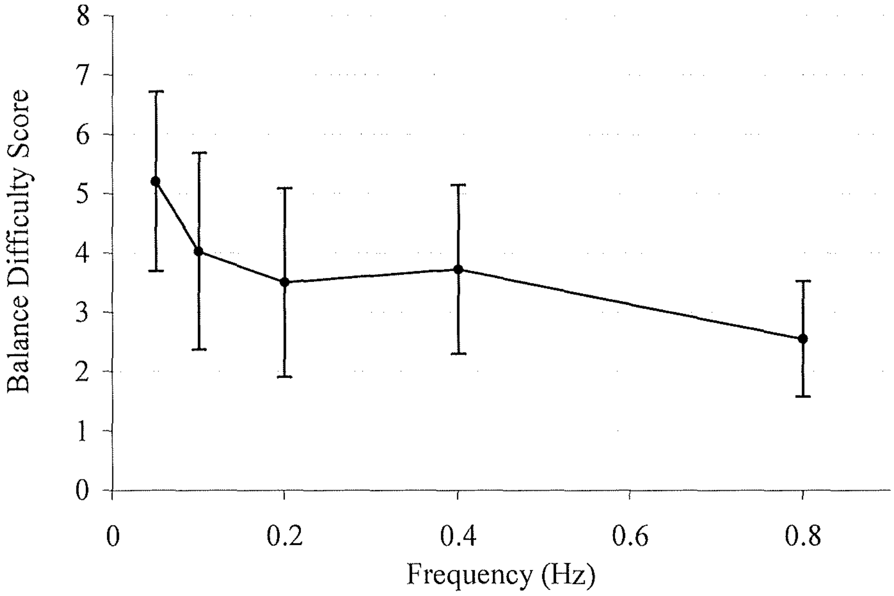


Figure 3.9: Mean (±S.D.) subjective balance difficulty rating as a function of roll oscillation frequency

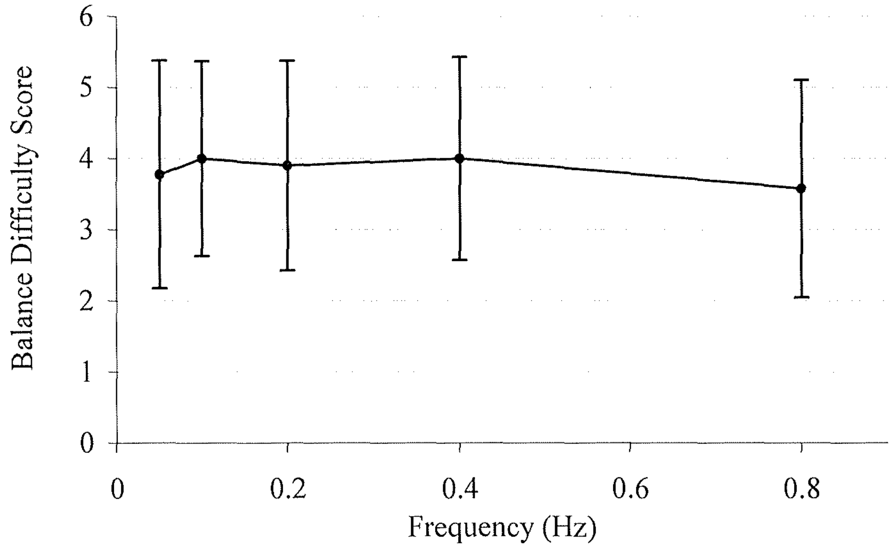


Figure 3.10: Mean (±S.D.) subjective balance difficulty rating as a function of fore-and-aft oscillation frequency

Data for fore-and-aft visual stimulus session passed the Shapiro-Wilk normality test ($p = 0.0674$), but not for roll visual stimulus session ($p = 0.0173$). Box-Cox transformation was performed on roll visual stimulus session data, and successfully achieved data normality (Shapiro-Wilk test: $p = 0.5971$ for roll session, and $p = 0.1896$ for fore-and-aft session).

ANOVA (Table 3.13 and Table 3.14) showed significant main effect of visual stimulus frequency for roll session ($F_{4,40} = 4.46$, $p = 0.0045$), but not for fore-and-aft session ($F_{4,40} = 0.13$, $p = 0.9696$). Gender was not a significant main effect.

Table 3.13: ANOVA on Sharpened Rhomberg stance balance difficulty score (Box-Cox transformed) analyzing the effect of roll visual stimulus frequency and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Frequency	4	0.32919	0.08230	4.46	0.0045
Gender	1	0.00040	0.00040	0.02	0.8837
Frequency*Gender	4	0.03855	0.00964	0.52	0.7197
Error	40	0.73796	0.01845		
Total	49	1.10610			

Table 3.14: ANOVA on Sharpened Rhomberg stance balance difficulty score analyzing the effect of fore-and-aft visual stimulus frequency and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Frequency	4	1.28750	0.32188	0.13	0.9696
Gender	1	0.18750	0.18750	0.08	0.7827
Frequency*Gender	4	1.49375	0.37344	0.15	0.9603
Error	40	97.28125	2.43203		
Total	49	100.25000			

Grouping and ordering of the frequency conditions for roll visual stimulus session data revealed by Student-Newman-Keuls test are shown in Table 3.15.

Table 3.15: SNK tests indicating the effect of roll visual stimulus frequency on Sharpened Rhomberg stance balance difficulty score (Box-Cox transformed)

SNK Grouping		Mean	N	Frequency
	A	5.20	10	0.05
B	A	4.03	10	0.1
B	A	3.50	10	0.2
B	A	3.73	10	0.4
B		2.55	10	0.8

Table 3.16 shows a summary of Wilcoxon Signed Rank test results (p-values) of all fore-and-aft visual stimulus frequency conditions. Clearly, none of the difference in balance difficulty score between frequency conditions reached the required level of significance.

Table 3.16: Summary of Wilcoxon Signed Rank test (*p*-values) on Sharpened Rhomberg stance balance difficulty for fore-and-aft visual stimulus frequency conditions

Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
0.05	x				
0.1	*p*=0.4453	x			
0.2	1.0000	0.9023	x		
0.4	0.5820	1.0000	0.7188	x	
0.8	0.6016	0.1172	0.1133	0.1016	x

There is an obvious disagreement between roll and fore-and-aft visual stimulus session on the amount of postural disturbance subjects experienced immediately after the visual stimulus exposure during Sharpened Rhomberg stance. The Sharpened Rhomberg stance requires subjects to stand with feet aligned in anterior-posterior direction, which means the ease of balance in medial-lateral direction is reduced. Therefore, roll visual stimulus, which mainly induces postural disturbance in medial-lateral direction, could increase balance difficulty during Sharpened Rhomberg stance. In contrast, subjective balance difficulty could be less sensitive to fore-and-aft visual stimulus, since such stimulus mainly induce postural disturbance in anterior-posterior direction.

3.4.3 Vection measures

Plots of vection presence time course for all 10 subjects are shown in Appendix H.

3.4.3.1 Magnitude of vection perception

Subjective scores of vection perception magnitude rating from four trials were averaged for each and every frequency condition. Vection magnitude ratings of 10 participants are plotted in Figure 3.11 (roll visual stimulus session) and Figure 3.12 (fore-and-aft visual stimulus session) as a function of oscillation frequency.

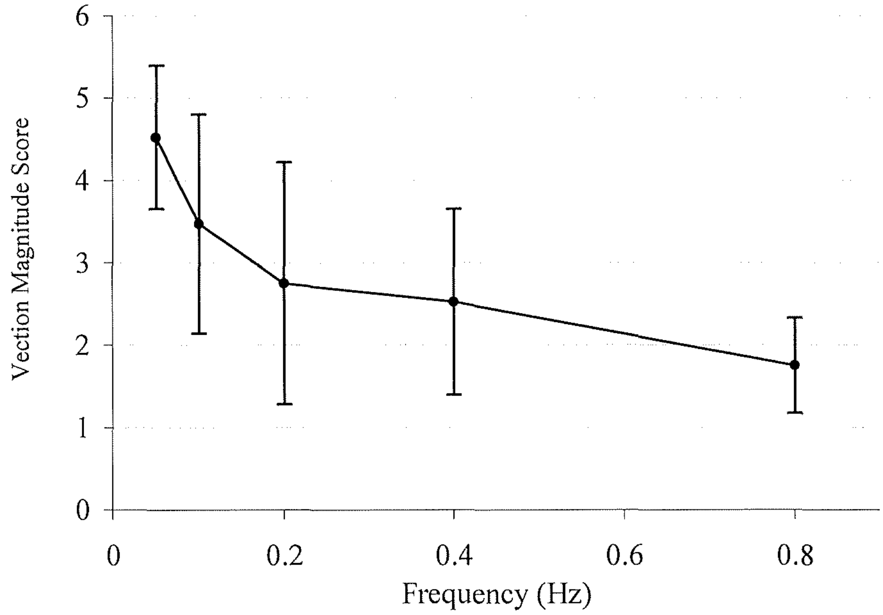


Figure 3.11: Mean (±S.D.) magnitude of vection perception rating as a function of roll oscillation frequency

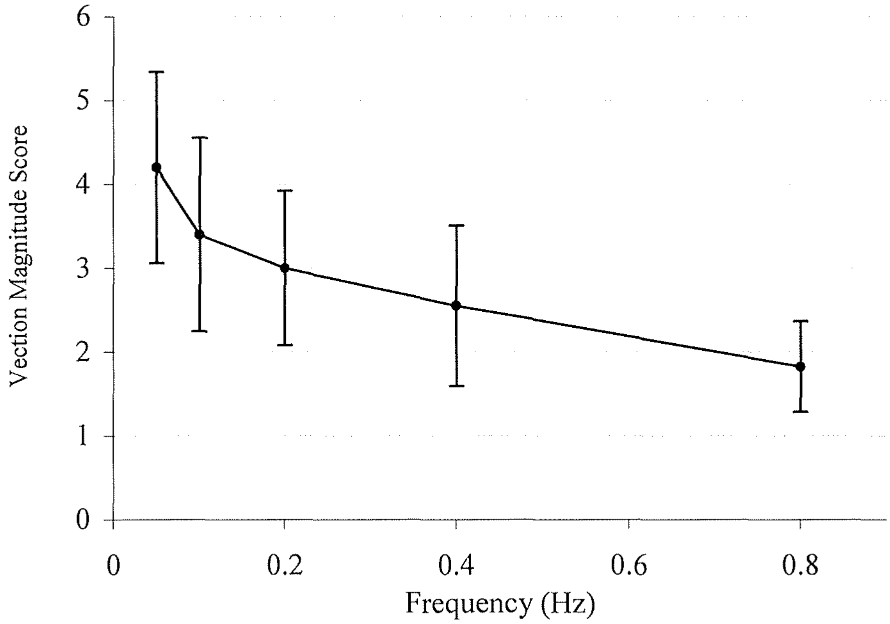


Figure 3.12: Mean (±S.D.) magnitude of vection perception rating as a function of fore-and-aft oscillation frequency

Vection perception magnitude data passed the Shapiro-Wilk normality test for fore-and-aft visual stimulus session (p = 0.2599), but not for roll session data (p = 0.0046). Box-Cox transformations (λ = -0.5) were performed on the roll session data, but could not achieve data normality (Shapiro-Wilk test: p = 0.0159).

Since the data were not normal for roll visual stimulus session, Friedman's non-parametric rank test was applied on the original data set, and showed the significant effect of visual stimulus frequency (F = 25.2240, $p < 0.0001$). On the other hand, Kruskal-Wallis test failed to show difference in mean vection perception magnitude between the two gender groups (Chi-square = 1.8507, $d.f.$ = 1, p = 0.1737).

ANOVA (Table 3.17) showed significant main effect of visual stimulus frequency on fore-and-aft vection data ($F_{4,40}$ = 8.08, p < 0.0001). The effect of gender and its interaction term were not significant.

Table 3.17: ANOVA on vection perception magnitude analyzing the effect of fore-and-aft visual stimulus frequency and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Frequency	4	31.83000	7.95750	8.08	<0.0001
Gender	1	0.11021	0.11021	0.11	0.7397
Frequency*Gender	4	2.73042	0.68260	0.69	0.6011
Error	40	39.39063	0.98477		
Total	49	74.06125			

Table 3.18 shows the rank scores and grouping of frequency condition resulted from Wilcoxon Signed Rank test (p-values) and Friedman's ranking on all frequency conditions.

Table 3.18: Vection perception magnitude rank scores, grouping and summary of Wilcoxon Signed Rank test (p-values) for roll visual stimulus frequency conditions

Sum of ranks (Friedman)	Grouping (Wilcoxon)		Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
46.5	A		0.05	x				
35.5	B		0.1	p=0.0117	x			
27.5	B		0.2	0.0117	0.0977	x		
26.5	B	C	0.4	0.0039	0.0313	0.6328	x	
14.0		C	0.8	0.0020	0.0078	0.0195	0.0156	x

Grouping and ordering of the frequency conditions for fore-and-aft visual stimulus frequency revealed by Student-Newman-Keuls test are shown in Table 3.19.

Table 3.19: SNK test indicating the effect of fore-and-aft visual stimulus frequency on vection perception magnitude (Box-Cox transformed)

SNK Grouping		Mean	N	Frequency
	A	4.20	10	0.05
B	A	3.40	10	0.1
B		3.00	10	0.2
B	C	2.55	10	0.4
	C	1.83	10	0.8

3.4.3.2 Vection onset time

Vection onset time was defined as the time it took for participants to first press the mouse button to indicate vection occurrence. Vection onset time of 10 participants are plotted in Figure 3.13 (roll visual stimulus session) and Figure 3.14 (fore-and-aft visual stimulus session) as a function of oscillation frequency.

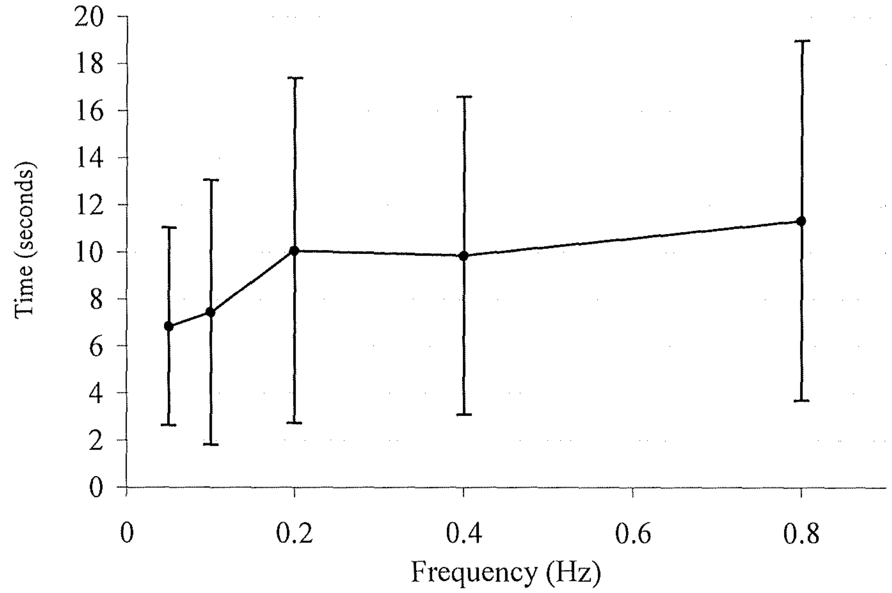


Figure 3.13: Mean (±S.D.) vection onset time as a function of roll oscillation frequency

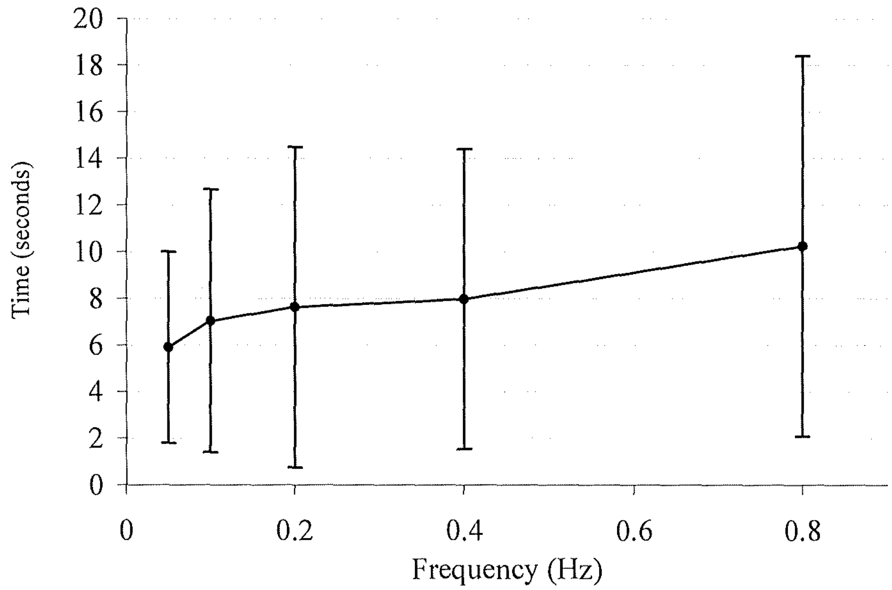


Figure 3.14: Mean (±S.D.) vection onset time as a function of fore-and-aft oscillation frequency

Data for vection onset time did not pass the Shapiro-Wilk normality test ($p < 0.005$). Box-Cox transformations were performed on the data and did not achieve data normality (Shapiro-Wilk test: $p < 0.05$).

Since the data were not normal, Friedman's non-parametric rank test was applied on the original data, and showed the lack of significant effect of frequency for both roll (F = 8.08, *d.f.* = 4, p = 0.0887) and fore-and-aft (F = 0.1633, *d.f.* = 4, p = 0.9968) visual stimulus sessions. Kruskal-Wallis test failed show difference in mean vection onset time between the two gender groups for roll session (Chi-square = 0.83, *d.f.* = 1, p = 0.3623). However, the difference between the two gender in fore-and-aft session data was significant (Chi-square = 6.9925, *d.f.* = 1, p =0.0082), with female having a higher onset time score (see Table 3.20).

Table 3.20: Wilcoxon Scores (Rank Sums) for vection onset time classified by gender

Gender	N	Sum of Rank Scores	Mean Score
F	20	643.50	32.1750
M	30	631.50	21.0500

Further analysis was performed on the data of four female subjects for fore-and-aft session. However, Friedman test showed that the effect of frequency was not significant (F = 8.20, *d.f.* = 4, p = 0.0845) for the four female subjects.

Table 3.21 and Table 3.22 show the rank scores and grouping of frequency condition resulted from Wilcoxon Signed Rank test (p-values) and Friedman's ranking on all frequency conditions for roll and fore-and-aft visual stimulus sessions.

Table 3.21: Vection onset time rank scores and summary of Wilcoxon Signed Rank test (*p*-values) for roll visual stimulus frequency conditions

Sum of ranks (Friedman)	Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
22.0	0.05	x				
23.0	0.1	*p*=0.9219	x			
32.0	0.2	0.0840	0.1309	x		
36.0	0.4	0.0371*	0.1055	0.7695	x	
37.0	0.8	0.0195*	0.1309	0.4922	0.1934	x

*significant at the 0.05 level

Table 3.22: Vection onset time rank scores and summary of Wilcoxon Signed Rank test (*p*-values) for fore-and-aft visual stimulus frequency conditions

Sum of ranks (Friedman)	Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
31.0	0.05	x				
30.0	0.1	*p*=0.7695	x			
29.0	0.2	0.8457	1.0000	x		
29.0	0.4	0.3223	0.4316	0.9219	x	
31.0	0.8	0.2324	0.3594	0.2500	0.4316	x

For roll visual stimulus session, vection onset time for 0.05 Hz condition (average of 6.84 seconds) is significantly lower than that of 0.4 Hz (average of 9.85 seconds) and 0.8 Hz (average of 11.34 seconds) condition. For all other conditions, none of the differences reached statistical significance. For fore-and-aft visual stimulus session, the differences between all frequency conditions were not statistically significant.

3.4.3.3 Vection duration

Vection duration was defined as the percentage of total exposure time that the mouse button was pressed. Vection duration of 10 participants are plotted in Figure 3.15 (roll visual stimulus session) and Figure 3.16 (fore-and-aft visual stimulus session) as a function of visual stimulus oscillation frequency.

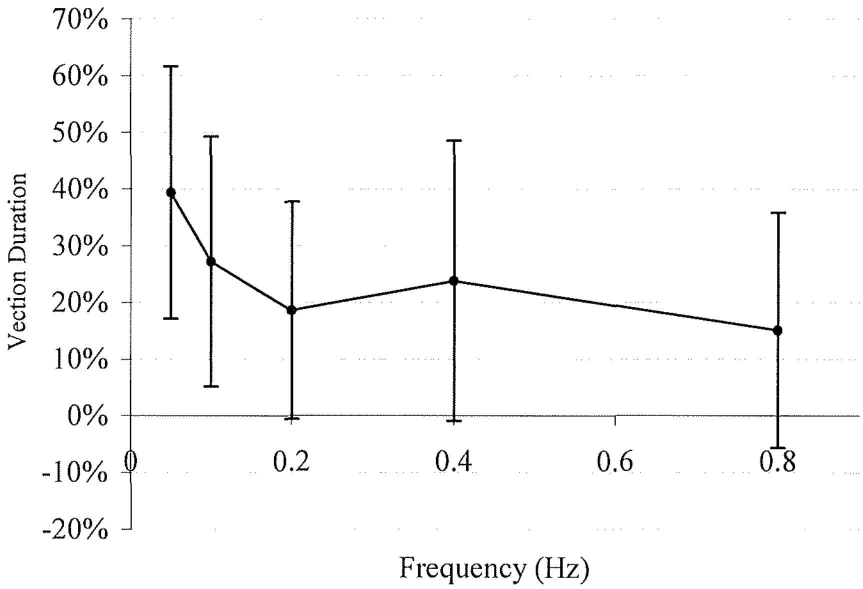


Figure 3.15: Mean (±S.D.) vection duration as a function of roll oscillation frequency

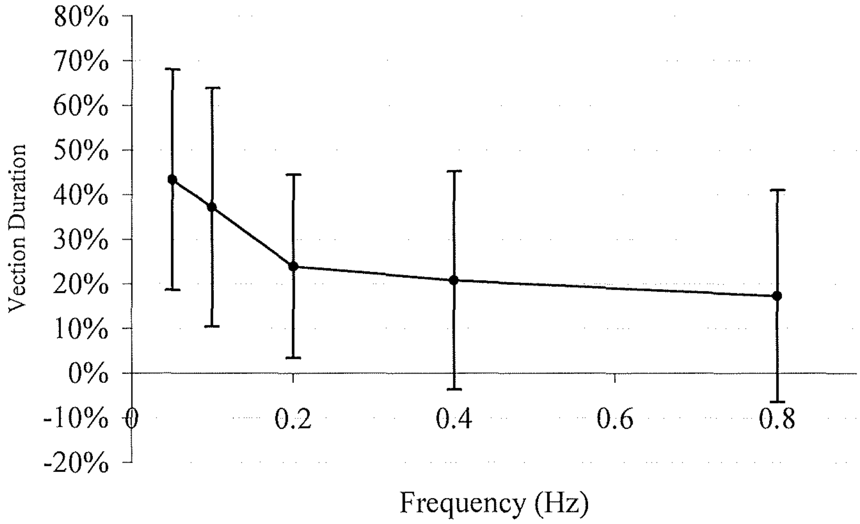


Figure 3.16: Mean (±S.D.) vection duration as a function of fore-and-aft oscillation frequency

Since the data did not pass the Shapiro-Wilk normality test (p = 0.002), Box-Cox transformations were performed. The transformed data conformed to normality for fore-and-aft session (p = 0.0656), but not for roll session (p = 0.0039). Friedman's non-parametric rank test showed significant effect of frequency (F = 19.36, *d.f.* = 4, p = 0.0007) for roll visual stimulus session. On the other hand, Kruskal-Wallis test failed to show difference in mean vection duration between the two gender groups (Chi-square = 0.83, *d.f.* = 1, p = 0.3623).

ANOVA (Table 3.23) failed to show significant main effect of visual stimulus frequency for fore-and-aft session ($F_{4,40}$ = 2.37, p = 0.0686). The effect of gender and its interaction term were not significant.

Table 3.23: ANOVA on vection duration (Box-Cox transformed) analyzing the effect of fore-and-aft visual stimulus frequency and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Frequency	4	0.64315	0.16079	2.37	0.0686
Gender	1	0.03920	0.03920	0.58	0.4515
Frequency*Gender	4	0.06812	0.01703	0.25	0.9073
Error	40	2.71234	0.06780		
Total	49	3.46287			

Table 3.24 and Table 3.25 show the rank scores and grouping of frequency conditions resulted from Wilcoxon Signed Rank test (p-values) and Friedman's ranking on all frequency conditions for roll visual stimulus session data and fore-and-aft visual stimulus sessions data (Box-Cox transformed).

Table 3.24: Vection duration rank scores, grouping and summary of Wilcoxon Signed Rank test (p-values) for roll visual stimulus frequency conditions

Sum of ranks (Friedman)	Grouping (Wilcoxon)	Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
43.0	A	0.05	x				
38.0	B	0.1	p=0.0410	x			
25.0	C	0.2	0.0039	0.0039	x		
29.0	C	0.4	0.0098	0.3750	1.0000	x	
15.0	D	0.8	0.0137	0.0371	0.2754	0.0488	x

Table 3.25: Summary of Wilcoxon Signed Rank test (*p*-values) on Vection duration for fore-and-aft visual stimulus frequency conditions

Freq. (Hz)	0.05	0.1	0.2	0.4	0.8
0.05	x				
0.1	*p*=0.0488	X			
0.2	0.0137	0.0195	x		
0.4	0.0137	0.0645	0.4316	x	
0.8	0.0136	0.0117	0.1289	0.1309	x

For fore-and-aft session data, vection duration experienced at 0.05 Hz condition is significantly longer than all other frequency conditions. Also, vection duration experienced at 0.1 Hz condition is significantly longer than 0.2 and 0.8 Hz conditions.

3.5 Comparison of roll and fore-and-aft frequency response

Postural disturbance and vection scores were compared pair-wise between roll and fore-and-aft session for each and every frequency condition. In particular, RMS value of head and body position data, balance difficulty in maintaining Sharpened Rhomberg stance and vection perception magnitude were compared, as these were the measures used in Duh *et al.* (2004) and Berthoz *et al.* (1974) work. As the data failed to pass normality test, Wilcoxon Signed Rank test was used to compare the scores.

3.5.1 Postural disturbance

Wilcoxon Signed Rank test revealed that RMS values of head and body position data were not significantly different between roll and fore-and-aft session for all of the five frequency conditions. Table 3.26 summarizes the *p*-values of Wilcoxon Signed Rank tests for every frequency condition.

Table 3.26: Summary of Wilcoxon Signed Rank tests (*p*-values) for comparing postural disturbance response magnitude between roll and fore-and-aft visual stimulus session of every frequency condition

Frequency condition	RMS value of head movement data	RMS value of body movement data
0.05 Hz	p = 0.2324	0.4922
0.1 Hz	0.3750	0.9219
0.2 Hz	0.5566	0.6953
0.4 Hz	0.9219	0.6953
0.8 Hz	0.4316	0.6953

3.5.2 Vection perception magnitude

It was found that difference in vection perception magnitude between roll and fore-and-aft stimulus sessions were not significantly different for all five frequency conditions. Table 3.27 summarizes the *p*-values of Wilcoxon Signed Rank tests for all frequency conditions.

Table 3.27: Summary of Wilcoxon Signed Rank tests (*p*-values) for comparing vection response magnitude between roll and fore-and-aft visual stimulus session of every frequency condition

Frequency condition	*p*-value of Wilcoxon Signed Rank test
0.05 Hz	$p = 0.4785$
0.1 Hz	0.8828
0.2 Hz	0.5508
0.4 Hz	0.9375
0.8 Hz	0.5156

3.6 Discussion

Results of the current study show that postural disturbance and vection perception decreased as a function of visual stimulus oscillation frequency.

When viewing oscillating visual stimulus in either roll or fore-and-aft direction, normalized RMS measure of head and body position data decreased as a function of visual stimulus roll oscillation frequency. The frequency response pattern in roll direction obtained from current study shows a remarkable correspondence with the pattern of balance disturbance scores obtained from Duh *et al.* (2004) experiment. The decreasing trend in subjective balance difficulty ratings on maintaining the Sharpened Rhomberg stance immediately after oscillating roll visual stimulus exposure also paralleled with Duh *et al.* (2004)'s results over the same frequency range. The decreasing trend in vection magnitude over the 0.05 – 0.8Hz frequency range in fore-and-aft visual stimulus session also echoed Berthoz *et al.*(1974)'s results on linear vection. Also, vection duration when viewing the visual stimulus significantly decreased over the 0.05 Hz and 0.8 Hz range. Overall, the hypothesis (H1a) that frequency has significant effect on postural disturbance and vection was supported.

Current study also showed that response magnitude over 0.05 Hz and 0.8 Hz range did not significantly differ between the roll and fore-and-aft direction for postural disturbance (head and body sway) and vection ratings. Therefore, the original hypothesis (H1b) was not supported. It is acknowledged that the lack of difference between roll and fore-and-aft response magnitude could also be the result of the careful "matching" of stimuli velocity between roll and fore-and-aft direction. As the number of black-and-white contrast cycles per oscillation period is consistent between roll and fore-and-aft direction, the amount of postural disturbance induced in the corresponding direction might also be “matched”.

The lack of significant difference in frequency response magnitude between roll and fore-and-aft direction suggests that it was not completely unreasonable for Duh *et al.* (2004) to average the frequency response curve of two different directions (using data from different experiments) in order to obtain an overall frequency response curve for the purpose of crossover frequency computation. In addition, the lack of difference in frequency response magnitude between roll and fore-and-aft direction suggests that the crossover frequency for both fore-and-aft and roll direction should approximately be the same.

Mean postural disturbance frequency response of 10 participants were standardized on the same scale using standardization method as Duh *et al.* (2004): offset (subtract) all postural disturbance scores by the lowest score among the five frequency conditions, and set the highest score as 1.0, then express all other scores as a ratio thereof. The standardized postural disturbance frequency curves of body and head movement RMS data were averaged, and are plotted against vestibular frequency response curve (Melvill Jones & Milsum, 1965) in Figure 3.17 (roll response) and Figure 3.18 (fore-and-aft response). To account for variation across participants, the standard deviation curves were also standardized, and are included in the plots for computing the crossover frequency range.

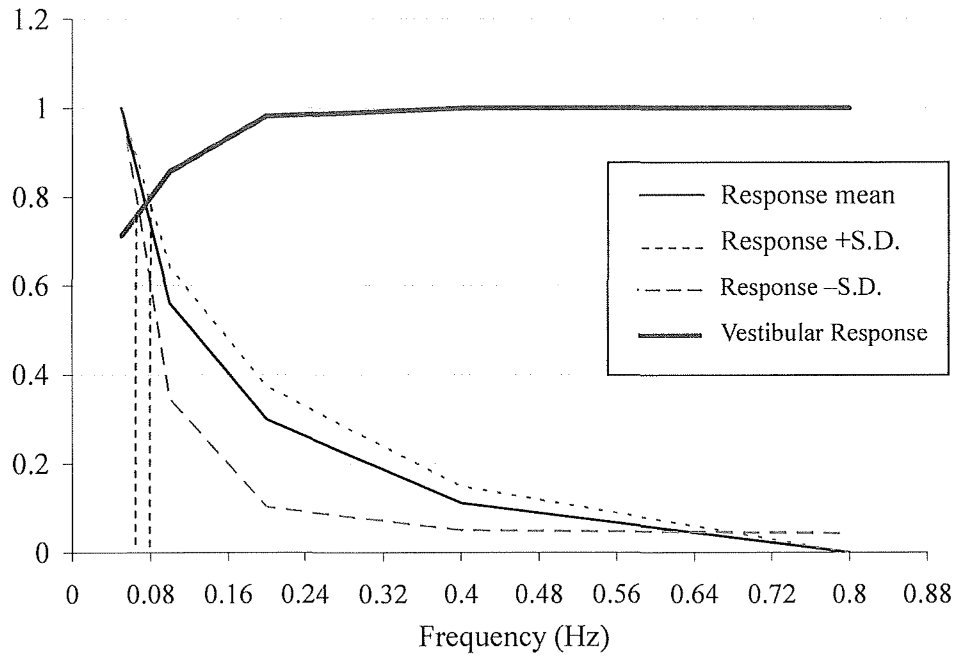


Figure 3.17: Crossover frequency computation for roll postural disturbance response

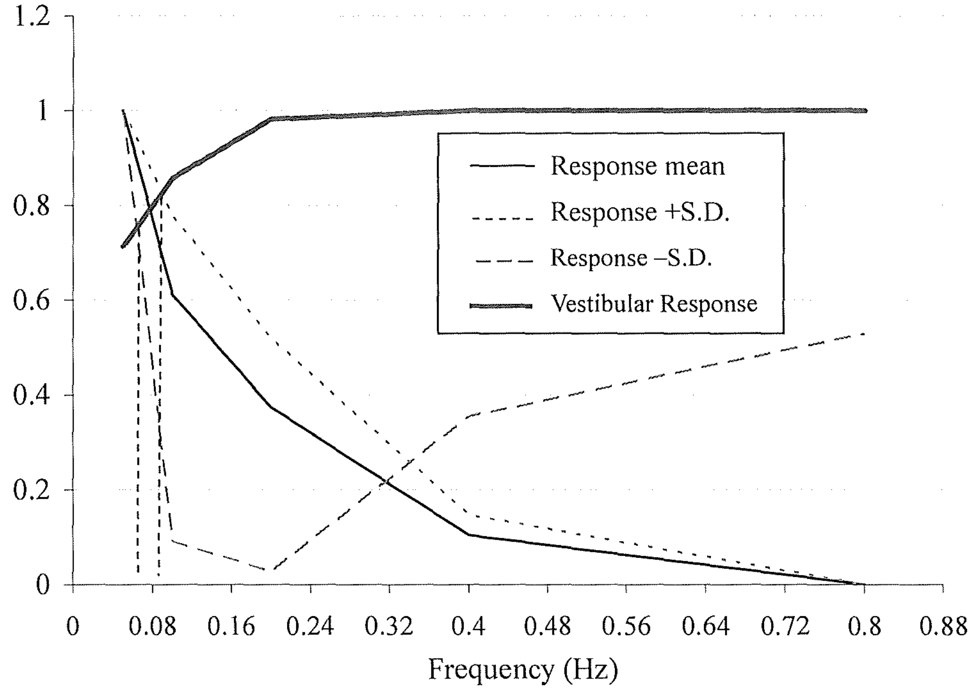


Figure 3.18: Crossover frequency computation for fore-and-aft postural disturbance response

The crossover frequency extracted from the plot was approximately 0.07 - 0.08 Hz for roll direction response, which is consistent with the results of Duh *et al.* (2004) and Lin *et al.* (2005)'s studies. On the other hand, the crossover frequency was also approximately 0.07 - 0.08 Hz for fore-and-aft direction response, which is much lower than 0.2 Hz suggested by Diels (2008)'s results. A possible explanation is that current study uses vestibular frequency response curve of the semi-circular canal (which detects only roll motion), which probably has a different response shape or slope than that of the otolith organ (which detects linear motion). Consequently, the otolith response curve may intersect the fore-and-aft postural disturbance response curve at a different cross-over frequency value.

3.7 Conclusion

In summary, the current study showed that frequency response of postural disturbance and vection perception when viewing oscillating fore-and-aft and roll visual stimulus have low-pass filter characteristic over the frequency range of 0.05 – 0.8 Hz, and that frequency response magnitudes in roll direction did not significantly differ from fore-and-aft direction. From the current data, computed crossover frequency for roll response (0.07 - 0.08 Hz) confirmed the computation method put forth by Duh *et al.* (2004). On the other hand, the computed crossover frequency for fore-and-aft response was also 0.07 - 0.08 Hz.

CHAPTER 4

STUDY 2 - THE EFFECT OF PEAK VELOCITY OF OSCILLATING VISUAL STIMULUS ON POSTURAL DISTURBANCE AND VECTION

4.1 Summary

This chapter describes an experiment which investigated the magnitude of postural disturbance and vection when viewing oscillating roll visual stimulus with varying oscillation peak velocity. Recent studies have showed evidence of disagreements between frequency responses to oscillating roll visual stimulus of different motion profiles, namely the peak amplitude and peak velocity. The current experiment showed that while holding frequency constant, postural disturbance and vection at 35°/sec condition are significantly lower than other velocity conditions (70, 100, 140°/sec). This result suggested that the frequency response curve of postural disturbance and vection obtained from Study 1 and Duh *et al.* (2004) could be shifted at lower peak oscillation velocities, possibly yielding different crossover frequency values.

4.2 Procedures and participants

The procedure was identical to Study 1, except the following differences. The visual stimulus oscillated sinusoidally in roll direction at 0.05 Hz frequency at four peak-velocity conditions: 35, 70, 100 and 140°/s. 0.05 Hz was chosen since it was observed from Study 1 that this frequency produced relatively large postural disturbance and vection. Note that 70°/s condition was the exact same condition as 0.05 Hz condition in Study 1. All participants completed the four conditions on a Latin square design, with immediate sequential learning effect balanced (Bradley, 1958).

Twelve Hong Kong Chinese participants (7 male and 5 female; mean age = 27.6) participated in the study. All participants were measured for their height and foot dimensions, and were tested for visual acuity by an Optec2000 Vision Tester (Stereo Optical Corp.) at far test distance (20 feet). All participants had normal or corrected-to-normal vision. Each participant was paid HK$50.0 per hour as compensation for his / her time for participating the experiment. In addition, all participants completed the Motion Sickness Susceptibility Survey (So *et al.*, 1999), as shown in Appendix C. See Appendix D for measurement records of all participants, and Appendix E for participants' responses of the Motion Sickness Susceptibility Survey.

4.3 Results

The computation and analysis of postural disturbance and vection scores were identical to those of Study 1. All trajectory plots of head and body displacement can be found in Appendix G.

4.3.1 Order Effect

To determine whether order effect was present, Pearson correlation test between the visual stimulus presentation order and all postural and vection measures were performed. A summary of test statistics of Pearson correlation test is shown on Table 4.1. Clearly, there was no apparent correlation between the presentation order and any of the postural and vection measure. Hence, presentation order effect was not present.

Table 4.1: Summary of Pearson Correlation Coefficient between visual stimulus presentation order and all postural and vection measure

Measure	Pearson Correlation Coefficient (p-value)
RMS value of head position data	0.04109 (p=0.7815)
RMS value of body position data	0.02524 (p=0.8648)
Balance difficulty score	0.09250 (p=0.5318)
Time to SR stance break	-0.00163 (p=0.9912)
Vection perception magnitude	0.03472 (p=0.8148)
Vection duration	-0.12973 (p=0.3795)
Vection onset time	0.01763 (p=0.9053)

4.3.2 Postural disturbance measures

4.3.2.1 RMS value of head position data

RMS value of head position data of 12 participants are plotted in Figure 4.1 as a function of oscillation peak velocity.

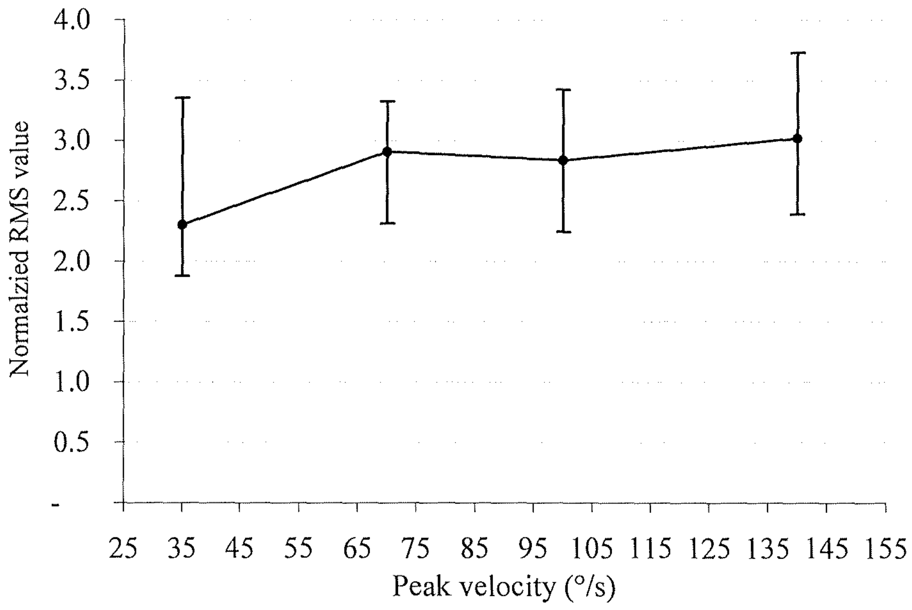


Figure 4.1: Median (±25%-tile) postural disturbance (RMS value of head position data) as a function of roll visual stimulus oscillation peak velocity

Similar to Study 1, the data did not pass the Shapiro-Wilk test of normality ($p < 0.0001$), but achieved normality after Box-Cox transformation (λ = -0.75). ANOVA (Table 4.2) on the transformed data failed to show significant main effect of visual stimulus peak velocity. The effect of gender and its interaction term were not significant.

Table 4.2: ANOVA on postural disturbance (RMS value of head movement data; Box-Cox transformed) analyzing the effect of visual stimulus peak velocity and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Peak Velocity	3	0.0157	0.0052	0.24	0.870
Gender	1	0.0041	0.0041	0.18	0.670
Velocity*Gender	3	0.0615	0.0205	0.93	0.435
Error	40	0.8821	0.0221		
Total	47	0.9634			

However, Wilcoxon Signed Rank tests performed on each and every velocity condition (Table 4.3) showed that postural disturbance in terms of head sway when viewing 35°/s roll stimulus is significantly lower than that of 70°/s.

Table 4.3: Wilcoxon Signed Rank tests on RMS value of head position data (Box-Cox transformed) for each and every roll visual stimulus peak velocity condition

Velocity (°/s)	35	70	100	140
35	x			
70	$p=0.0425$*	x		
100	0.9097	0.5693	x	
140	0.6221	0.9097	0.2334	x

*significant at the 0.05 level

4.3.2.2 RMS value of body position data

RMS value of body position data of 12 participants are plotted in Figure 4.2 as a function of peak velocity.

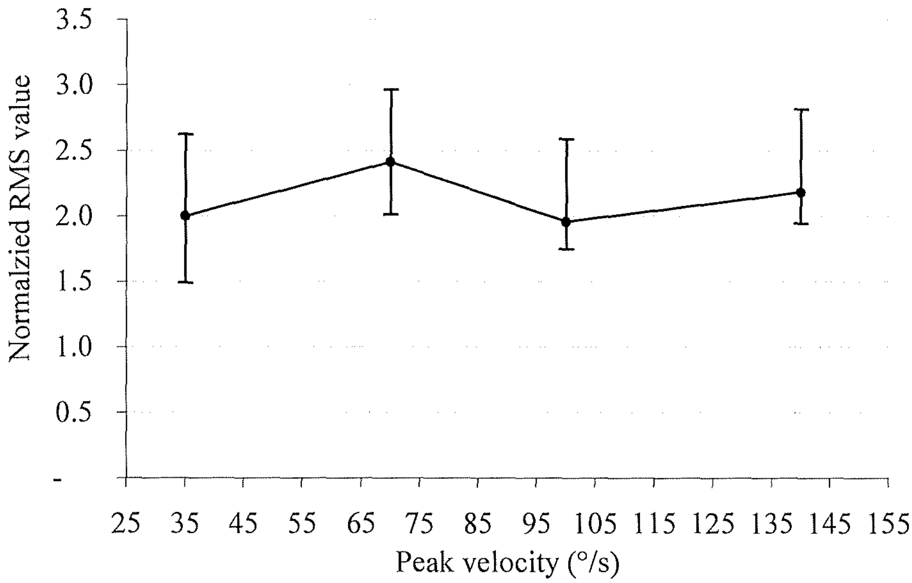


Figure 4.2: Median (±25%-tile) postural disturbance (RMS value of body position data) as a function of roll visual stimulus oscillation peak velocity

The data did not pass the Shapiro-Wilk test of normality ($p < 0.0001$), but achieved normality after Box-Cox transformation ($\lambda = -0.75$). ANOVA (Table 4.4) on the transformed data failed to show significant main effect of visual stimulus peak velocity. The effect of gender and its interaction term were not significant.

Table 4.4: ANOVA on postural disturbance (RMS value of body movement data; Box-Cox transformed) analyzing the effect of visual stimulus peak velocity and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Peak Velocity	3	0.0280	0.0093	0.29	0.832
Gender	1	0.0101	0.0101	0.31	0.579
Velocity*Gender	3	0.0479	0.0160	0.50	0.687
Error	40	1.2883	0.0322		
Total	47	1.3743			

However, Wilcoxon Signed Rank tests performed on each and every velocity condition (Table 4.5) showed that postural disturbance in terms of body sway when viewing 35°/s roll stimulus is significantly lower than that of 70°/s.

Table 4.5: Wilcoxon Signed Rank test on RMS value of body position data for each and every roll visual stimulus peak velocity condition

Velocity. (°/s)	35	70	100	140
35	x			
70	*p*=0.0342*	x		
100	0.9697	0.2661	x	
140	0.9097	0.5693	0.1763	x

*significant at the 0.05 level

4.3.2.3 Balance difficulty rating of Sharpened Rhomberg stance

Mean Sharpened Rhomberg stance balance difficulty score of 12 participants are plotted in Figure 4.3 as a function of oscillation peak velocity.

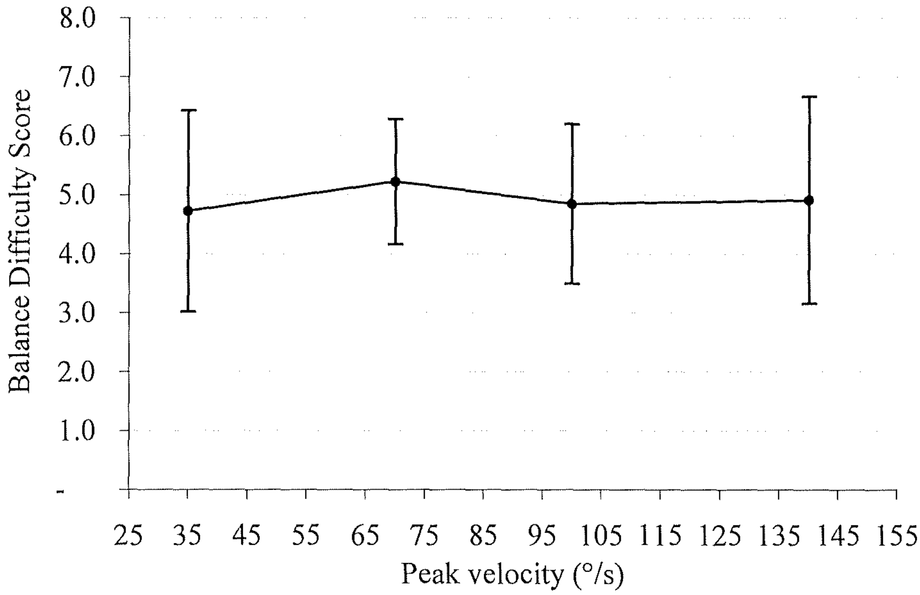


Figure 4.3: Mean (±S.D.) Sharpened Rhomberg stance balance difficulty score as a function of roll visual stimulus oscillation peak velocity

The data passed the Shapiro-Wilk test of normality. ANOVA (Table 4.6) was conducted to investigate the effect of velocity and gender on Sharpened Rhomberg stance balance difficulty score. It is clear that neither of the factor was significant main effect.

Table 4.6: ANOVA on Sharpened Rhomberg stance balance difficulty score analyzing the effect of roll visual stimulus peak velocity and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Peak Velocity	3	0.92806	0.30935	0.09	0.9662
Gender	1	0.88803	0.88803	0.25	0.6178
Velocity*Gender	3	0.53967	0.17989	0.05	0.9845
Error	40	140.46161	3.5115402		
Total	47	142.81738			

Results (p-values) of Wilcoxon Signed Rank test performed on each and every velocity condition (Table 4.7) confirm that balance difficulty rating between the four velocity conditions were not significantly different.

Table 4.7: Wilcoxon Signed Rank test on Sharpened Rhomberg stance balance difficulty rating for each and every roll visual stimulus peak velocity condition

Velocity. (°/s)	35	70	100	140
35	x			
70	p=0.3574	x		
100	0.8657	0.6289	x	
140	0.9526	0.7485	0.9414	x

4.3.2.4 Sharpened Rhomberg stance performance

Time to Sharpened Rhomberg stance break of 12 participants are plotted in Figure 4.4 as a function of oscillation peak velocity.

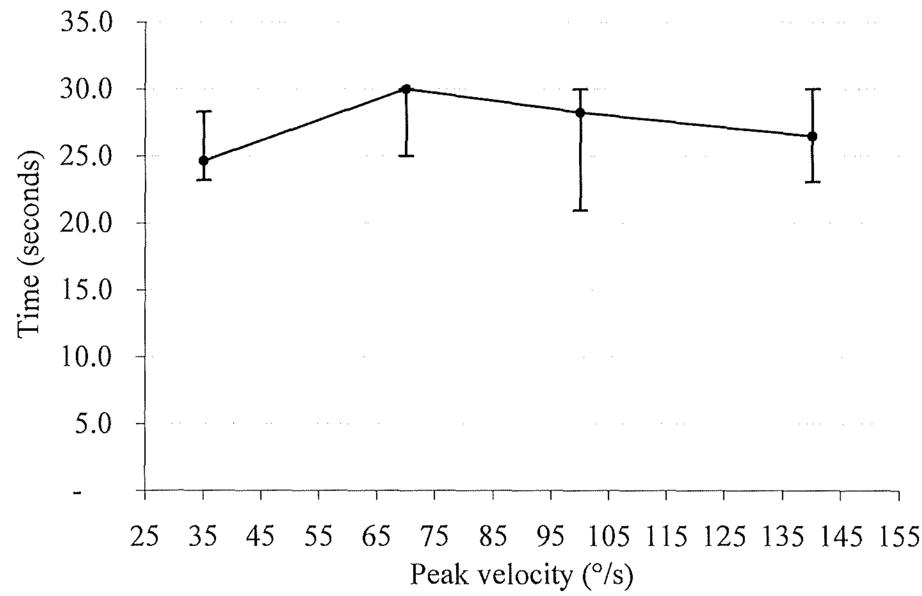


Figure 4.4: Median (±25%-tile) time to Sharpened Rhomberg stance break as a function of roll visual stimulus oscillation peak velocity

The original data did not pass Shapiro-Wilk test of normality ($p < 0.0001$). In addition, Box-Cox transformation did not achieve data normality. Since the data were not normal before and after Box-Cox transformation, non-parametric tests were used. Friedman's test failed to show the effect of stimulus velocity (F = 2.427, *d.f.* = 3, $p = 0.4886$) on time to Sharpened Rhomberg stance break. As well, Kruskal-Wallis test failed to show difference in mean time to Sharpened Rhomberg stance break between the two gender groups (Chi-square = 0.1004, *d.f.* = 1, $p = 0.7514$).

Non-parametric Wilcoxon Signed Rank tests on data from each and every velocity condition were performed (Table 4.8). It is clear that time to Sharpened Rhomberg stance break of the four velocity conditions were not significantly different.

Table 4.8: Wilcoxon Signed Rank test on time to Sharpened Rhomberg stance break for each and every roll visual stimulus peak velocity

Velocity. (°/s)	35	70	100	140
35	x			
70	p=0.2500	x		
100	0.6523	0.4688	x	
140	0.6035	0.7422	0.7422	x

4.3.3 Vection measures

Plots of vection presence time course for all 12 subjects are shown in Appendix I.

4.3.3.1 Magnitude of vection perception

Vection perception ratings of 12 participants are plotted in Figure 4.5 as a function of oscillation peak velocity.

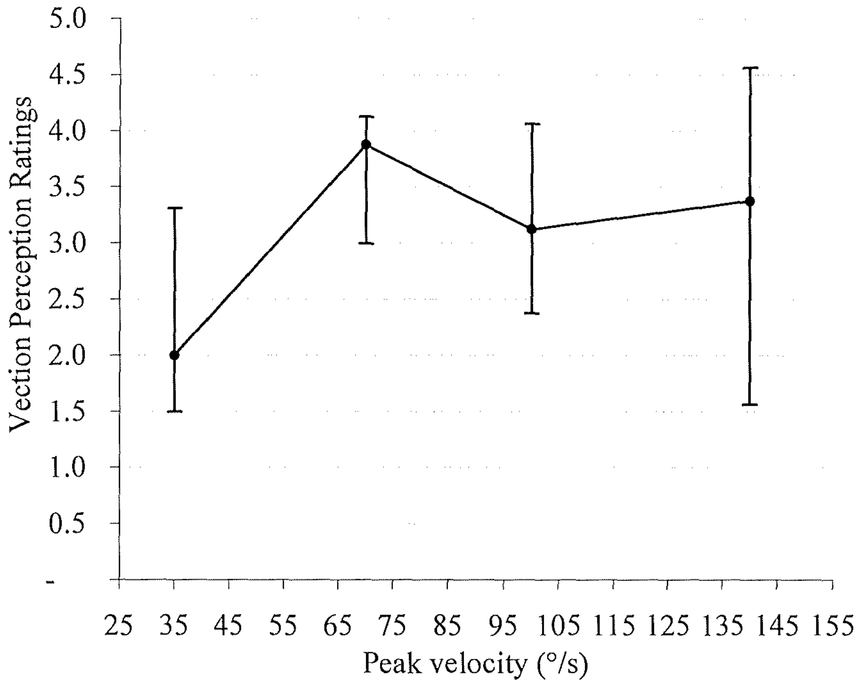


Figure 4.5: Median (±25%-tile) vection perception rating as a function of roll visual stimulus oscillation peak velocity

The original data did not pass Shapiro-Wilk test of normality ($p = 0.0286$). On the other hand, the Box-Cox transformed data ($\lambda = 0.5$) passed normality test ($p = 0.0813$). ANOVA (Table 4.9) on the transformed data was conducted to investigate the effect of velocity and gender on vection perception magnitude score. It is clear that neither of the factor was significant main effect.

Table 4.9: ANOVA on vection perception magnitude score (Box-Cox transformed) analyzing the effect of roll visual stimulus peak velocity and gender

Source	DF	Sum of Sq.	Mean Sq.	F Value	Pr > F
Peak Velocity	3	0.78178	0.26059	1.45	0.2434
Gender	1	0.32755	0.32755	1.82	0.1850
Velocity*Gender	3	0.22807	0.07602	0.42	0.7380
Error	40	7.20149	0.18004		
Total	47	8.53890			

Results (p-values) of Wilcoxon Signed Rank tests performed on each and every velocity condition (Table 4.10) show that vection perception magnitude score was significantly lower for the 35°/s velocity condition than 70°/s and 100°/s conditions.

Table 4.10: Wilcoxon Signed Rank test on vection perception magnitude score (Box-Cox transformed) for each and every roll visual stimulus peak velocity

Velocity. (°/s)	35	70	100	140
35	x			
70	*p*=0.0098*	x		
100	0.0469*	0.0688	x	
140	0.1543	0.3330	0.9434	x

*significant at the 0.05 level

4.3.3.2 Vection duration

Vection duration of 12 participants are plotted in Figure 4.6 as a function of oscillation peak velocity.

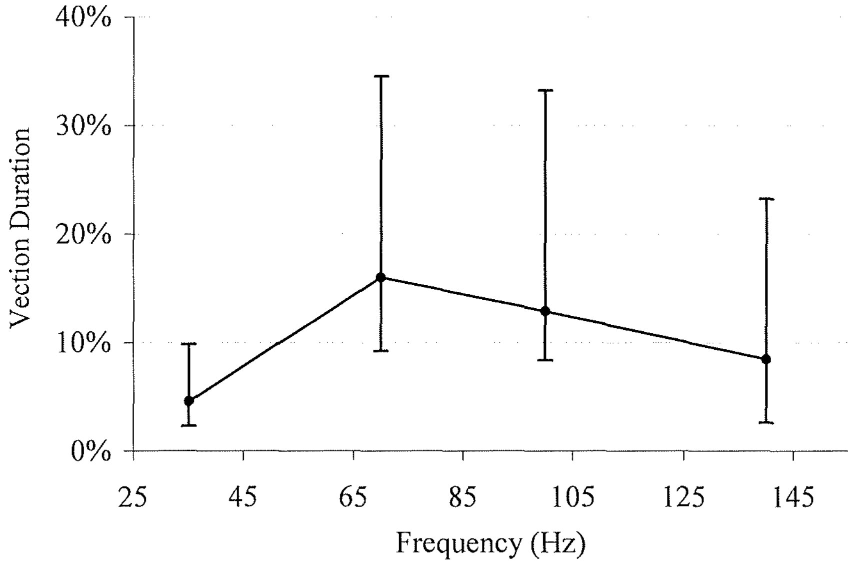


Figure 4.6: Median (±25%-tile) vection duration as a function of roll visual stimulus oscillation peak velocity

The data did not pass the Shapiro-Wilk test of normality ($p < 0.0001$). In addition, Box-Cox transformation ($\lambda = 0.5$) did not achieve data normality ($p = 0.0302$). Friedman's test failed to show the effect of stimulus velocity (F = 7.40, *d.f.* = 3, $p =$ 0.0602) on mean vection duration. As well, Kruskal-Wallis test failed to show difference in mean vection duration between the two gender groups (Chi-square = 2.5288, *d.f.* = 1, $p = 0.1118$).

Non-parametric Wilcoxon Signed Rank tests on data from each and every velocity condition were performed (Table 4.11). Vection duration for 35°/s velocity condition is significantly lower than that of 70°/s and 100°/s.

Table 4.11: Wilcoxon Signed Rank test on vection duration for each and every roll visual stimulus peak velocity

Velocity. (°/s)	35	70	100	140
35	X			
70	p=0.0122*	x		
100	0.0425*	0.6221	x	
140	0.5186	0.2334	0.2334	x

*significant at the 0.05 level

4.3.3.3 Vection onset time

Vection onset time of 12 participants are plotted in Figure 4.7 as a function of oscillation peak velocity.

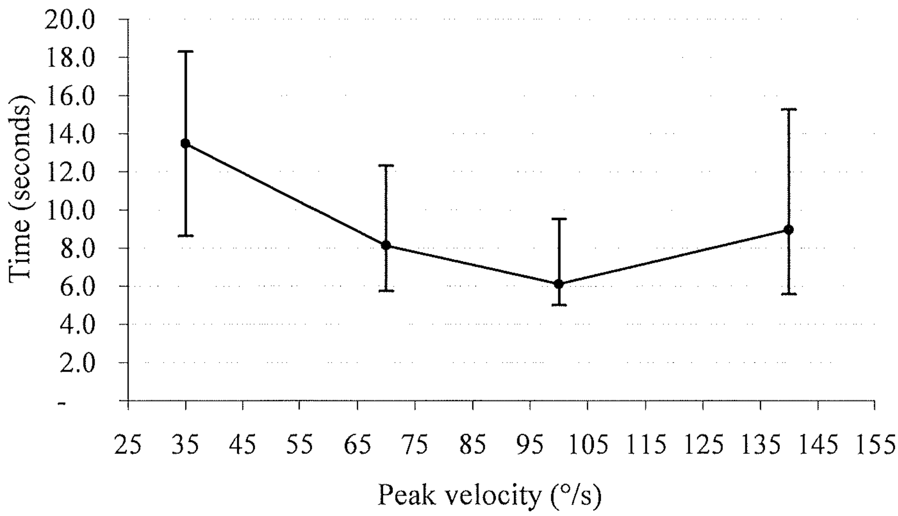


Figure 4.7: Median (±25%-tile) vection onset time as a function of roll visual stimulus oscillation peak velocity

The data did not pass the Shapiro-Wilk test of normality (p = 0.0005). In addition, Box-Cox transformation (λ = 0.25) did not achieve data normality (p = 0.0096). Friedman's test failed to show the effect of stimulus velocity (F = 6.50, *d.f.* = 3, p = 0.0897) on mean vection onset time. As well, Kruskal-Wallis test failed to show difference in mean vection onset time between the two gender groups (Chi-square = 0.6322, *d.f.* = 1, p = 0.4266). Wilcoxon Signed Rank tests on data from each and every velocity condition were performed (Table 4.12), and showed that vection onset time for 35°/s velocity condition is significantly higher than that of 100°/s condition.

Table 4.12: Wilcoxon Signed Rank test on vection onset time for each and every roll visual stimulus peak velocity

Velocity. (°/s)	35	70	100	140
35	x			
70	p=0.0923	x		
100	0.0161*	0.3394	x	
140	0.1763	0.4238	0.0640	x

*significant at the 0.05 level

4.4 Discussions

Results of current study shows evidence that postural disturbance is significantly lower when viewing oscillation visual stimulus at peak velocity 35°/s compared to other velocity conditions, which supported hypothesis (H2) that oscillating roll visual stimulus velocity has significant effect on postural disturbance. A similar trend is observed from the analysis of vection measures: visual stimulus with oscillation peak velocity 35°/s produced significantly less vection and shorter vection duration than 70°/s and 100°/s visual stimulus. In addition, it took significantly longer time to reach vection onset for 35°/s velocity condition than 100°/s condition.

Previc (1993)'s work showed that postural disturbance peaked at 15°/s (0.12 Hz) and vection magnitude peaked at 30°/s (0.25 Hz). However, in Previc's study, visual stimulus oscillation frequency and peak velocity were confounded. Current study factored out the effect of frequency, and successfully showed that postural disturbance and vection magnitude can significantly differ when viewing oscillating visual stimulus of different peak velocity in the roll direction.

Duh *et al.* (2004) and Study 1 of this thesis held the peak velocity of the oscillating visual stimulus fixed at 70°/s across all frequency conditions. The results of Study 2 thus imply that the postural disturbance and vection frequency response curves obtained by Duh *et al.* (2004) and Study 1 could be offset if the visual stimulus peak oscillation velocity was not 70°/s. In particular, current results suggest such shift would be in the downward direction (a reduction in frequency response magnitude) if the visual stimulus peak velocity is below 70°/s.

4.5 Conclusion

In summary, postural disturbance and vection when viewing oscillating roll visual stimulus is significantly lower when the peak velocity of the visual stimulus was changed from 70°/s to 35°/s. The current results suggest that visual stimulus at this velocity could yield postural disturbance and vection frequency response curves of lower magnitude, and, in the context of crossover frequency hypothesis and following the assumptions made in Duh *et al.* (2004), yield a different crossover frequency value.

CHAPTER 5

CONCLUSIONS, LIMITATIONS AND FUTURE WORK

5.1 Conclusions

The first study of this thesis examined the frequency response of postural disturbance and vection when viewing visual stimulus oscillating in roll direction and in fore-and-aft direction. Participants exhibited significantly lower postural disturbance and vection as the scene oscillating frequency increased. Furthermore, no significant difference on postural disturbance and vection was found between fore-and-aft and roll direction. In the context of crossover frequency hypothesis put forth by Duh *et al.* (2004), this implies the crossover frequency for roll and fore-and-aft direction are approximately the same. Current data suggest that the crossover frequency is at around 0.07 - 0.08 Hz for both roll direction and fore-and-aft direction. Current data also confirmed the computation method of the crossover frequency put forth by Duh *et al.* (2004).

A second study was conducted to examine the effect of peak roll oscillation velocity on postural disturbance and vection. Among the peak velocities being tested, postural disturbance and vection were found to be significantly lower for the 35°/sec condition, which suggested that the frequency response curve of postural disturbance and vection found in the first study may be shifted if lower peak oscillation velocities were employed.

5.2 Limitations and future work

It is acknowledged that the work of this thesis is limited to postural and vection response to only roll and fore-and-aft direction. Responses in other directions such as pitch, yaw, lateral and vertical directions are yet to be investigated. Moreover, durations of visual stimulus exposure were kept short for this study in order to replicate Duh *et al.* (2004) experiment for validation, and to avoid provoking visually-induced motion sickness in the participants (as VIMS is related to but outside the scope of the current study).

The two studies presented in this thesis can be continued in various ways. For Study 1, it is possible to conduct an additional study to investigate at which frequency condition does visually-induced motion sickness level peak under prolonged exposure of the same visual stimulus and apparatus presented in Study 1. As for Study 2, one could expand the study to include measurement of postural disturbance and vection response magnitude using frequency conditions other than 0.05 Hz. The resulting family of response curves due to different peak oscillation velocities could then be used to predict the corresponding crossover frequencies.

REFERENCES

Berthoz, A., Lacour, M., Soechting, J. F., & Vidal, P.P. (1979). The role of vision in the control of posture during linear motion. Progress in Brain Research, 50, 197-209.

Berthoz, A., Pavard, B., & Young, L. R. (1975). Perception of linear horizontal self-motion induced by peripheral vision (linearvection) basic characteristics and visual-vestibular interactions. Experimental Brain Research, 23 (5), 471-489

Bradley, J.V. (1958). Complete counterbalancing of immediate sequential effects in a latin square design. Journal of the American Statistical Association, 53, 525-528.

Chen, W. (2006). Effects of navigation velocities in fore-and-aft, lateral, yaw axes on cybersickness caused by exposure to a virtual environment. M.Phil. Thesis, The Hong Kong University of Science and Technology

Diels, C. (2008). Visually Induced Motion Sickness. Ph.D. Thesis, Loughborough University

Duh, H. B., Parker, D. E., Philips, J. O., Furness, T. A. (2004). "Conflicing" motion cues in the visual and vestibular self-motion systems around 0.06Hz evoke simulator sickness. Human Factors, 46(1), 142-153

Fischer, M. H. and Kornmüller, A. E. 1930. Optokinetisch ausgelöste Bewegungswahrnehmung und optokinetischer Nystagmus (Optokinetically induced motion perception and optokinetic nystagmus). Journal für Psychologie und Neurologie, 273-308.

Hamilton KM, Kantor L and Magee LE. (1989). Limitations of postural equilibrium tests for examining simulator sickness. Aviation, Space, Environment Medicine, 60, 246-251

Kennedy, R.S. and Stanney, K.M. (1996). Postural instability induced by virtual reality exposure: Development of a certification protocol. International Journal of Human Computer Interaction, 8(1), 25-47.

Lin, J.J.W., Razzaque, S. and Parker, D.E. (2005). Effects of Simulated Motion Frequency in Virtual Environments. Presented at the International Symposium on Theoretical Issues in Ergonomics Science, July, 2005, San Diego, CA, USA.

Mach, E. (1875). Grundlinien der Lehre von der Bewegungsempfindung. Engelmann, Leipzig, Germany.

Mayagoitia, R.E ., Lotters, J. C., Veltink, P. H., Hermens H. (2002). Standing balance evaluation using a triaxial accelerometer. Gait and Posture, 16 (1), 55–59.

McBurney, D. H. (1994). Research Methods (3rd Edition), 120-121

Musolino M. C., Loughlin P.J., Sparto P.J., Mark S. R. (2006). Spectrally similar periodic and non-periodic optic flows evoke different postural sway responses, Gait & Posture, 23, 180–188

Previc F.H., Kenyon R.V., Boer E.R., Johnson B.H. (1993). The effects of background visual roll stimulation on postural and manual control and self-motion perception. Perception & Psychophysics, 54 (1), 93-107

Prieto, T.E., Myklebust, J.B., Hoffmann, R.G., Lovett, E.G., Myklebust, B.M. (1996). Measures of postural steadiness: differences between healthy young and elderly adults, IEEE Transactions on Biomedical Engineering, 43 (9), 956-966

Reason, J. T. (1978). Motion sickness adaptation: a neural mismatch model. Journal of the Royal Society of Medicine, 71 (11), 819-829

Sharma V. K. (1975), An easy method of constructing Latin square designs balanced for the immediate residual and other order effects., The Canadian Journal of Statistics, 3 (1), 119-124.

So, R.H.Y., Finney, C.M. and Goonetilleke, R.S. (1999), Motion Sickness Susceptibility and Occurrence in Hong Kong Chinese., Contemporary Ergonomics 1999, pp. 88-92.

Stoffregen, T. A., & Smart, L. J. (1998). Postural instability precedes motion sickness. Brain Research Bulletin, 47, 437-448

Tanahashi S, Ujike H, Kozawa R, Ukai K. (2007), Effects of visually simulated roll motion on vection and postural stabilization., J Neuroeng Rehabil., 4 (1), 39-50

Tschermak, A. (1931). Optischer raumsinn. In Handbuch der Normalen und Pathologischen Physiologie, A. Bethe, G. Bergmann, G. Embden, and A. Ellinger, Eds. Springer, Berlin, 834-1000

Van Asten, W. N. J. C. , Gielen, C. C. A. M., Van der Gon, J. J. D., (1998) Postural movements induced by rotations of visual scenes, Journal of Optical Society of America A, 5 (10), 1781-1789

Webb, N. A. (2000). Visual acuity, eye movements, the illusion of motion and motion sickness with optokinetic stimuli. Ph.D. Thesis, University of Southampton

<u>APPENDIX A: EXPERIMENT INFORMATION AND PROCEDURE GUIDE FOR PARTICIPANTS</u>

<u>**Human Factor Experiment Information**</u>

<u>**Task:**</u> In this experiment, you will view a series of moving image sequences consists of black and white patterns.

<u>**Duration & Time Compensation in Money:**</u> The whole experiment consists of one / two sessions, with each session lasting approximately 90 minutes. You will receive a monetary compensation at a rate of HKD50.0 / hour.

<u>**Sharpened Rhomberg Stance:**</u> You will be requested to perform the Sharpened Rhomberg throughout the experiment. This requires you to stand in a heel-to-toe position, with arm across the chest, face towards the forward direction with your <u>**eyes closed**</u>. The experimenter will physically demonstrate this standing posture to you before the experiment begins. You will have time to practice this stance. [N.B.: Keep both lower and upper legs straight]

<u>**Vection:**</u> Before the experiment begins, you will view a moving image sequence to familiarize with the feeling of *vection*. Vection is a sensation of self-motion; an illusive feeling that you are actually moving while watching a moving image sequence. Please ensure that you understand this feeling, as you will be reporting it throughout the experiment. You will report your feeling of vection on a scale of 1-7, according to the following:

Vection (Perception of Self-Motion)	Rating
I perceive that the only thing moving is the visual stimulus and I remain stationary	1
	2
I perceive that visual stimulus to be moving but also experience weak feeling of self-motion	3
	4
I perceive that visual stimulus to be moving but also experience strong feeling of self-motion	5
	6
I perceive that the visual stimulus is stationary, and a strong feeling that I am moving	7

Equipment: You will be requested to wear a blue plastic cap and a belt with an instrument attached that measures your head and body position. Please ensure that the cap and the belt are tightly secured throughout the experiment. If there is any noticeable slippage of the cap or the belt during any time of the experiment, please inform the experimenter.

You will also be requested to wear a special goggle during the experiment. You will also be requested to take off your shoes and socks before the experiment. The experimenter will provide you with a pair of new socks to conduct the experiment.

Experiment Procedure

1) Stand upright, with feet pressed together, both hands on the sides, eyes opened, looking in the forward direction towards the screen. Hold the provided PC mouse on your right hand. When you are ready, please restrain from any voluntary body movement. A stationary image of black-and-white pattern is then displayed on the screen in front of you. Look towards the end of the tunnel. [N.B.: Eyes remained OPENED in this step]

2) After a short while, the black-and-white pattern will start to move.

While watching the moving image, please report vection by pressing the left mouse button; press and hold the left mouse button for as long as vection is present. Release the mouse button whenever the feeling disappear. Since vection could be a come-and-go feeling, press the button again whenever the sensation is present again, and release whenever it disappear again.

While watching the moving image, please restrain from any voluntary body movement (except using your finger to press the mouse button). [N.B.: Eyes remained OPENED in this step]

3) When the moving image is extinguished, immediately assume the Sharpened Rhomberg stance. Please note that the experimenter will instruct you which foot (right or left) is to be placed in the front.

   Once in the stance assumed, try your best to maintain an upright, steady posture. [N.B.: Eyes remained CLOSED in this step]

   If you feel that you have lost your balance during this stance, it is OK to break the stance by moving your feet or your hands. Proceed to step (4) if you do break the stance. Otherwise, maintain in this stance until the experimenter signal you to retreat from the stance.

4) You will then be asked to verbally report your subjective feeling of vection (perception of self-motion) while you were watching the moving image sequence on a scale of 1-7, according to the following:

Vection (Perception of Self-Motion)	Rating
I perceive that the only thing oscillating is the visual stimulus and I remain stationary	1
	2
I perceive that visual stimulus to be oscillating but also experience weak feeling of self-motion	3
	4
I perceive that visual stimulus to be oscillating but also experience strong feeling of self-motion	5
	6
I perceive that the visual stimulus is stationary, and a strong feeling that I am oscillating	7

Please also verbally report your feeling of difficulty in maintaining a steady, upright posture while performing Sharpened Rhomberg stance on a scale of 1-10, as follows:

1	2	3	4	5	6	7	8	9	10
Very Easy									Very Difficult

You will also be asked to report any feet fatigue and nausea (stomach awareness; 作嘔惡心)

5) You will then take a short break before viewing the next moving image sequence. During the break, you can relax and sit down comfortably on the chair provided to you.

APPENDIX B: EXPERIMENT CONSENT FORM FOR PARTICIPANTS

Consent Form for Human Factor Experiment Participation

1. Name ____
2. Are you feeling ill in any way? Yes/No
3. Do you suffer from diabetics (糖尿病) or epilepsy (癲癇症)? Yes / No
4. Are you under medical treatment or suffering disability which affects your daily life? Yes / No
5. Have you had any intake of alcohol (酒精) 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? Yes / No

If your answer is "Yes" to question (2) - (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 withdrawal 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.

Signature of Subject ______________________ Date ______________________

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

Signature of Experimenter ___________________ Date ______________________

APPENDIX C: MOTION SICKNESS SUSCEPTIBILITY SURVEY

Motion Sickness Susceptibility Survey
暈浪敏感調查

Instructions: Please fill in this survey. Circle the answer which most closely corresponds to your own experience. Feel free to add comments you would like to make at the end of the survey.

請圈出你的答案。

Age 年齡：

Sex 性別：

The term motion sickness refers to symptoms, such as dizziness, fatigue, nausea, headache, sweating, and vomiting, which can be evoked in susceptible individuals by the perception of various kinds of periodic motion.

暈浪的定義就是一種病徵，例如流汗，作嘔，頭暈，頭痛或嘔吐。

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

在過去十二個月中有否在乘搭交通工具中有暈浪的經驗？例如：當你在三百次乘巴士經驗中，有三十次感到暈浪不適，答案就是10%)

Car/Taxi 私家車/的士	0%	1%-10%	11%-40%	41%-74%	75%-100%
Buses 巴士	0%	1%-10%	11%-40%	41%-74%	75%-100%
Cross-Ferry 輪渡	0%	1%-10%	11%-40%	41%-74%	75%-100%
Jet-Foil 飛翔船	0%	1%-10%	11%-40%	41%-74%	75%-100%
Trains 火車	0%	1%-10%	11%-40%	41%-74%	75%-100%
Elevators 升降機	0%	1%-10%	11%-40%	41%-74%	75%-100%

2. Please circle the symptoms experienced while in the following situations:
請圈出在暈浪的病徵？

Car/Taxi 私家車/的士	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Bus 巴士	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Cross-Ferry 輪渡	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Jet-Foil 飛翔船	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Trains 火車	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Elevators 升降機	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐

3. In general, how susceptible to motion sickness are you?
通常，你對暈浪的敏感程度有幾大？

Not at all 從不	Slightly 很少	Moderately 一般	Very 非常	Extremely 極端

APPENDIX D: PARTICIPANTS INFORMATION & MEASUREMENTS

	Subject			Visual		Foot Dimension	
						Left	Right
	Abbrv.	Gender	Age	Score	Height (cm)	W x L (cm)*	W x L (cm)*
Study 1	cyu	M	28	20/17	177.5	9.5 x 25.0	9.5 x 25.0
	dav	F	28	20/20	161.5	8.5 x 24.0	8.5 x 24.0
	ech	F	28	20/18	162.0	8.0 x 22.5	8.0 x 22.5
	fsk	M	25	20/15	172.0	8.5 x 22.0	8.5 x 22.0
	haz	M	25	20/17	171.5	7.5 x 22.5	7.5 x 23.0
	jon	M	26	20/20	154.0	9.0 x 23.0	9.0 x 23.0
	mag	M	27	20/20	157.5	7.5 x 23.5	7.5 x 23.5
	rta	F	26	20/20	163.0	9.0 x 22.5	9.0 x 22.0
	vin	F	28	20/17	173.0	10.0 x 26.5	10.0 x 26.5
	xyu	M	24	20/20	162.0	7.5 x 23.0	7.5 x 23.0
Study 2	chc	F	27	20/18	164.0	8.0 x 22.5	8.0 x 22.5
	che	F	28	20/17	168.0	9.5 x 25.0	9.5 x 25.0
	cin	F	26	20/20	158.5	7.5 x 19.5	7.5 x 19.5
	cui	F	30	20/20	153.0	8.0 x 21.0	8.0 x 21.0
	dav	F	28	20/20	161.5	8.5 x 24.0	8.5 x 24.0
	jas	M	28	20/17	170.0	8.5 x 23.5	8.5 x 23.5
	lhy	M	29	20/20	156.5	9.0 x 22.0	9.0 x 22.0
	man	M	26	20/17	165.0	9.0 x 26.0	9.0 x 26.0
	pan	M	29	20/20	165.5	9.0 x 24.0	9.0 x 24.0
	pho	M	23	20/18	152.0	7.0 x 23.5	7.0 x 23.5
	wcc	M	28	20/17	173.0	10 x 26.5	10 x 26.5
	yue	M	29	20/20	166.5	8.5 x 20.5	8.5 x 20.5

* W = Width of widest part of the foot

L = Length of longest part of the foot

APPENDIX E: MOTION SICKNESS SUSCEPTIBILITY SURVEY PARTICIPANT RESPONSES

Responses for Question 1 (In the past 12 months, how often have you experienced motion sickness while traveling as a passenger in the following situations?):

	Subject Abbrv.	Car / Taxi	Buses	Cross-Ferry	Jet-Foil	Trains	Elevators
Study 1	cyu	-	-	-	-	1-10%	-
	dav	-	1-10%	1-10%	-	-	-
	ech	-	-	-	-	-	-
	fsk	-	-	-	-	-	-
	haz	-	-	-	1-10%	-	-
	jon	-	-	-	-	-	-
	mag	-	1-10%	-	-	-	-
	rta	1-10%	-	41-74%	41-74%	-	1-10%
	vin	-	-	-	-	-	-
	xyu	-	-	-	-	-	-
Study 2							
	chc	-	-	-	-	-	-
	che	-	-	-	11-40%	-	-
	cin	1-10%	-	-	-	-	-
	cui	-	-	-	-	-	-
	dav	-	1-10%	1-10%	-	-	-
	jas	-	-	-	-	-	-
	lhy	1-10%	-	-	-	-	1-10%
	man	-	-	75-100%	75-100%	-	-
	pan	-	11-40%	-	-	-	-
	pho	-	-	-	-	-	-
	wcc	-	-	-	-	-	-
	yue	-	-	1-10%	-	-	-

Responses for Question 2 (Please indicate the symptoms experienced while in the following situations):

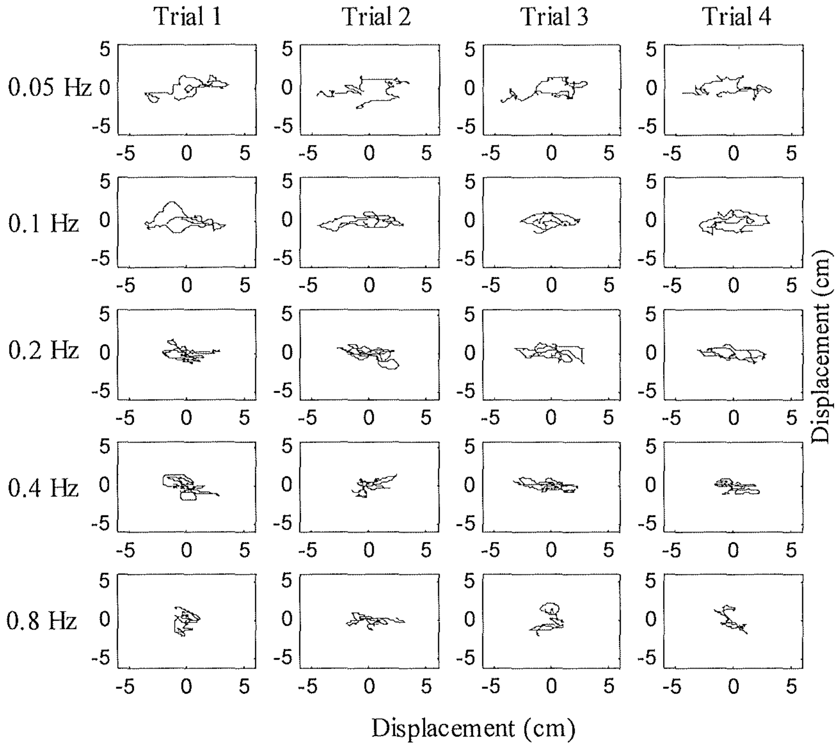
	Subject Abbrv.	Car / Taxi	Buses	Cross-Ferry	Jet-Foil	Trains	Elevators
Study 1	cyu	-	-	-	-	Headache	-
	dav	-	Nausea	Nausea	-	-	-
	ech	-	-	-	-	-	-
	fsk	-	-	-	-	-	-
	haz	-	-	-	Dizziness	-	-
	jon	-	-	-	-	-	-
	mag	-	Headache	-	-	-	-
	rta	Dizziness	-	Dizziness	Sweating	-	Dizziness
	vin	-	-	-	-	-	-
	xyu	-	-	-	-	-	-
Study 2	chc	-	-	-	-	-	-
	che	-	-	-	Nausea	-	-
	cin	Headache	-	-	-	-	-
	cui	-	-	-	-	-	-
	dav	-	Nausea	Nausea	-	-	-
	jas	-	-	-	-	-	-
	lhy	Dizziness	-	-	-	-	Dizziness
	man	-	-	Dizziness	Dizziness	-	-
	pan	-	Nausea	-	-	-	-
	pho	-	-	-	-	-	-
	wcc	-	-	-	-	-	-
	yue	-	-	Dizziness	-	-	-

Responses for Question 3 (In general, how susceptible to motion sickness are you?):

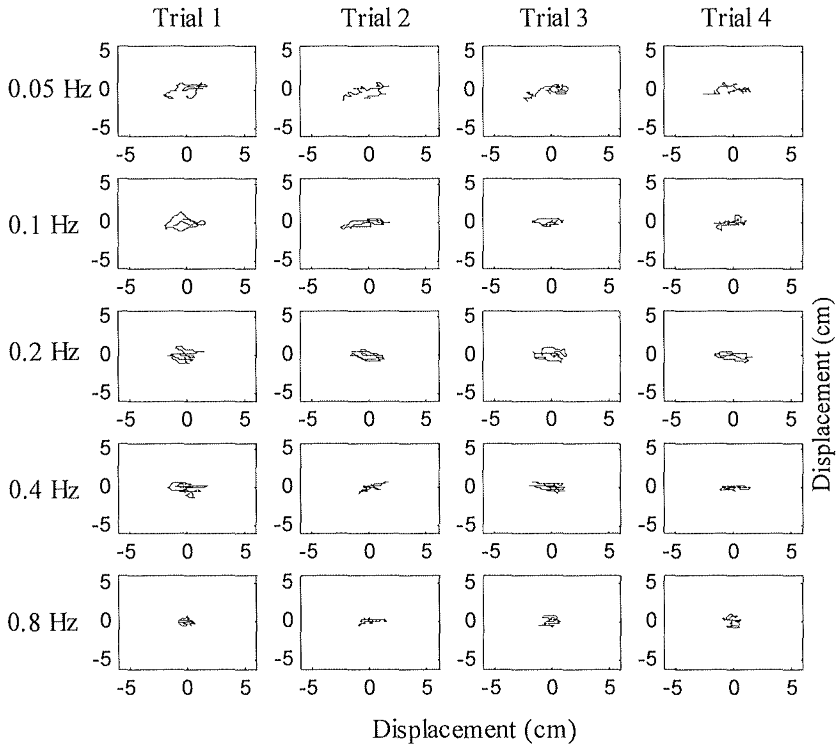
	Subject's abbreviation	
Study 1	cyu	Slightly
	dav	Slightly
	ech	Not at all
	fsk	Not at all
	haz	Slightly
	jon	Not at all
	mag	Slightly
	rta	Moderately
	vin	Not at all
	xyu	Not at all
Study 2	chc	Not at all
	che	Slightly
	cin	Slightly
	cui	Not at all
	dav	Slightly
	jas	Not at all
	lhy	Moderately
	man	Moderately
	pan	Slightly
	pho	Not at all
	wcc	Not at all
	yue	Slightly

APPENDIX F: BODY AND HEAD POSITION TRAJECTORY PLOTS (STUDY 1)

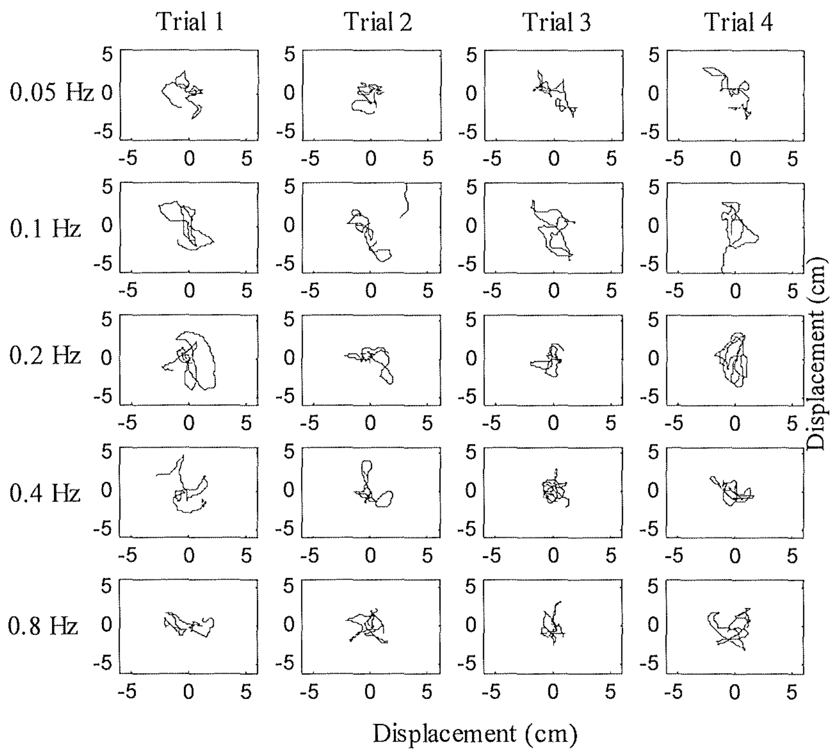
Subject: CYU (roll visual stimulus session; head movement trajectory)



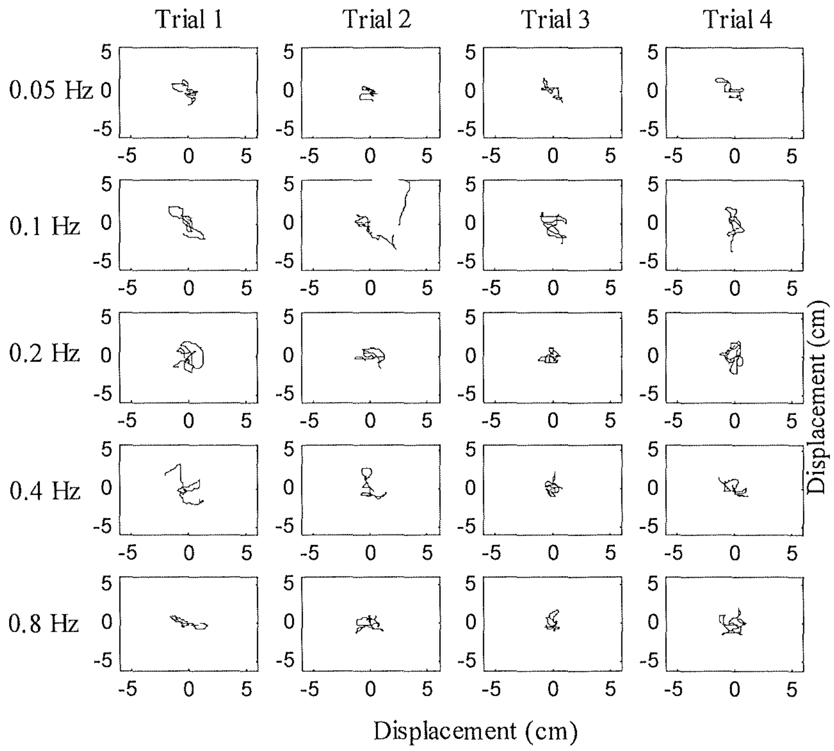
Subject: CYU (roll visual stimulus session; body movement trajectory)



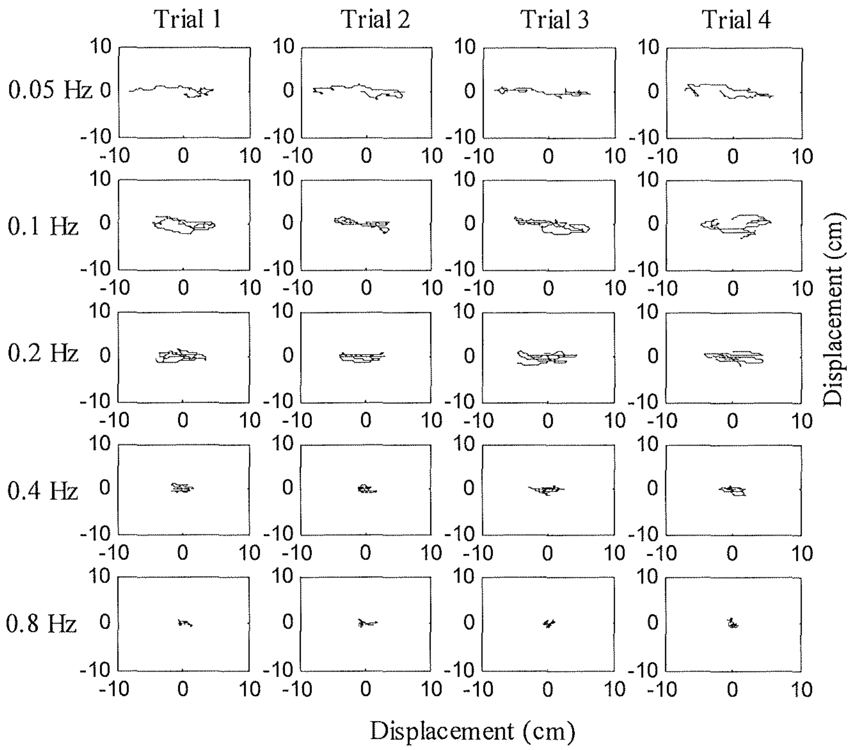
Subject: CYU (fore-and-aft visual stimulus session; head movement trajectory)



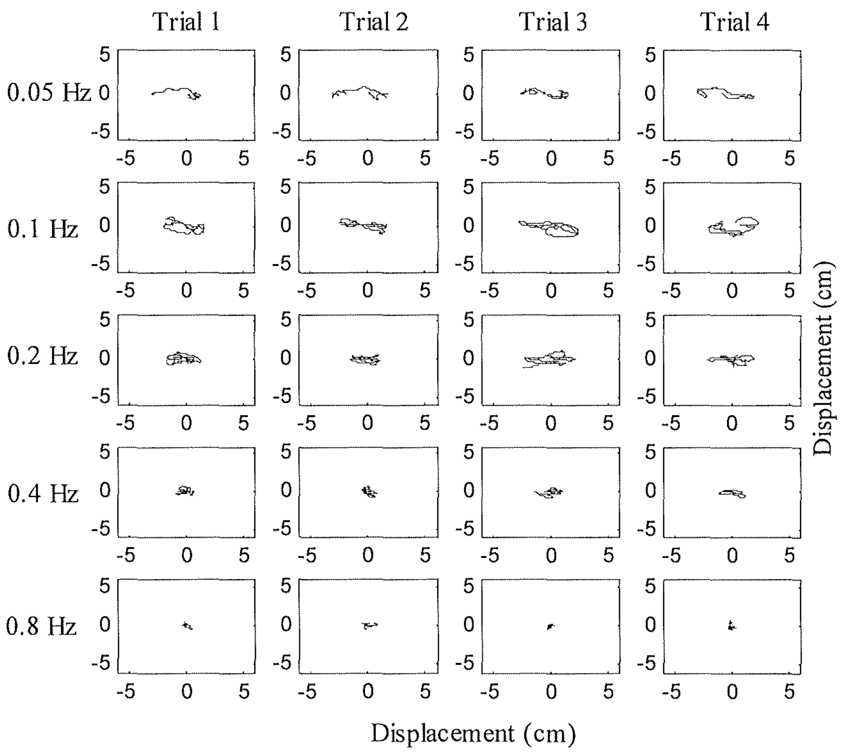
Subject: CYU (fore-and-aft visual stimulus session; body movement trajectory)



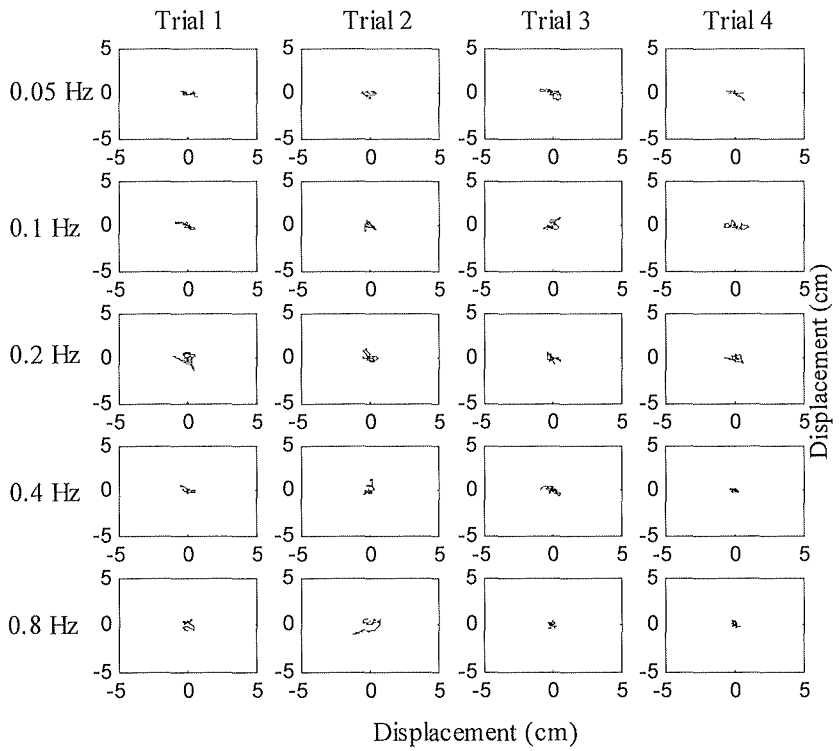
Subject: DAV (roll visual stimulus session; head movement trajectory)



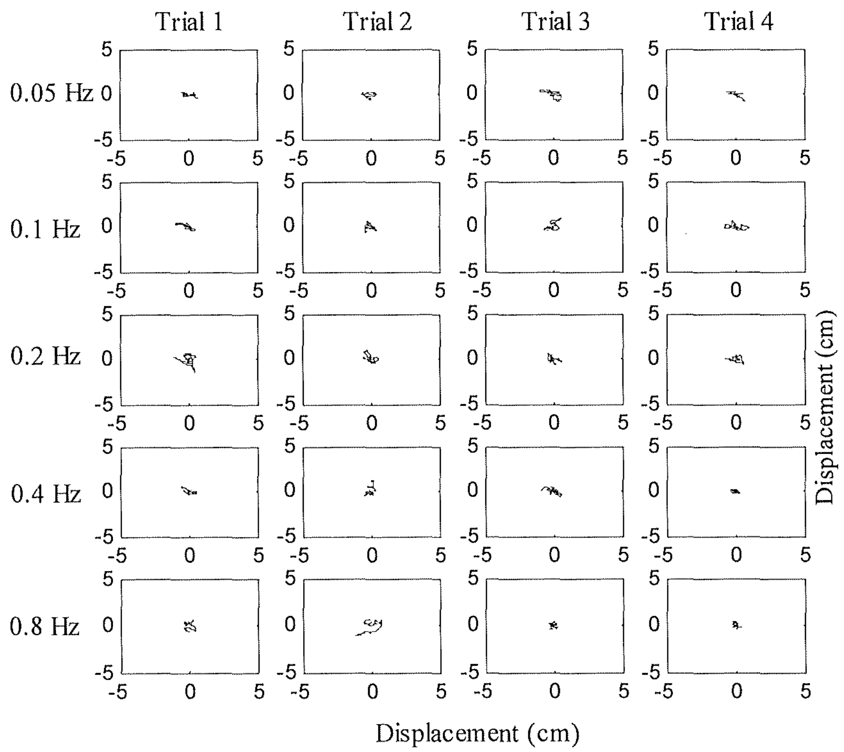
Subject: DAV (roll visual stimulus session; body movement trajectory)



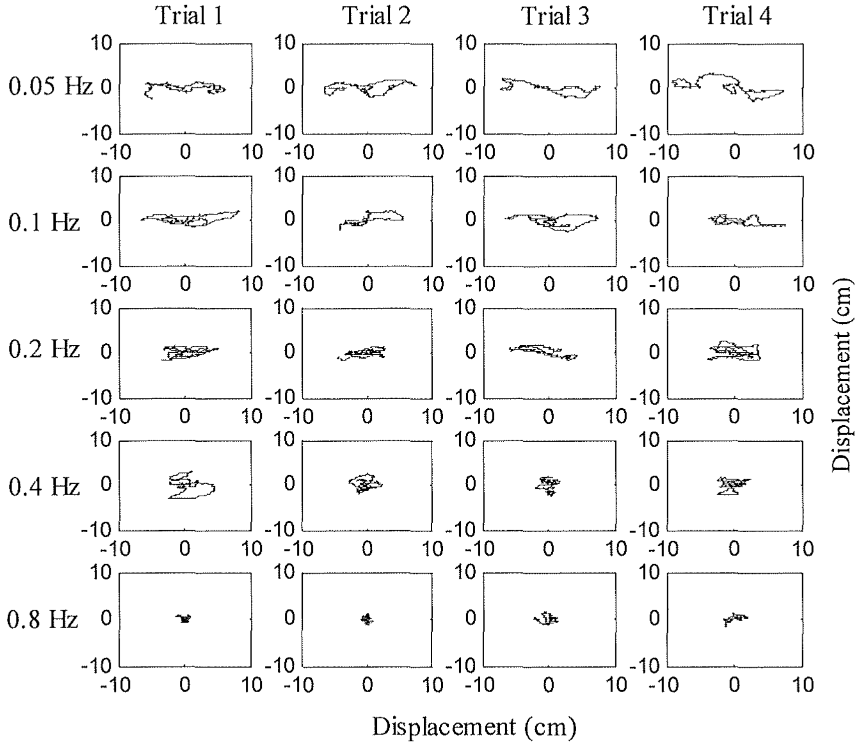
Subject: DAV (fore-and-aft visual stimulus session; head movement trajectory)



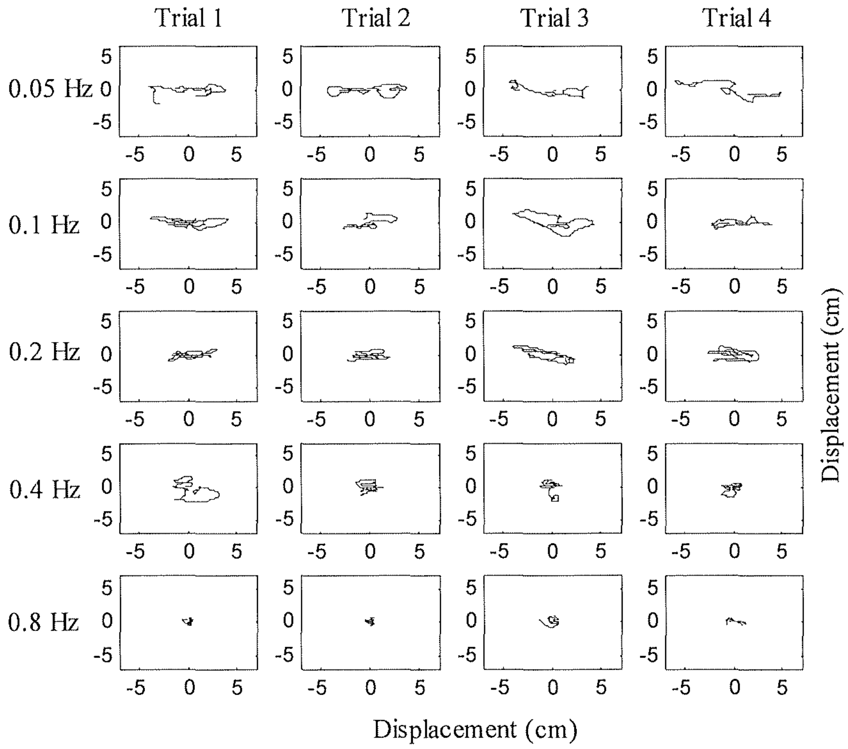
Subject: DAV (fore-and-aft visual stimulus session; body movement trajectory)



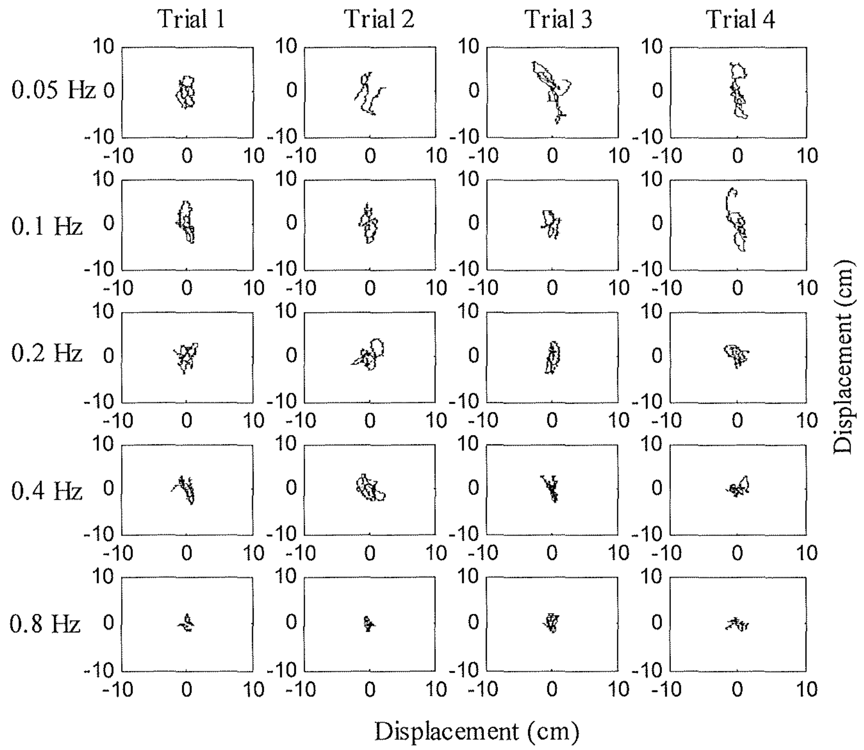
Subject: ECH (roll visual stimulus session; head movement trajectory)



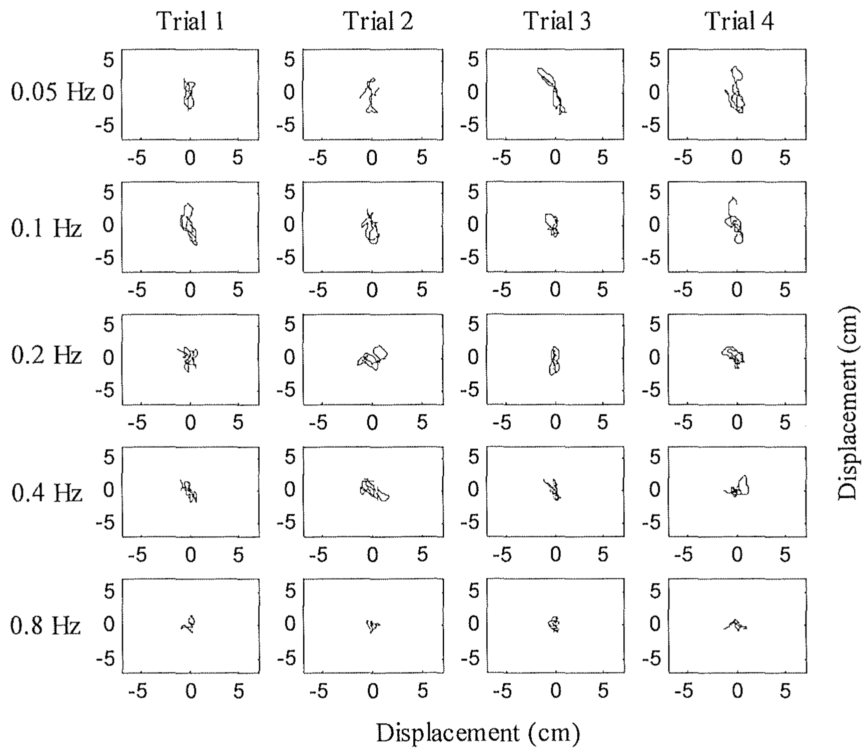
Subject: ECH (roll visual stimulus session; body movement trajectory)



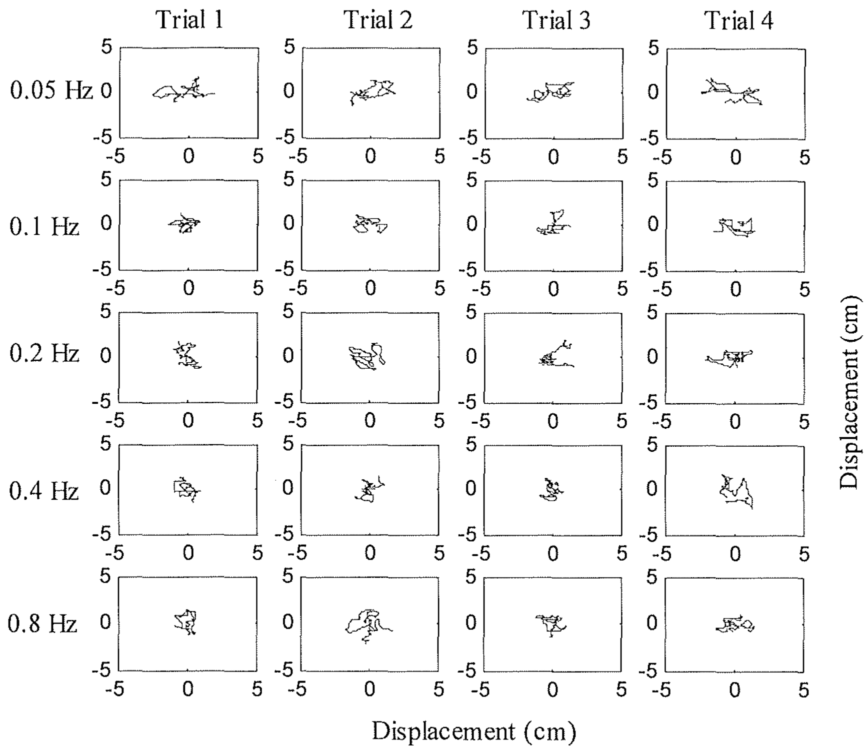
Subject: ECH (fore-and-aft visual stimulus session; head movement trajectory)



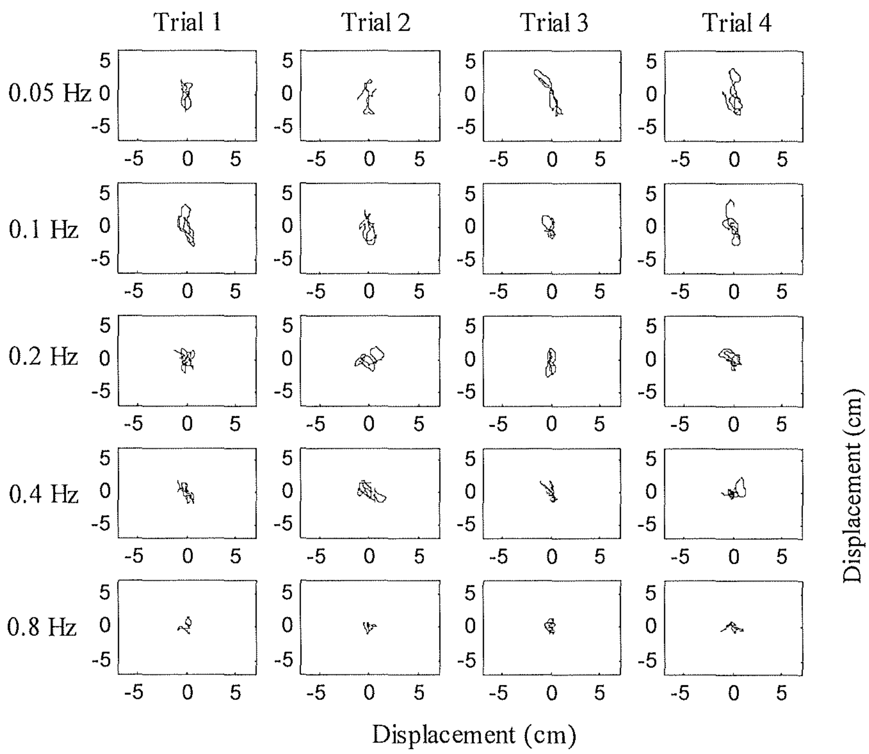
Subject: ECH (fore-and-aft visual stimulus session; body movement trajectory)



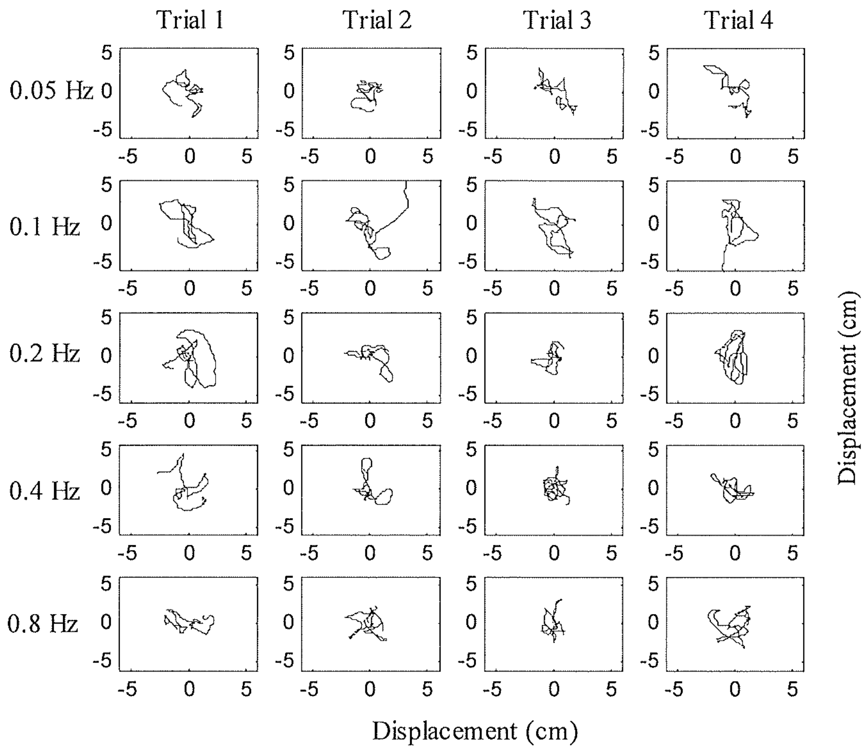
Subject: FSK (roll visual stimulus session; head movement trajectory)



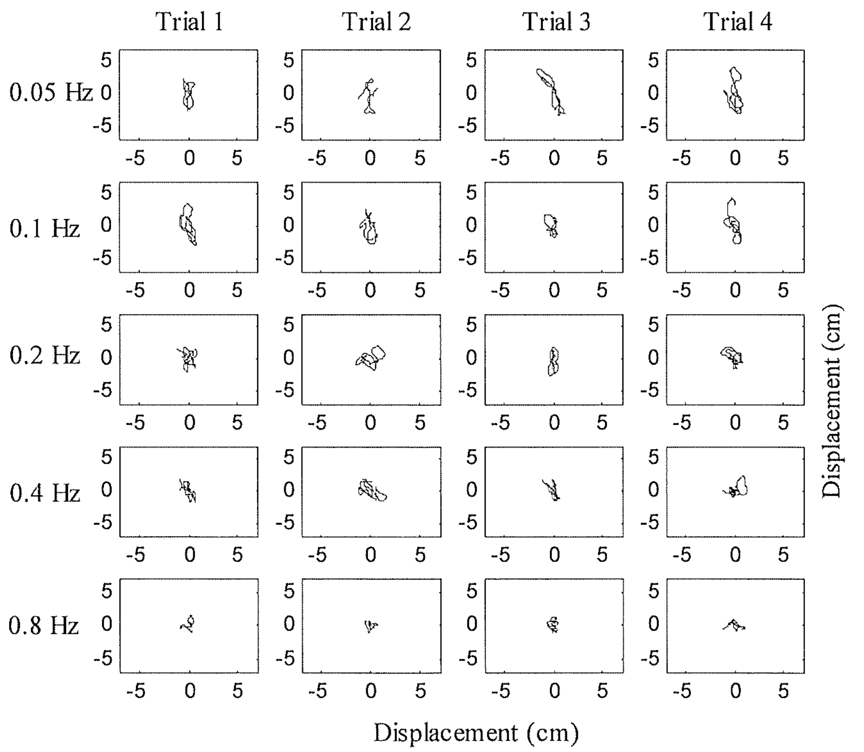
Subject: FSK (roll visual stimulus session; body movement trajectory)



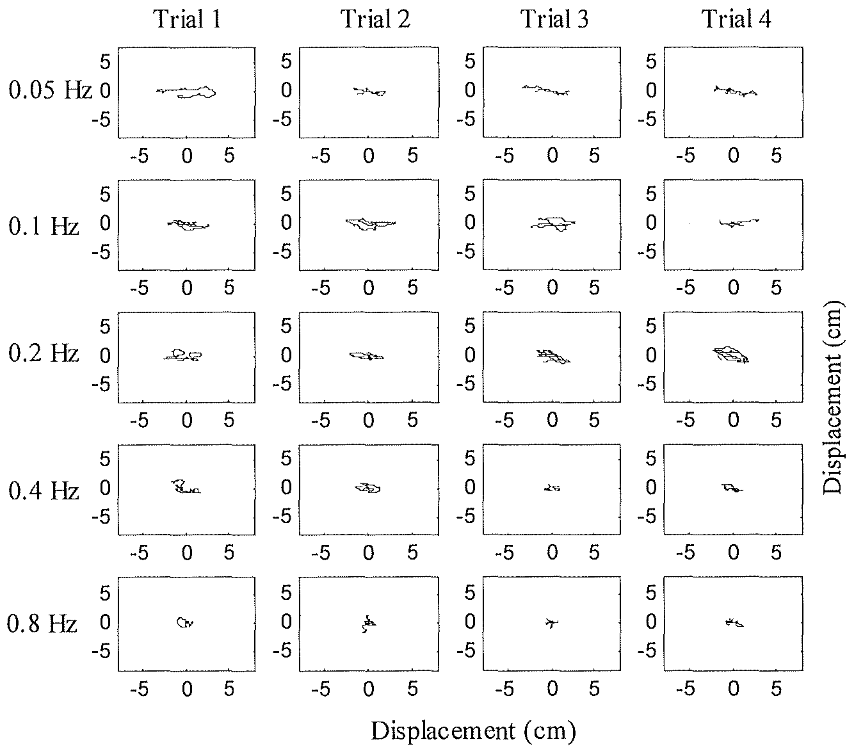
Subject: FSK (fore-and-aft visual stimulus session; head movement trajectory)



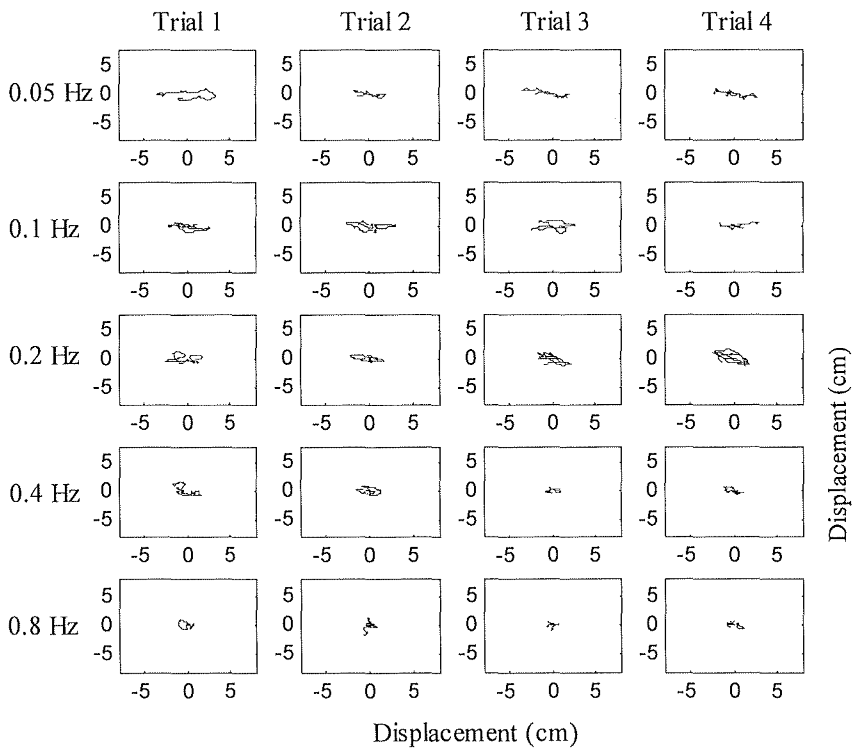
Subject: FSK (fore-and-aft visual stimulus session; body movement trajectory)



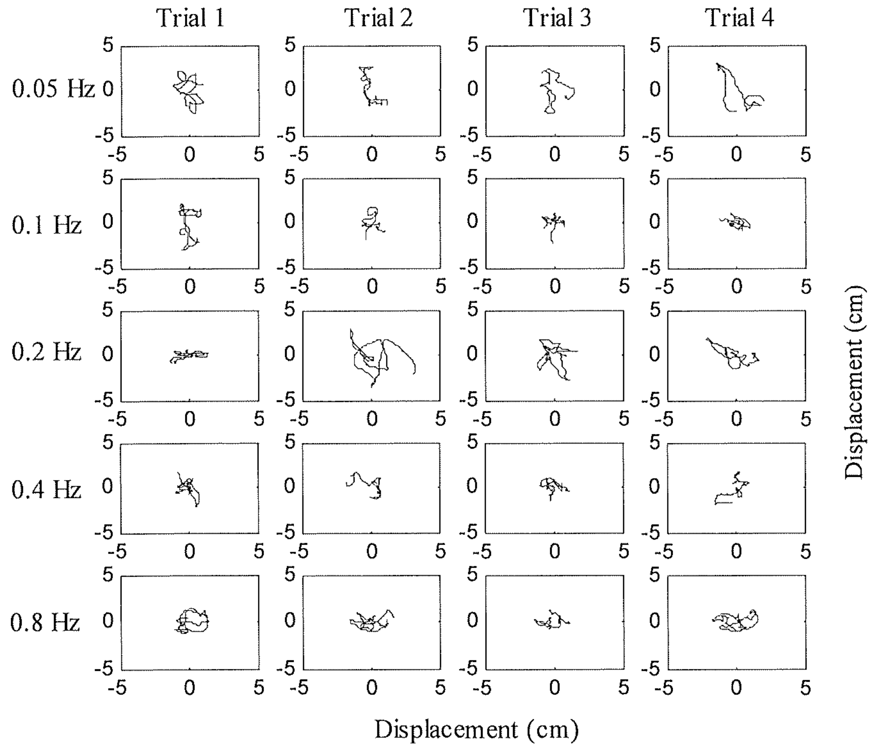
Subject: HAZ (roll visual stimulus session; head movement trajectory)



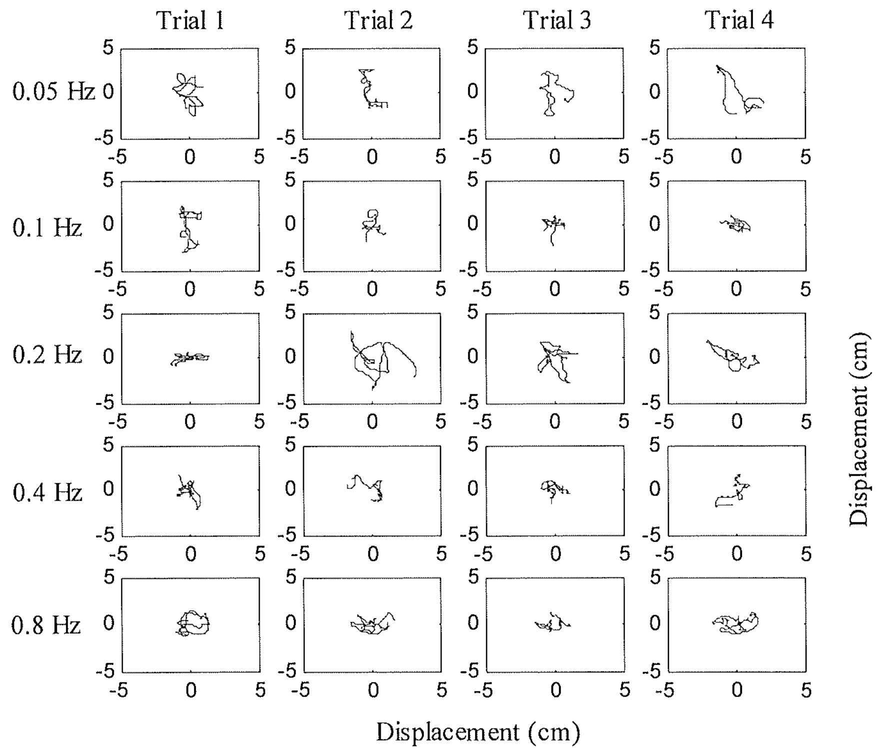
Subject: HAZ (roll visual stimulus session; body movement trajectory)



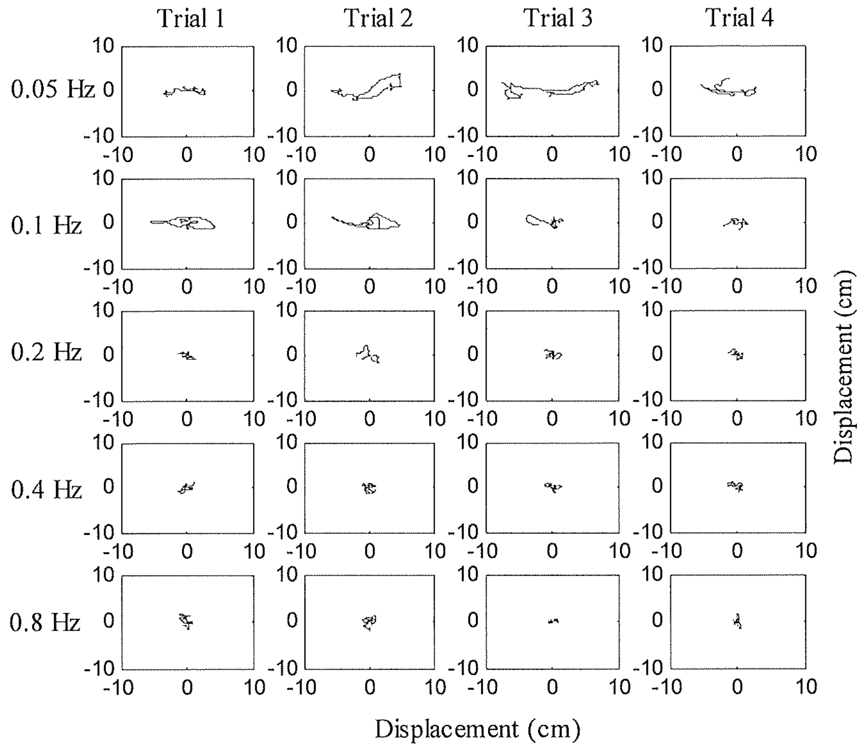
Subject: HAZ (fore-and-aft visual stimulus session; head movement trajectory)



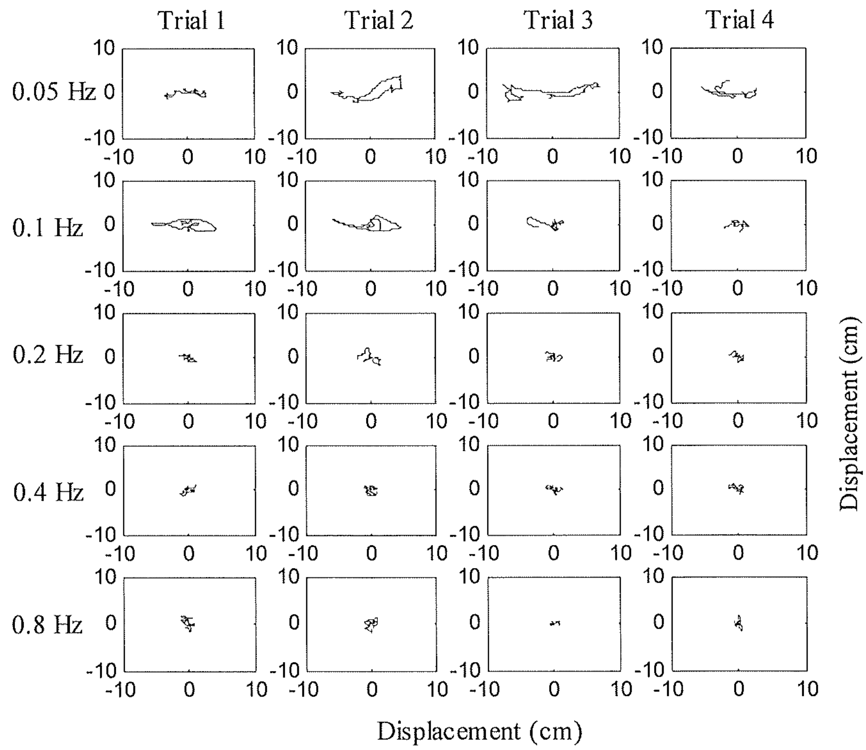
Subject: HAZ (fore-and-aft visual stimulus session; body movement trajectory)



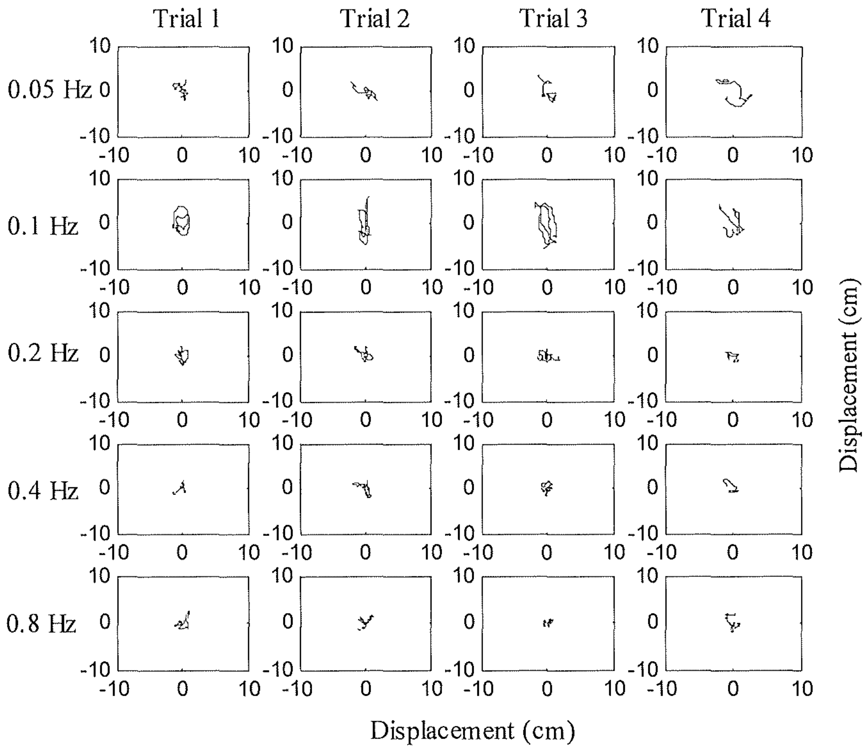
Subject: JON (roll visual stimulus session; head movement trajectory)



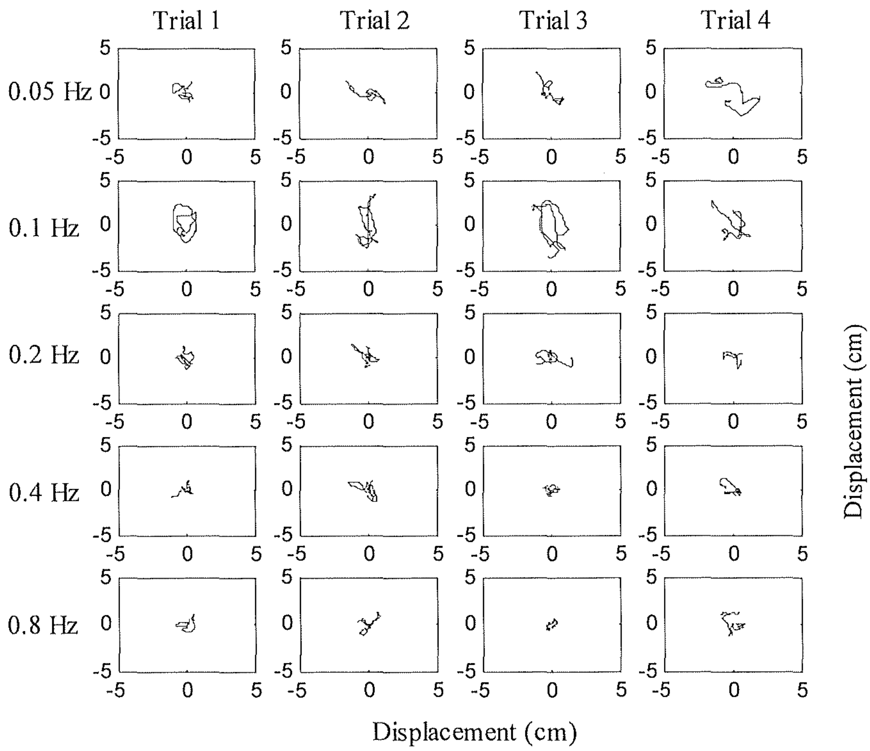
Subject: JON (roll visual stimulus session; body movement trajectory)



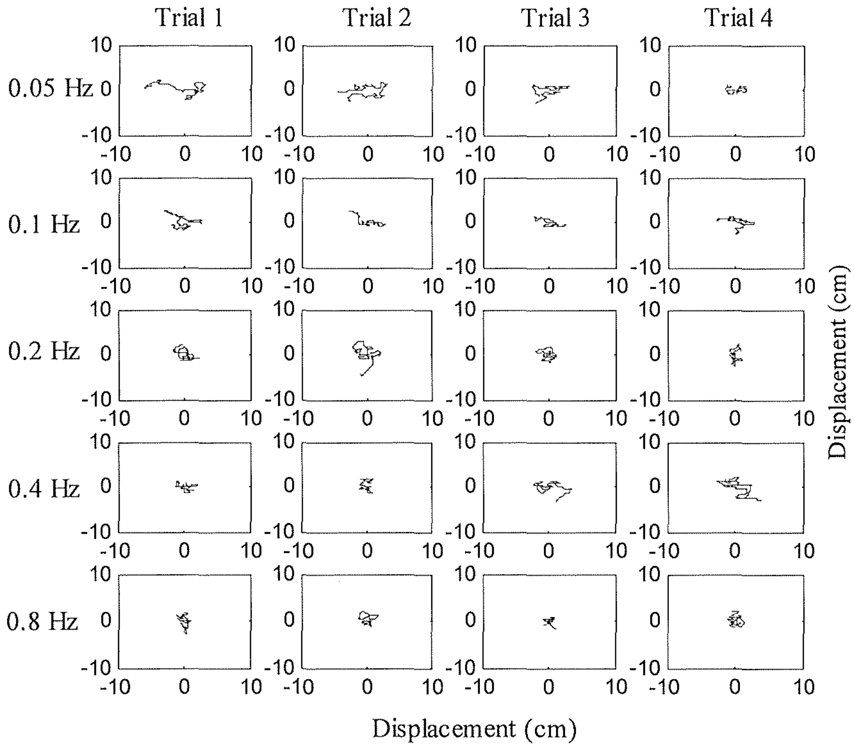
Subject: JON (fore-and-aft visual stimulus session; head movement trajectory)



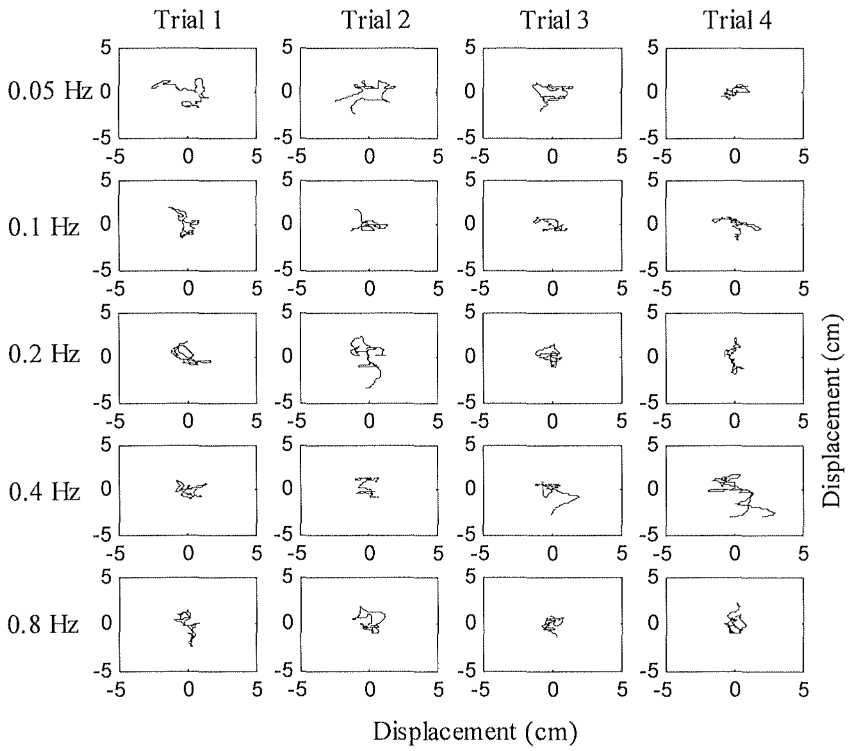
Subject: JON (fore-and-aft visual stimulus session; body movement trajectory)



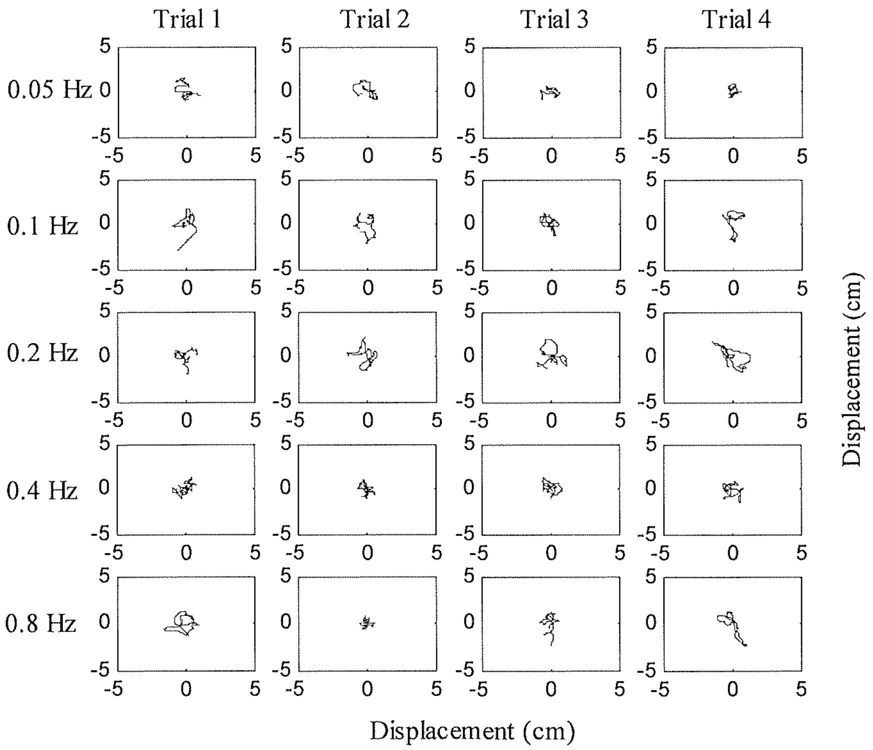
Subject: MAG (roll visual stimulus session; head movement trajectory)



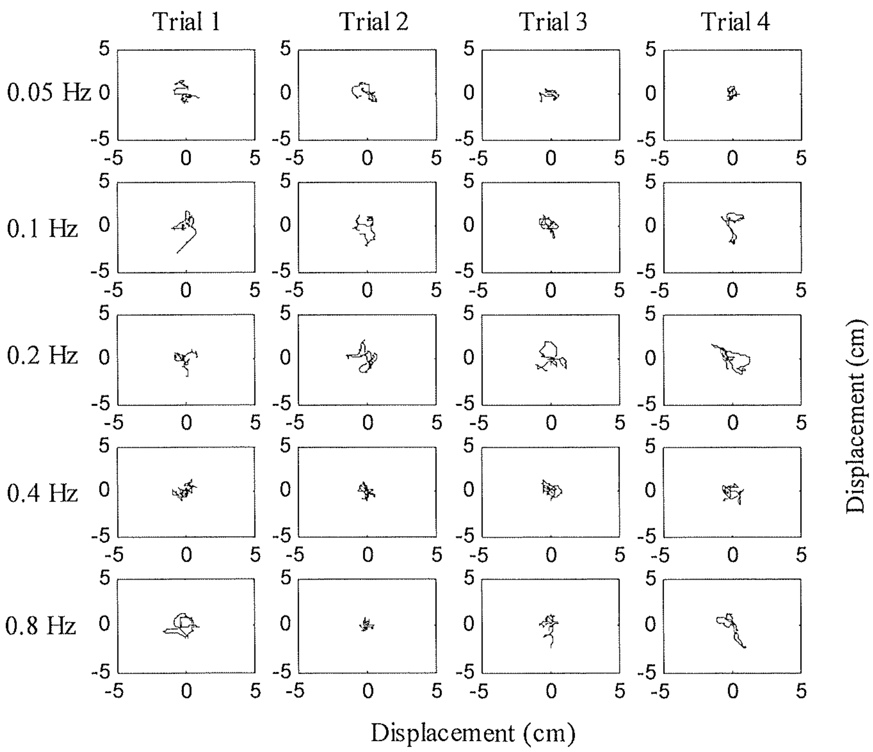
Subject: MAG (roll visual stimulus session; body movement trajectory)



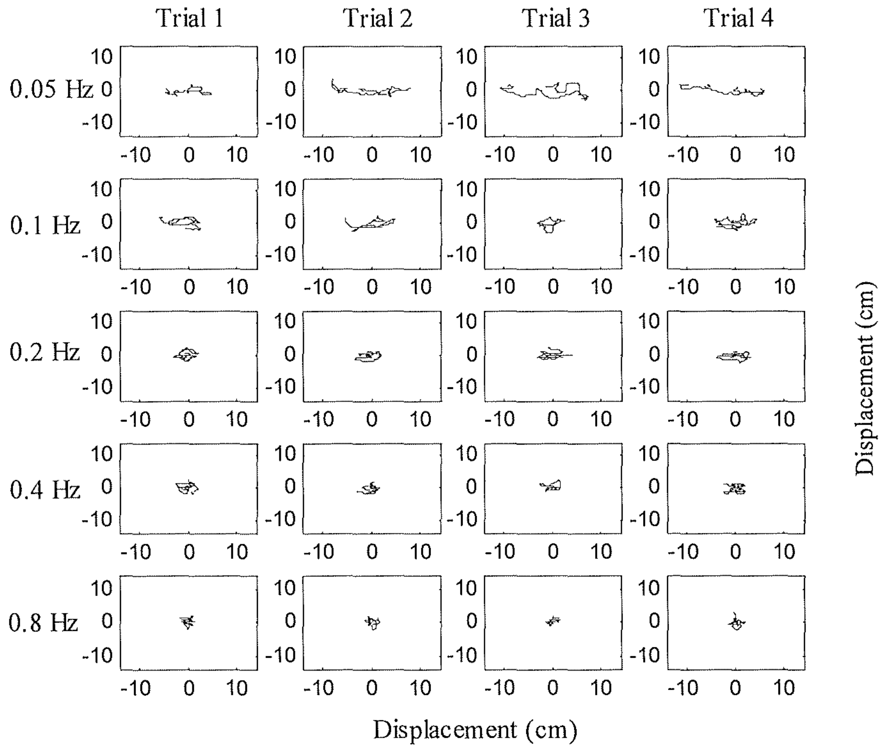
Subject: MAG (fore-and-aft visual stimulus session; head movement trajectory)



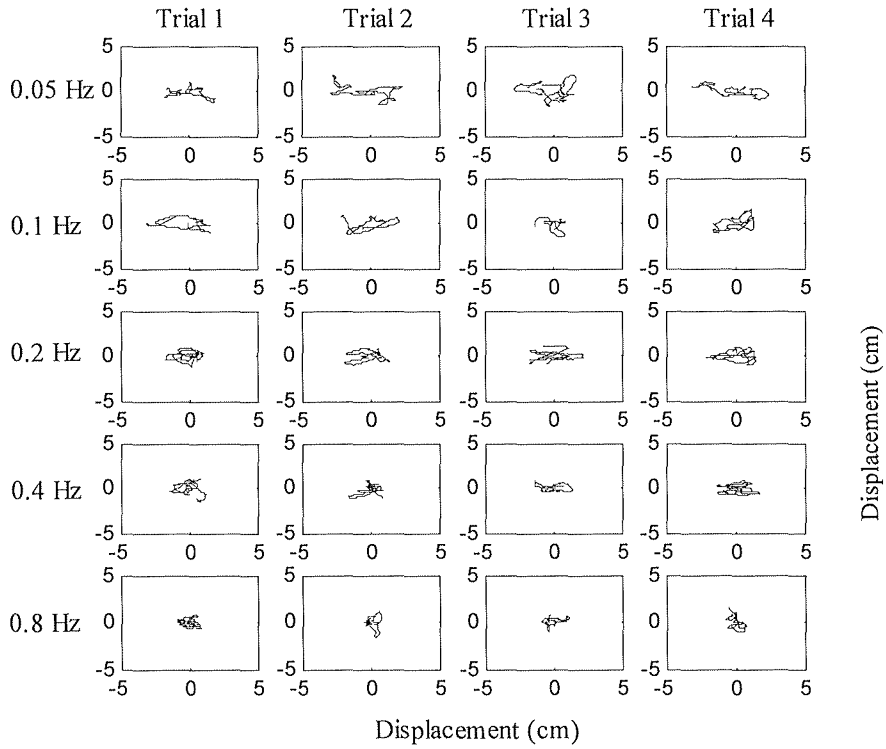
Subject: MAG (fore-and-aft visual stimulus session; body movement trajectory)



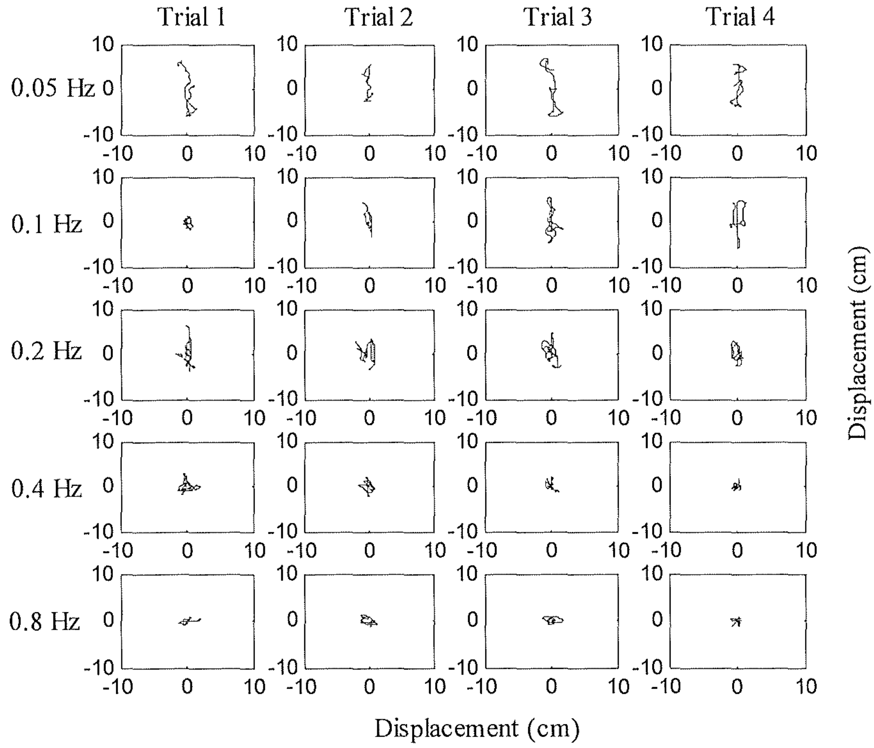
Subject: RTA (roll visual stimulus session; head movement trajectory)



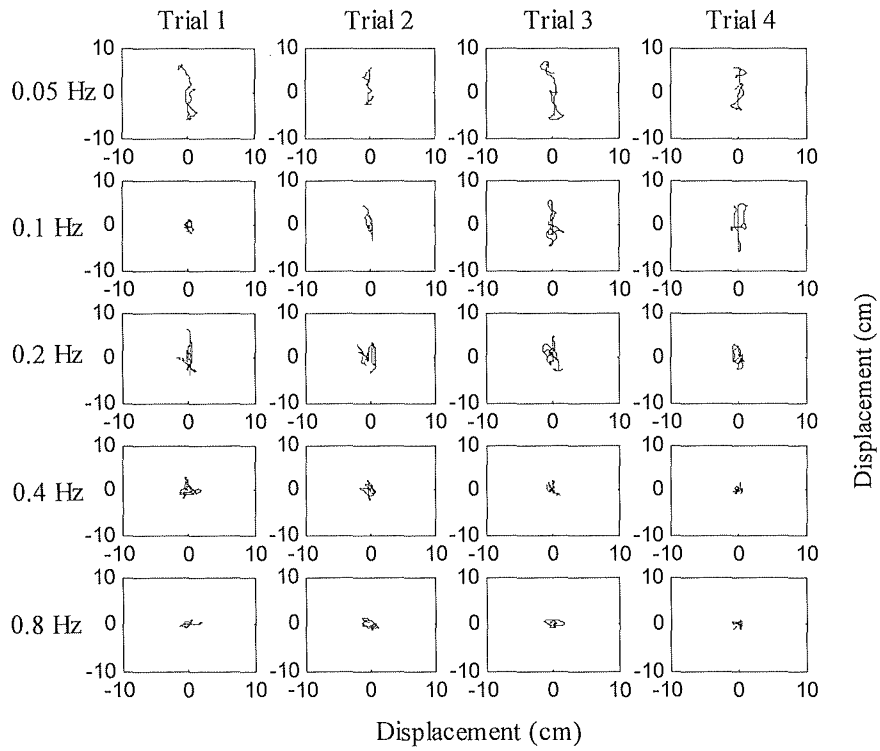
Subject: RTA (roll visual stimulus session; body movement trajectory)



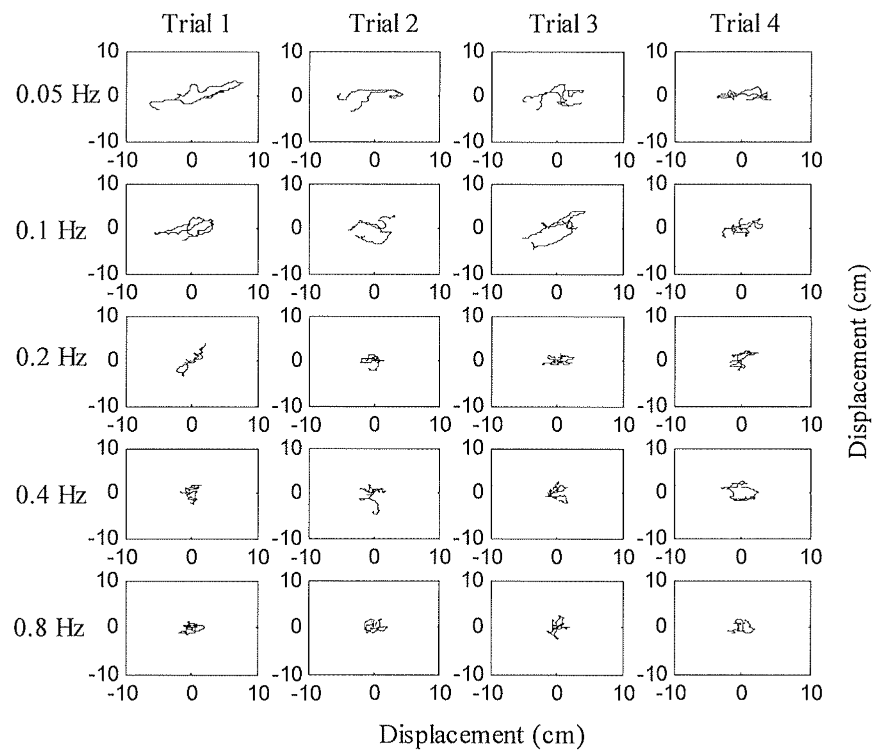
Subject: RTA (fore-and-aft visual stimulus session; head movement trajectory)



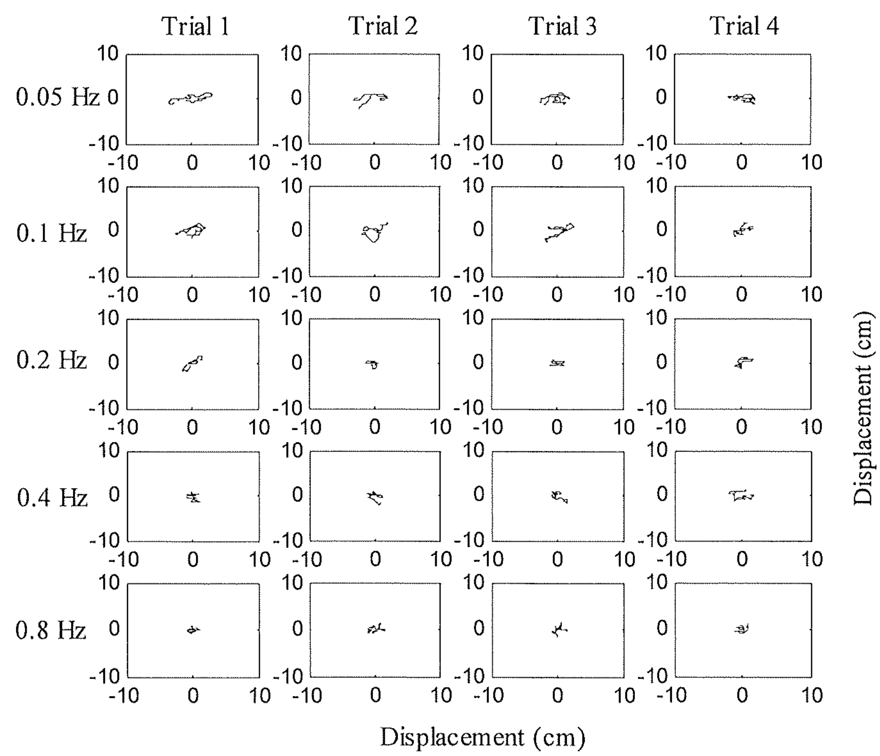
Subject: RTA (fore-and-aft visual stimulus session; body movement trajectory)



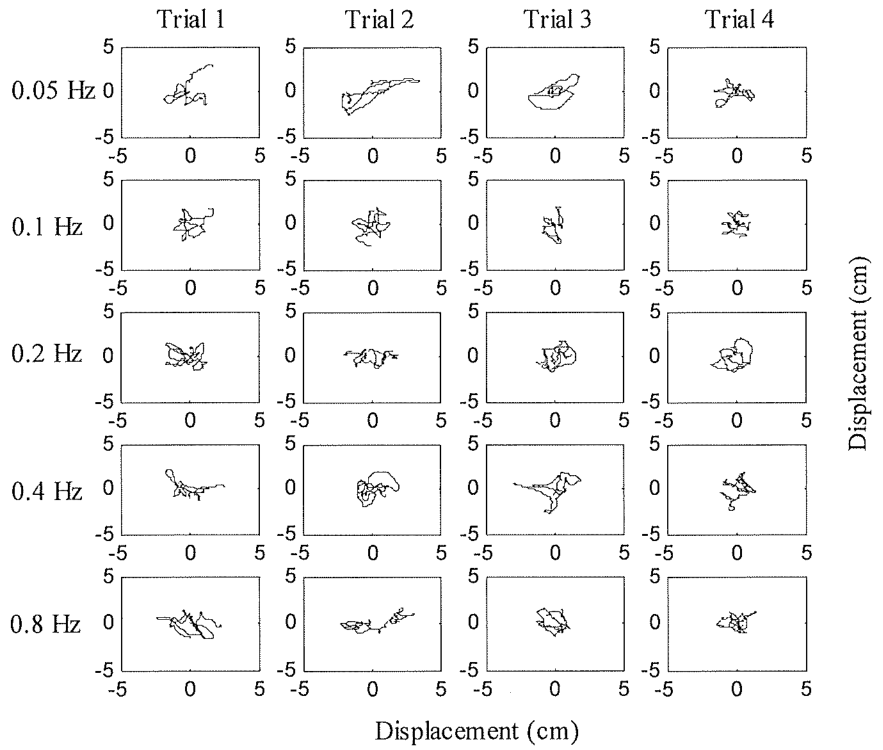
Subject: VCW (roll visual stimulus session; head movement trajectory)



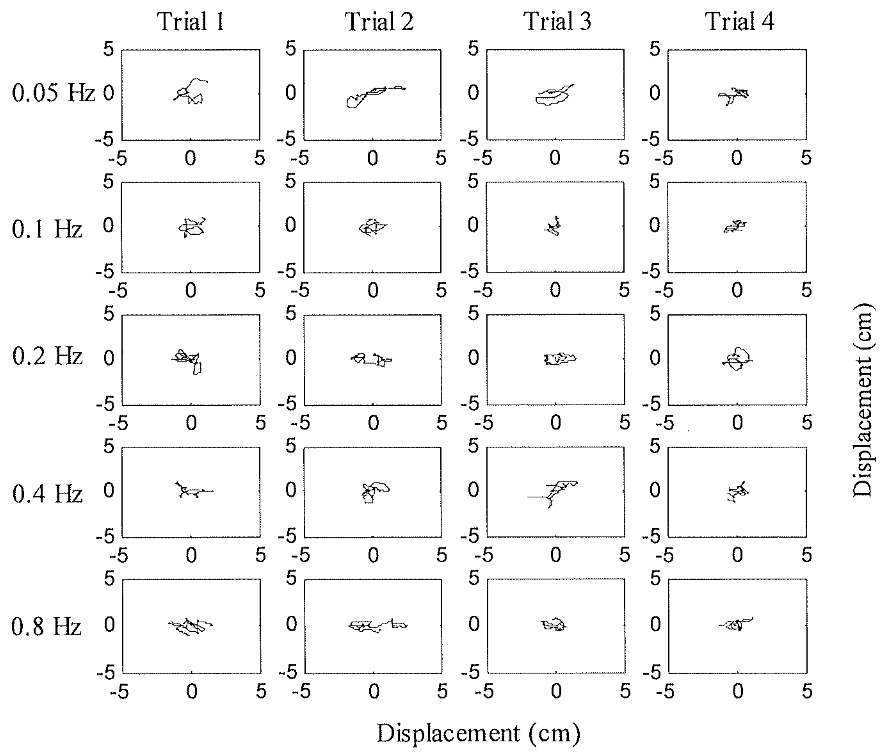
Subject: VCW (roll visual stimulus session; body movement trajectory)



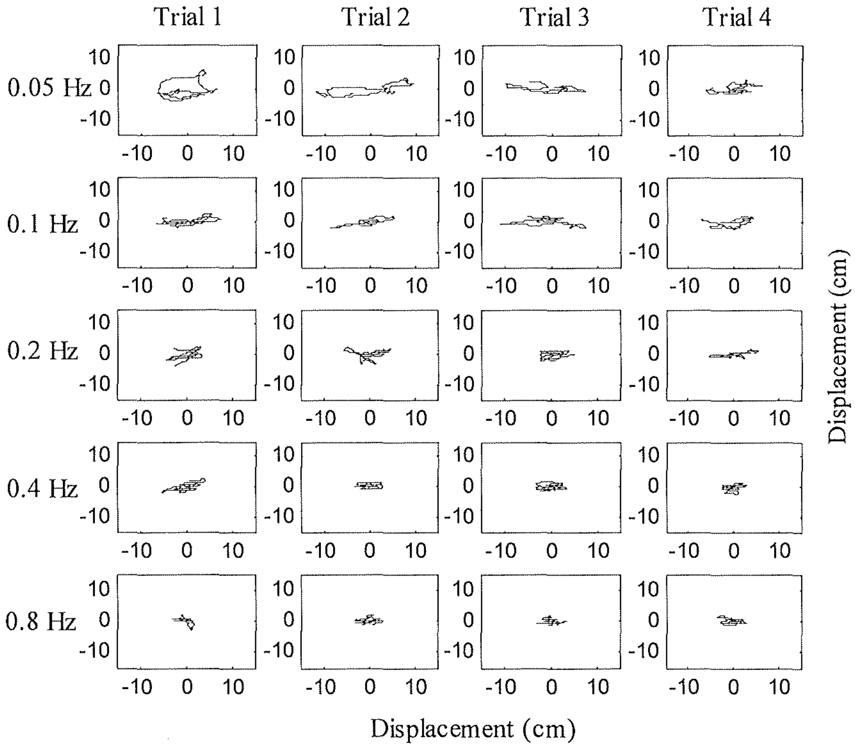
Subject: VCW (fore-and-aft visual stimulus session; head movement trajectory)



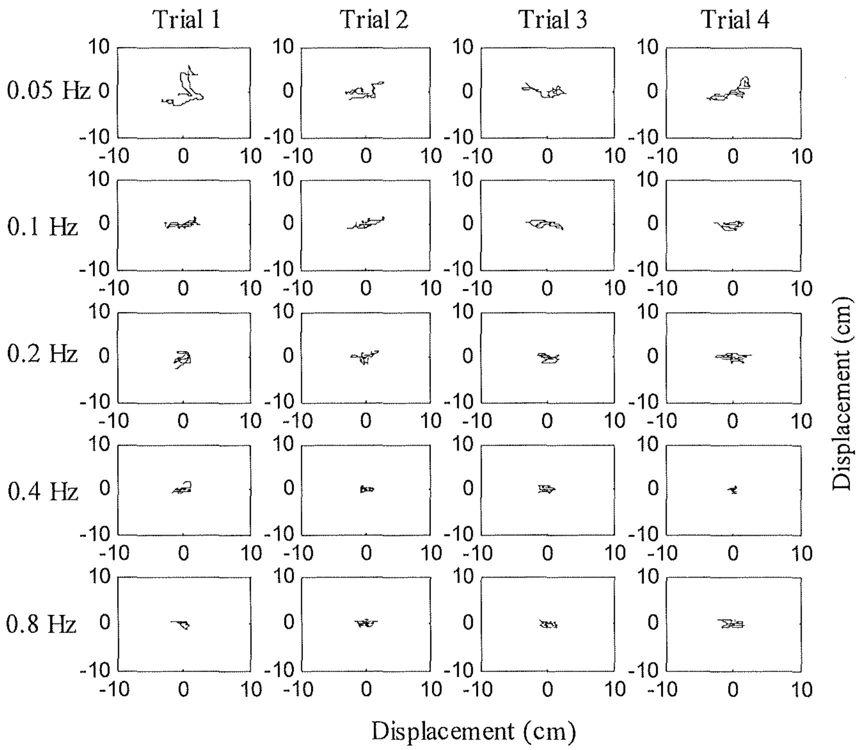
Subject: VCW (fore-and-aft visual stimulus session; body movement trajectory)



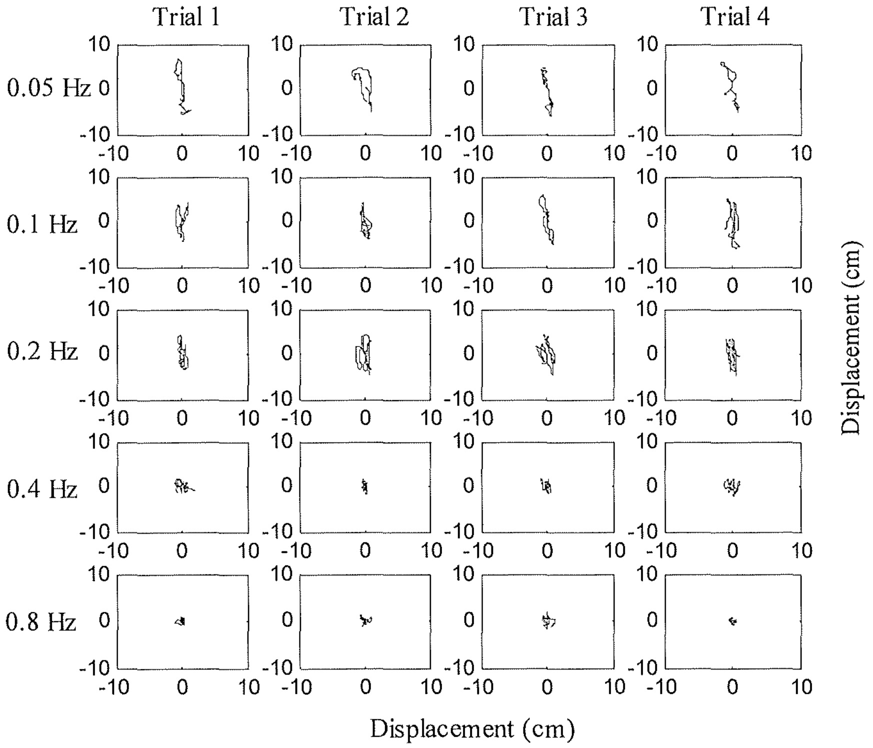
Subject: XYU (roll visual stimulus session; head movement trajectory)



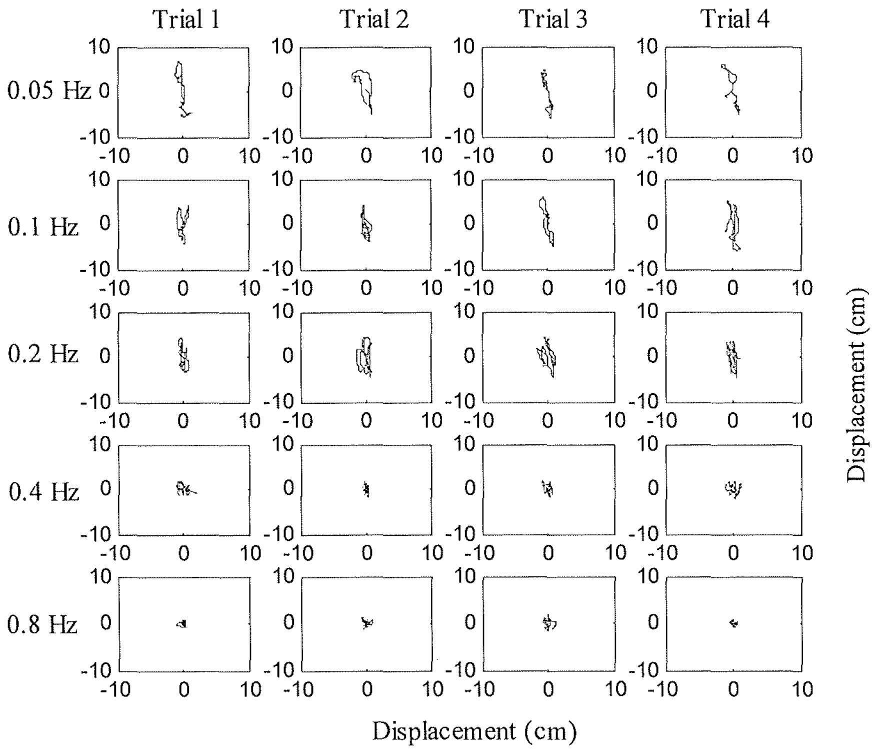
Subject: XYU (roll visual stimulus session; body movement trajectory)



Subject: XYU (fore-and-aft visual stimulus session; head movement trajectory)

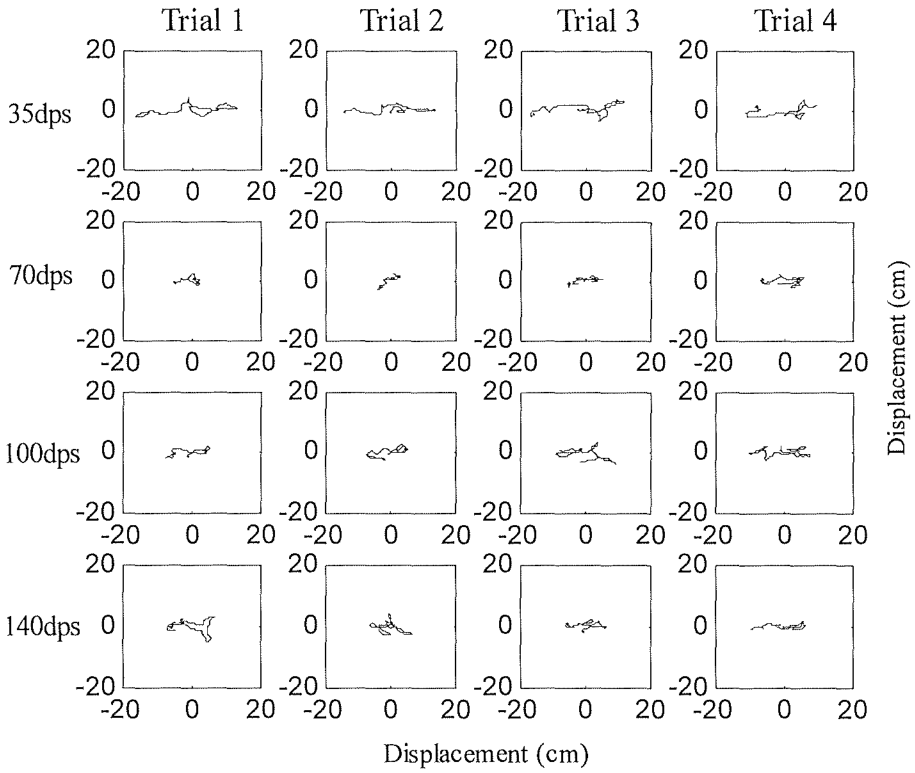


Subject: XYU (fore-and-aft visual stimulus session; body movement trajectory)

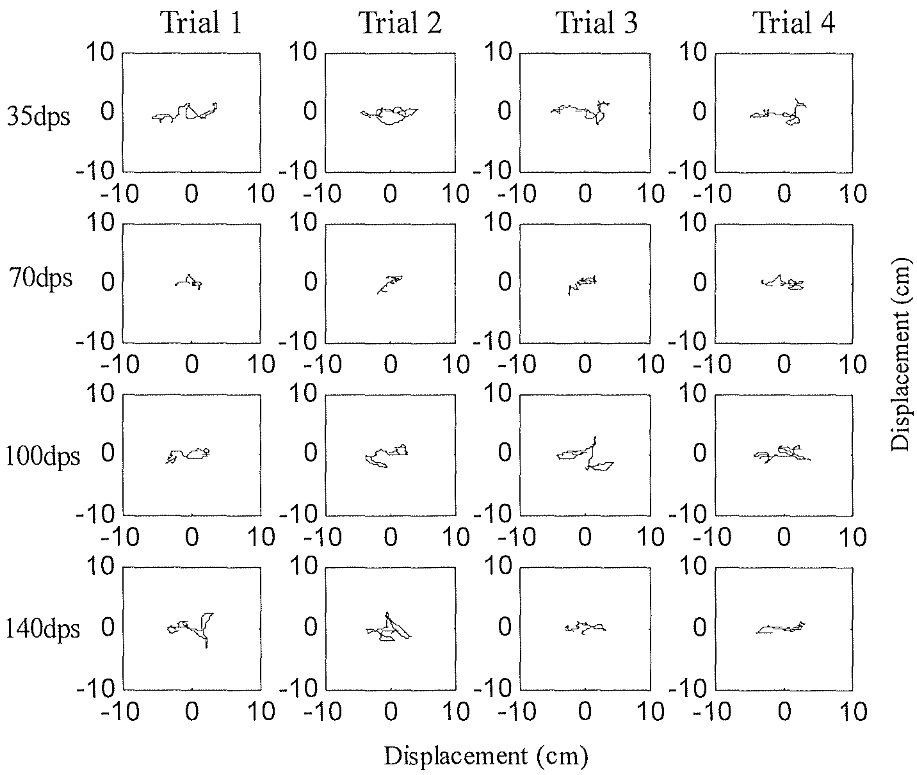


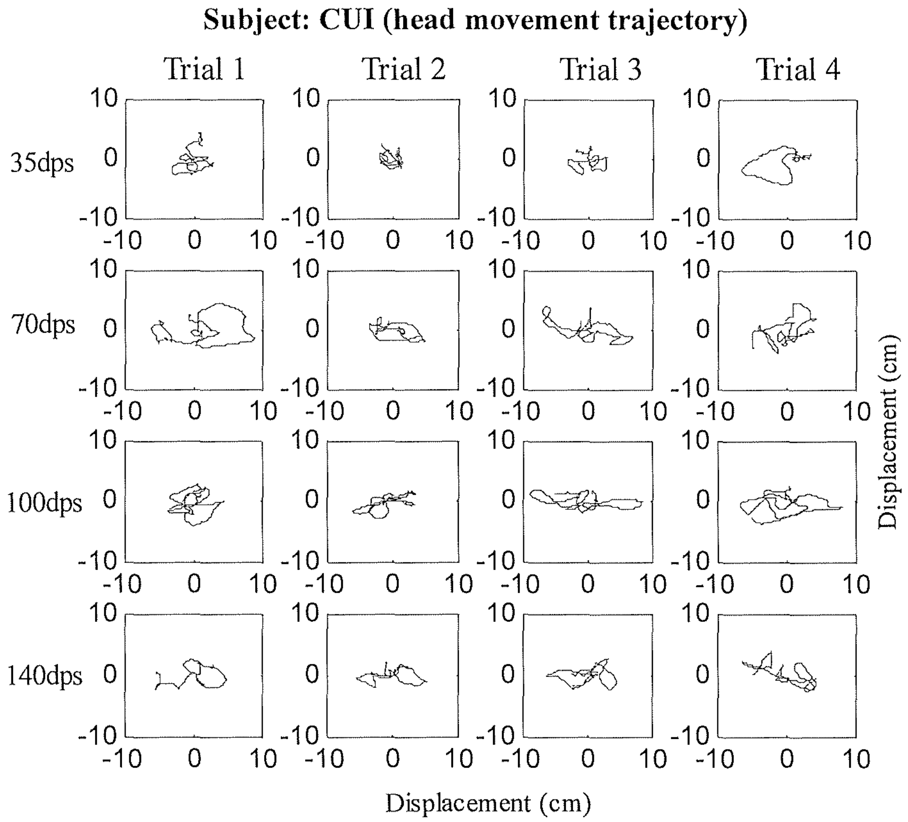
APPENDIX G: BODY AND HEAD POSITION TRAJECTORY PLOTS (STUDY 2)

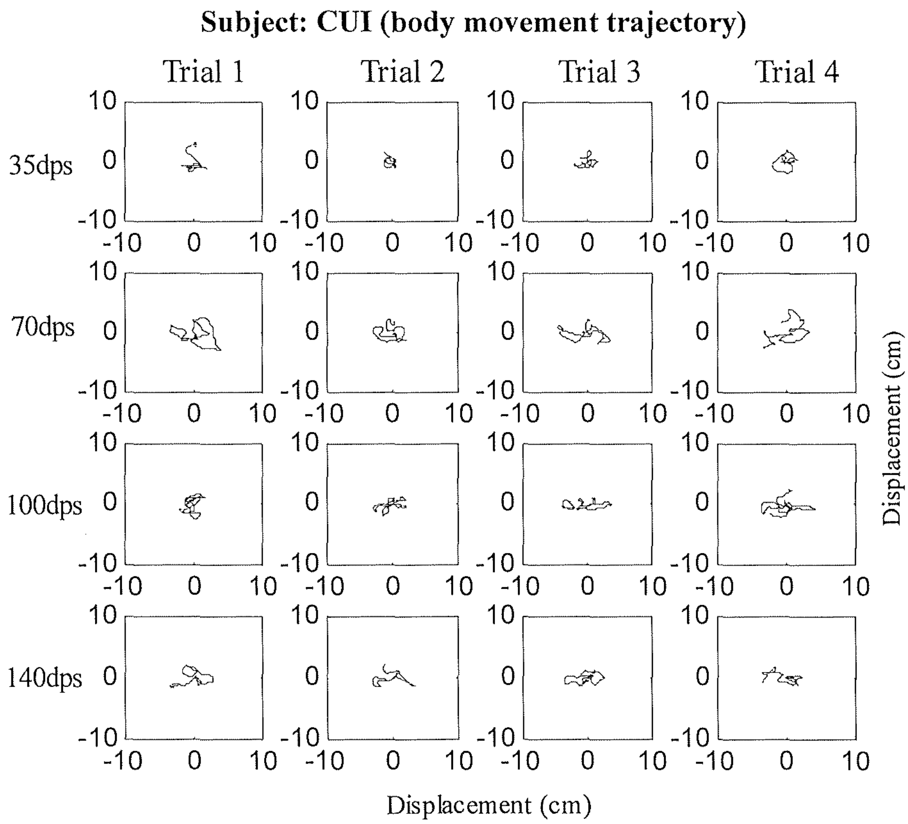
Subject: CHE (head movement trajectory)



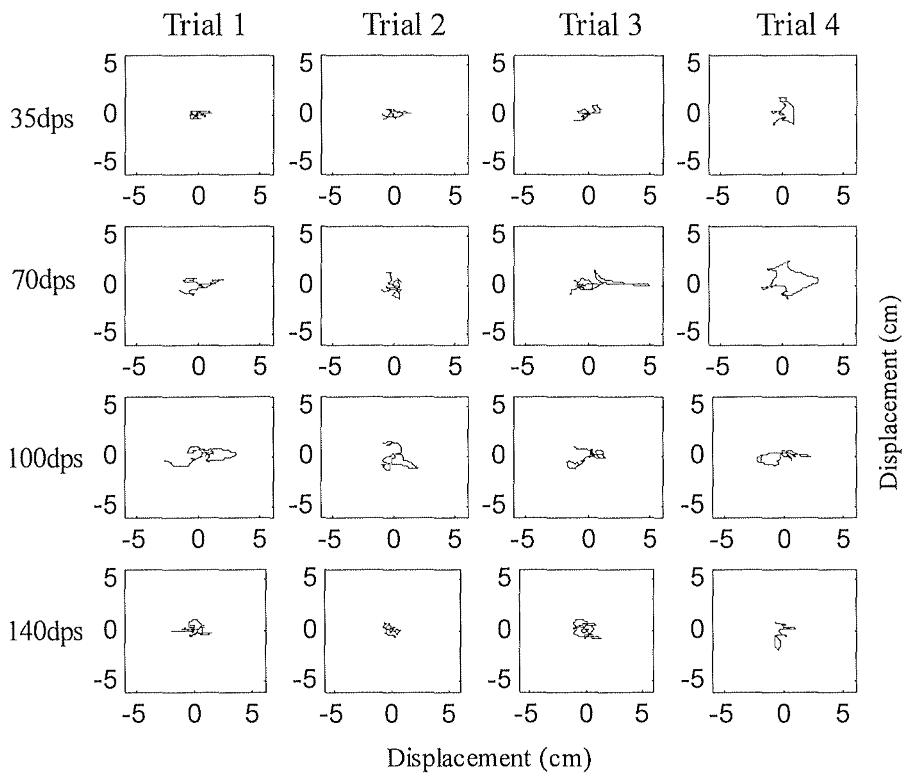
Subject: CHE (body movement trajectory)



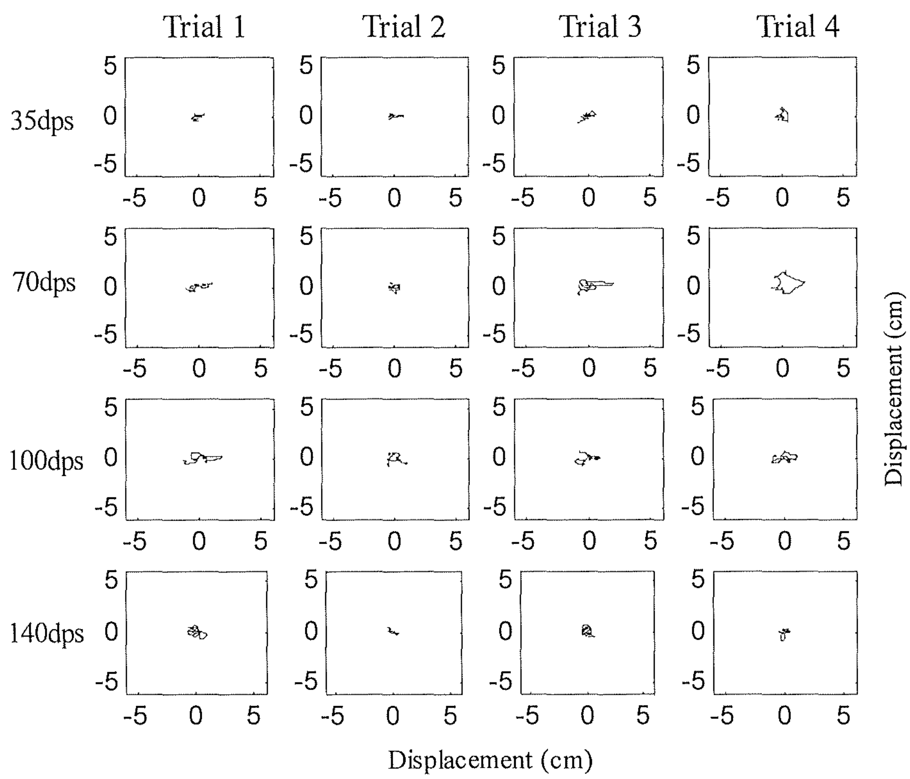

Subject: CUI (head movement trajectory)
Trial 1
Trial 2
Trial 3
Trial 4
35dps
70dps
100dps
140dps
10
0
-10
Displacement (cm)
Displacement (cm)


Subject: CUI (body movement trajectory)
Trial 1
Trial 2
Trial 3
Trial 4
35dps
70dps
100dps
140dps
10
0
-10
Displacement (cm)
Displacement (cm)

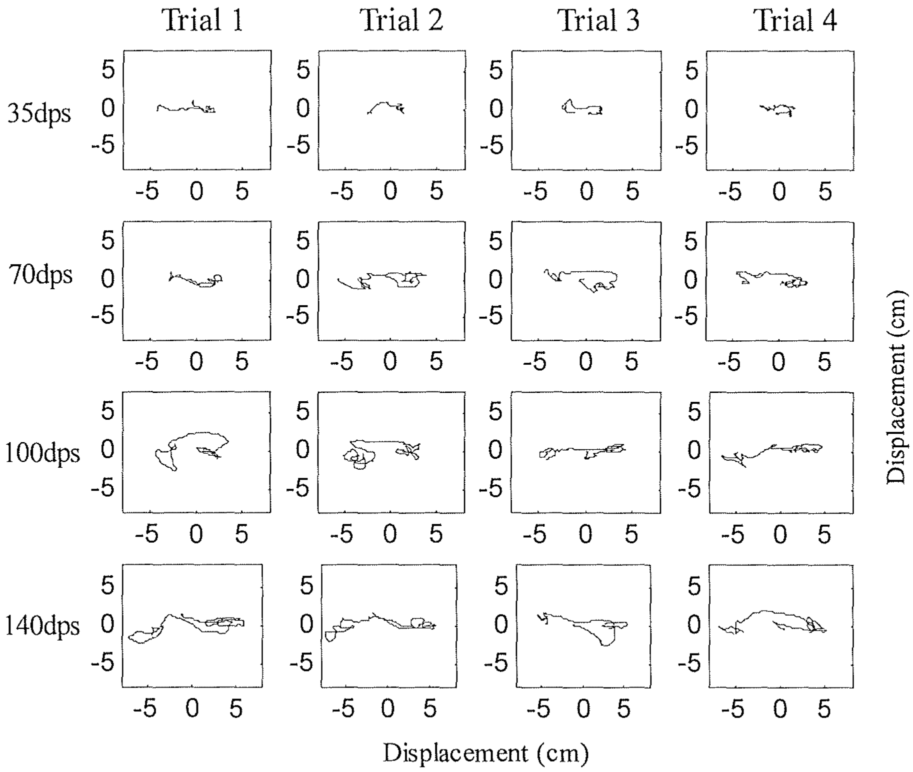
Subject: CUI (head movement trajectory)



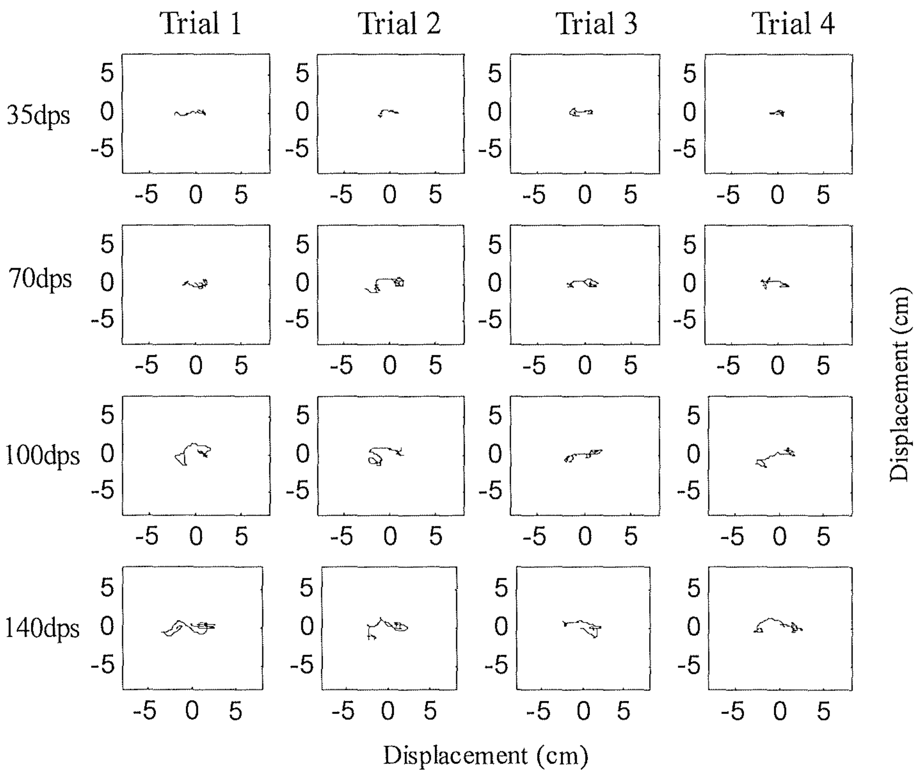
Subject: CUI (body movement trajectory)



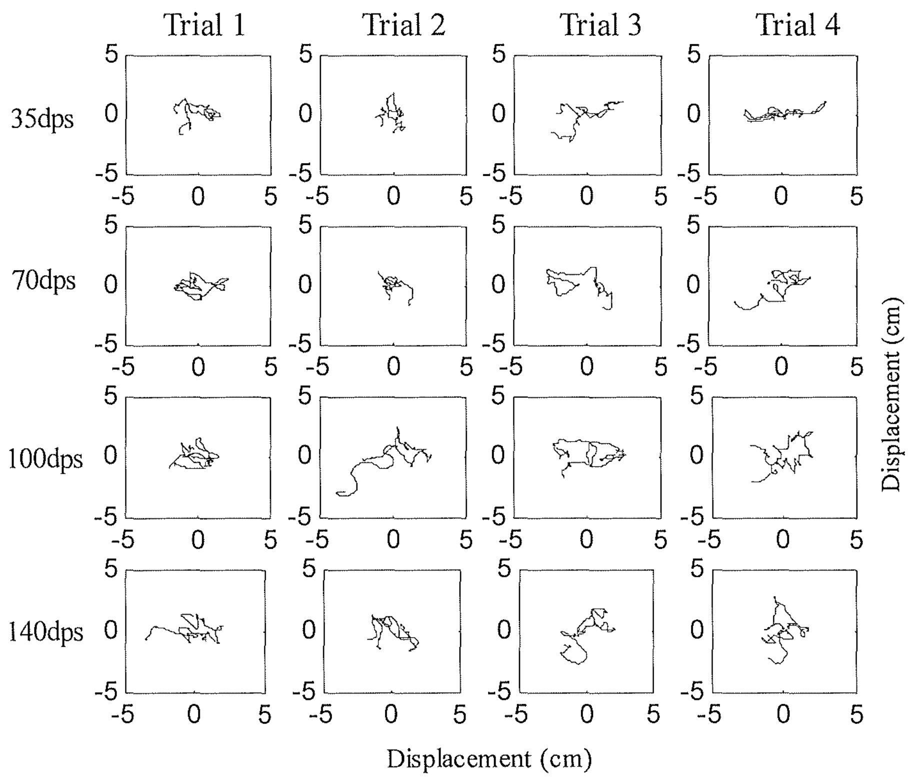
Subject: DAV (head movement trajectory)



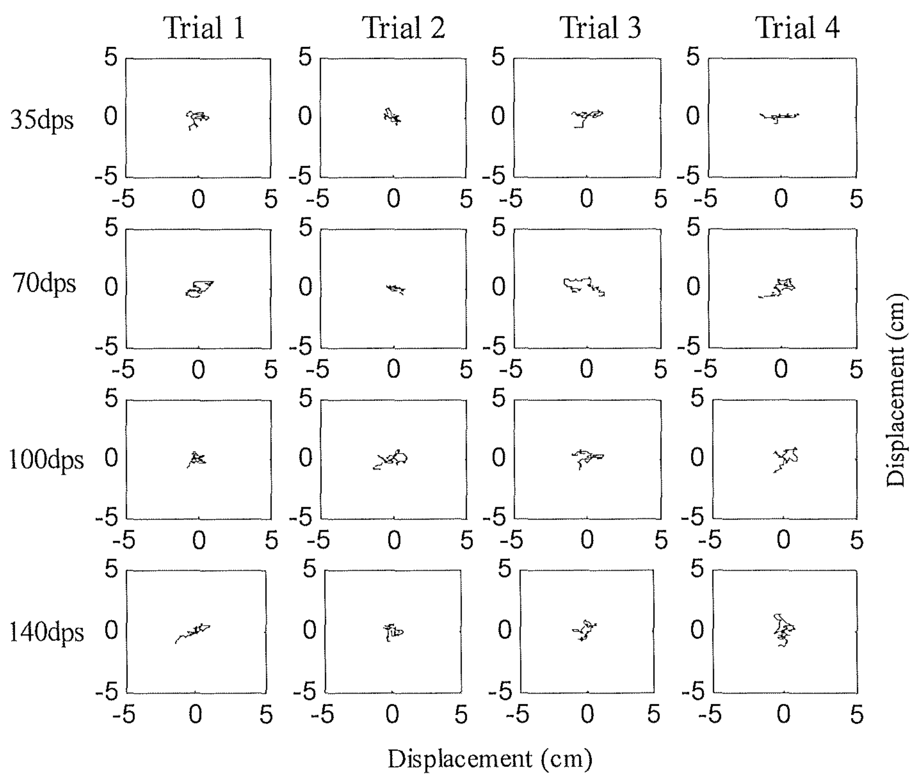
Subject: DAV (body movement trajectory)



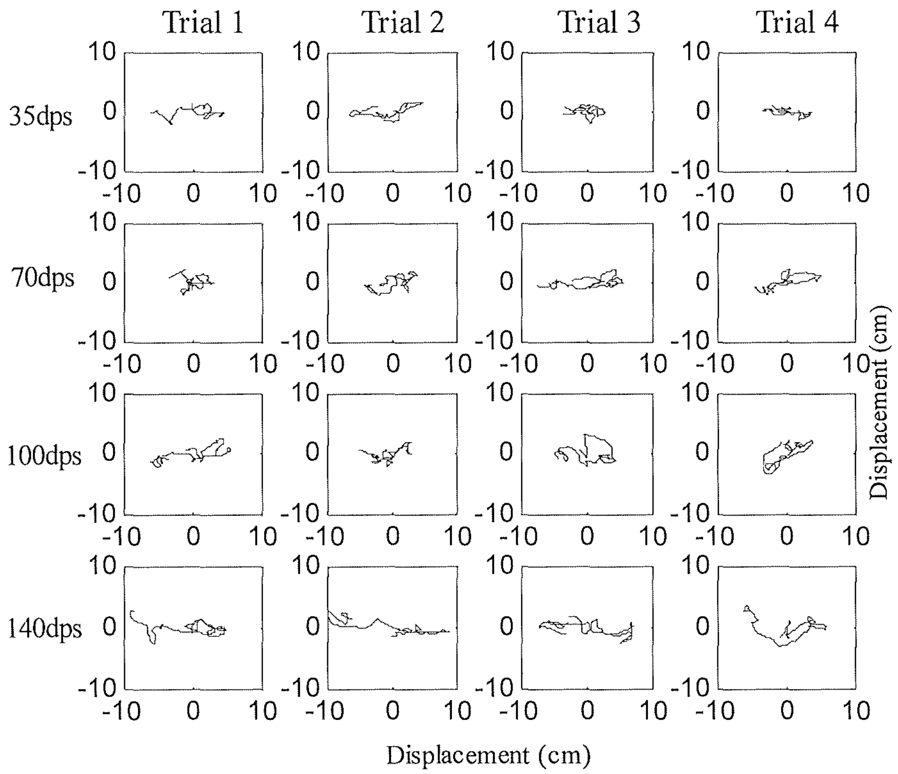
Subject: JAS (head movement trajectory)



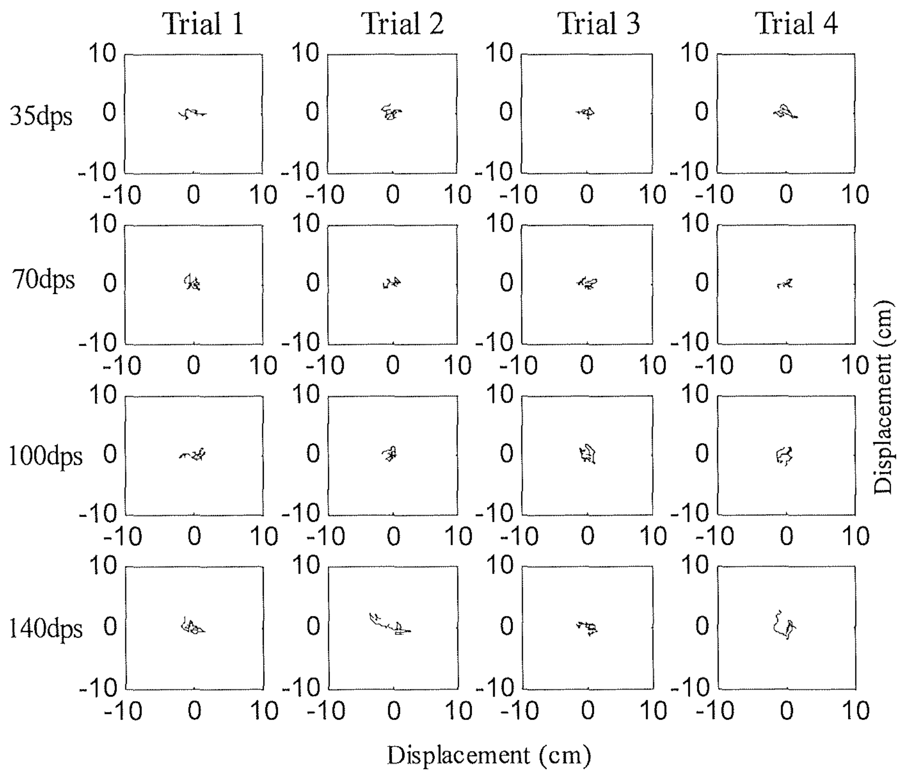
Subject: JAS (body movement trajectory)



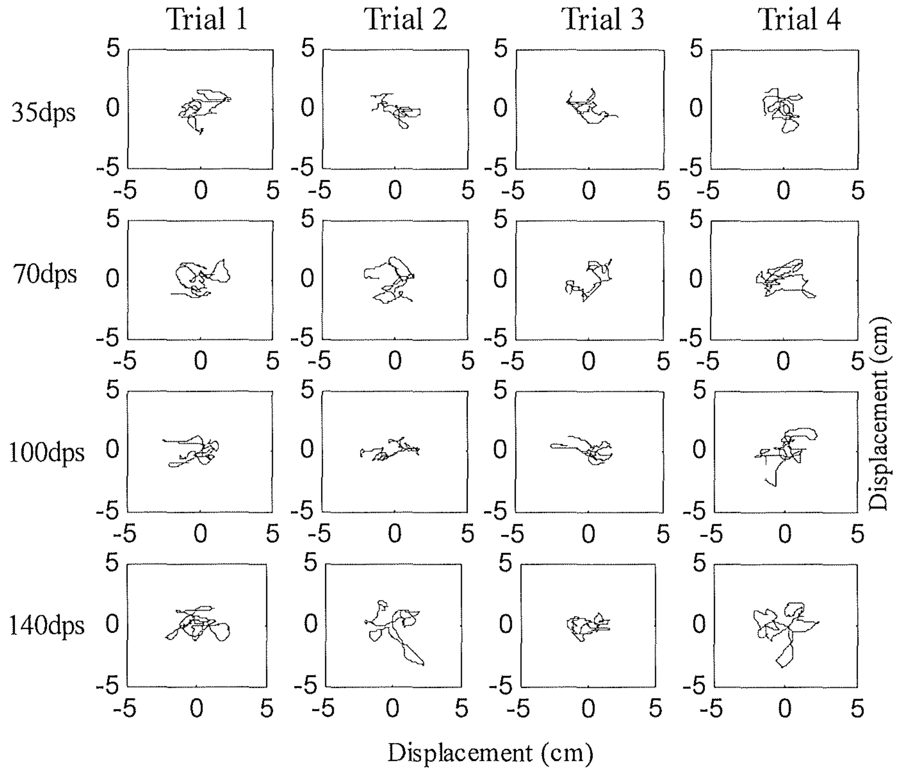
Subject: LHY (head movement trajectory)



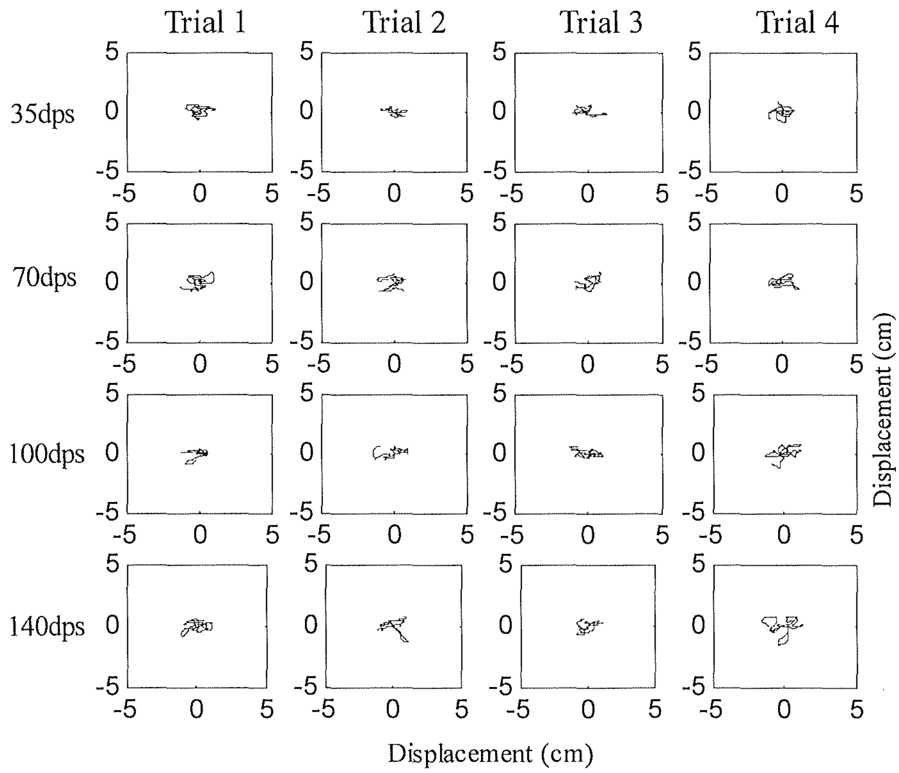
Subject: LHY (body movement trajectory)



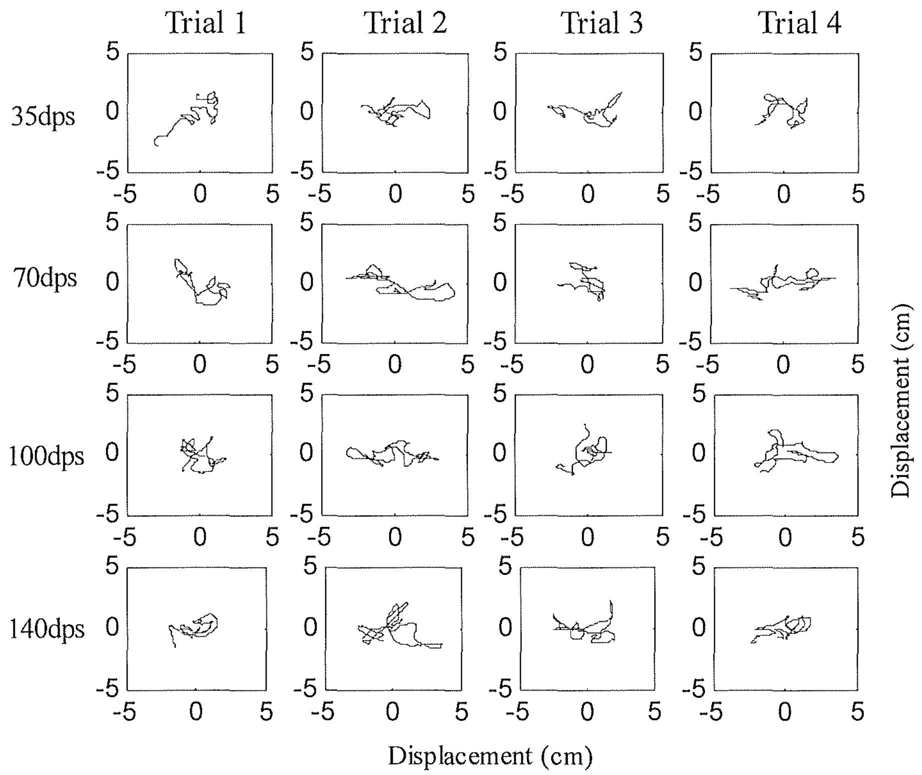
Subject: MAN (head movement trajectory)



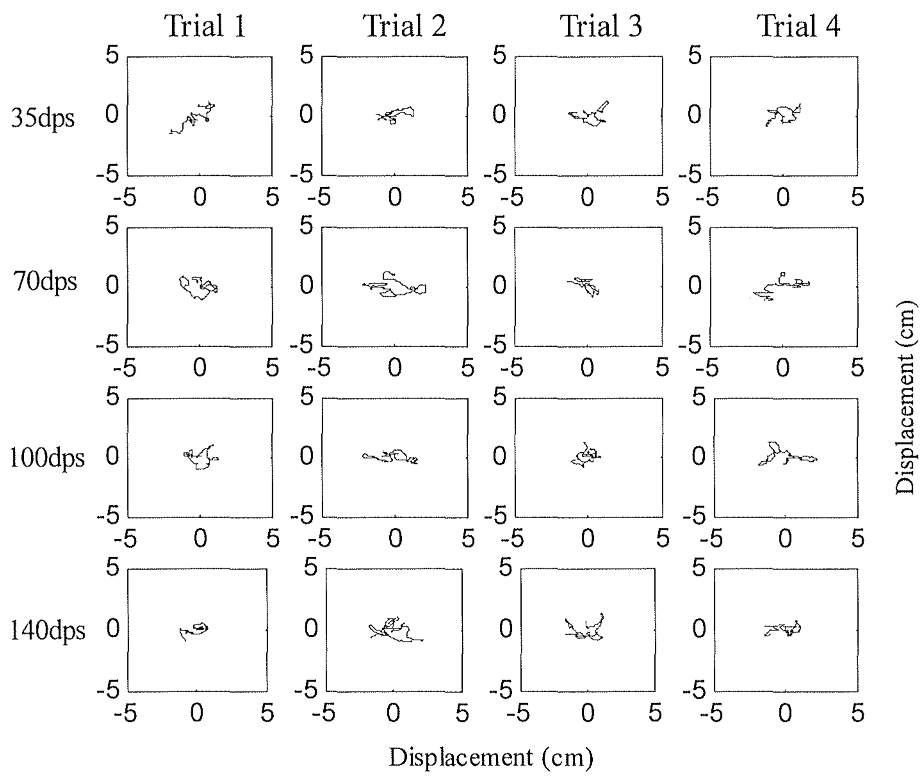
Subject: MAN (body movement trajectory)



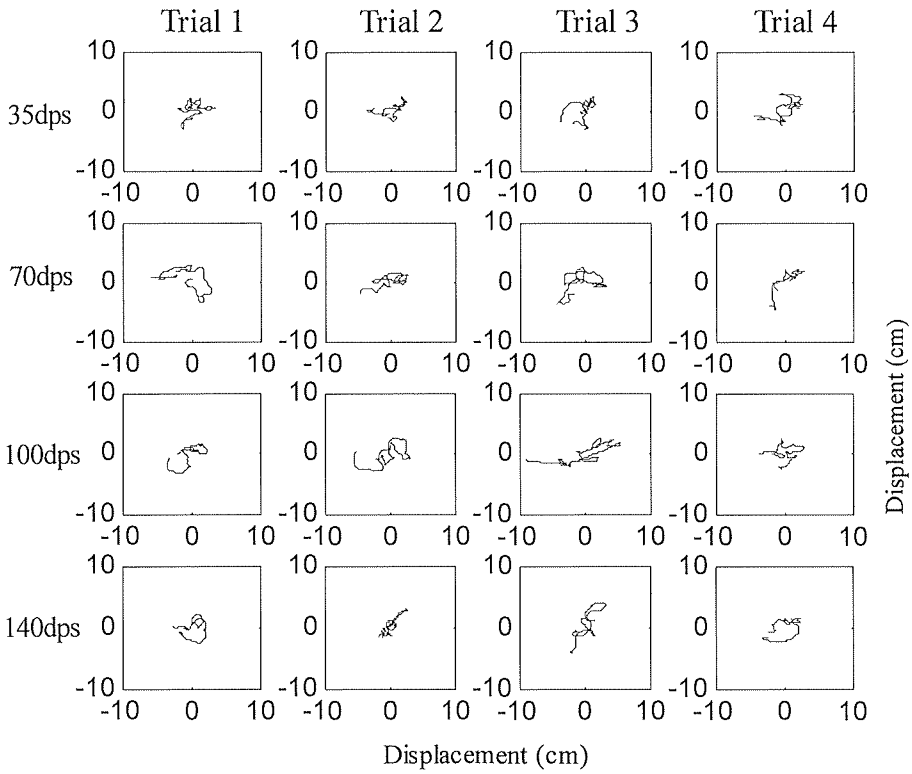
Subject: PAN (head movement trajectory)



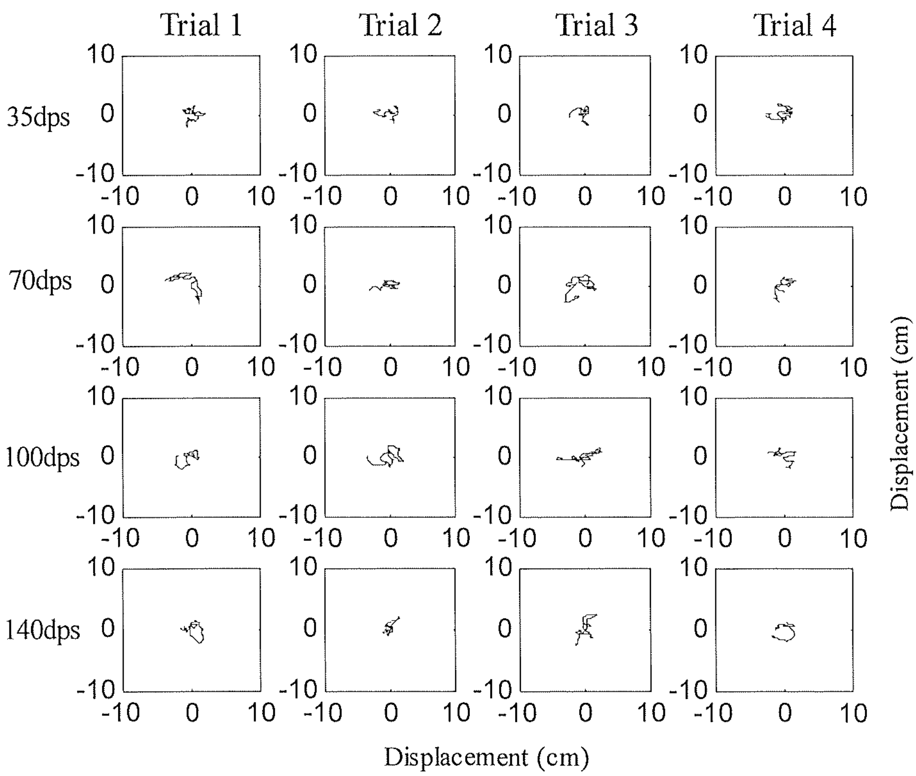
Subject: PAN (body movement trajectory)



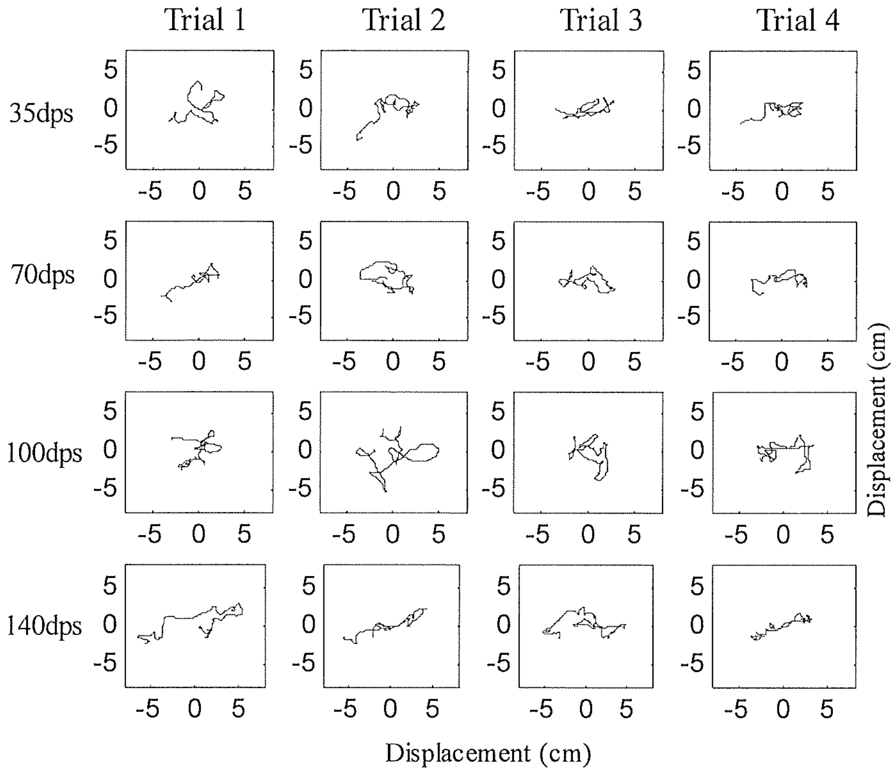
Subject: PHO (head movement trajectory)



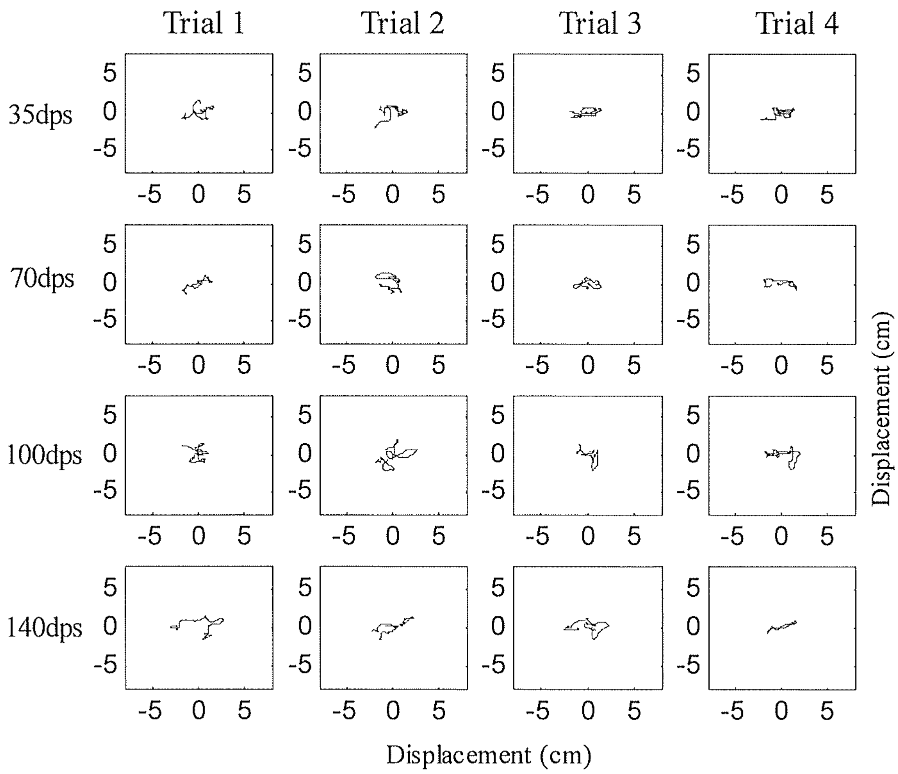
Subject: PHO (body movement trajectory)



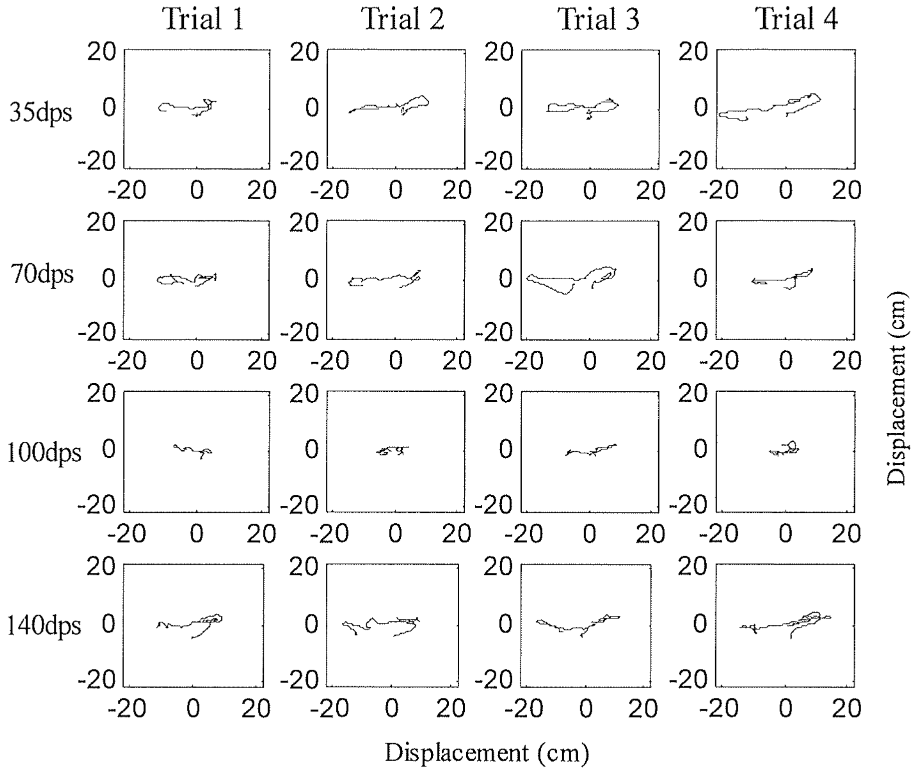
Subject: WCH (head movement trajectory)



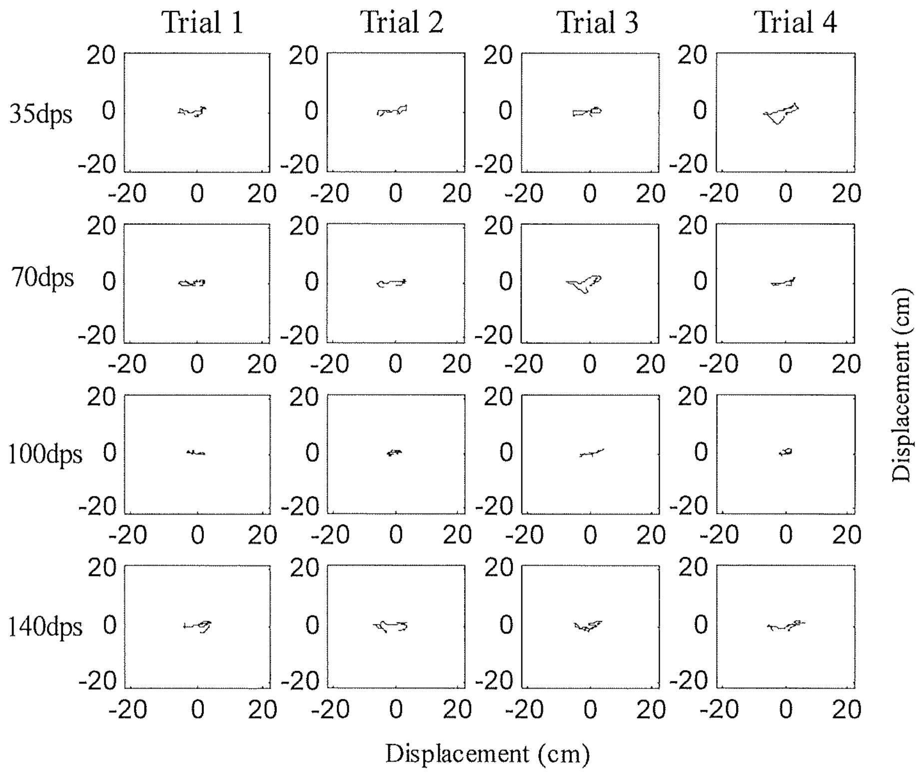
Subject: WCH (body movement trajectory)



Subject: YUE (head movement trajectory)

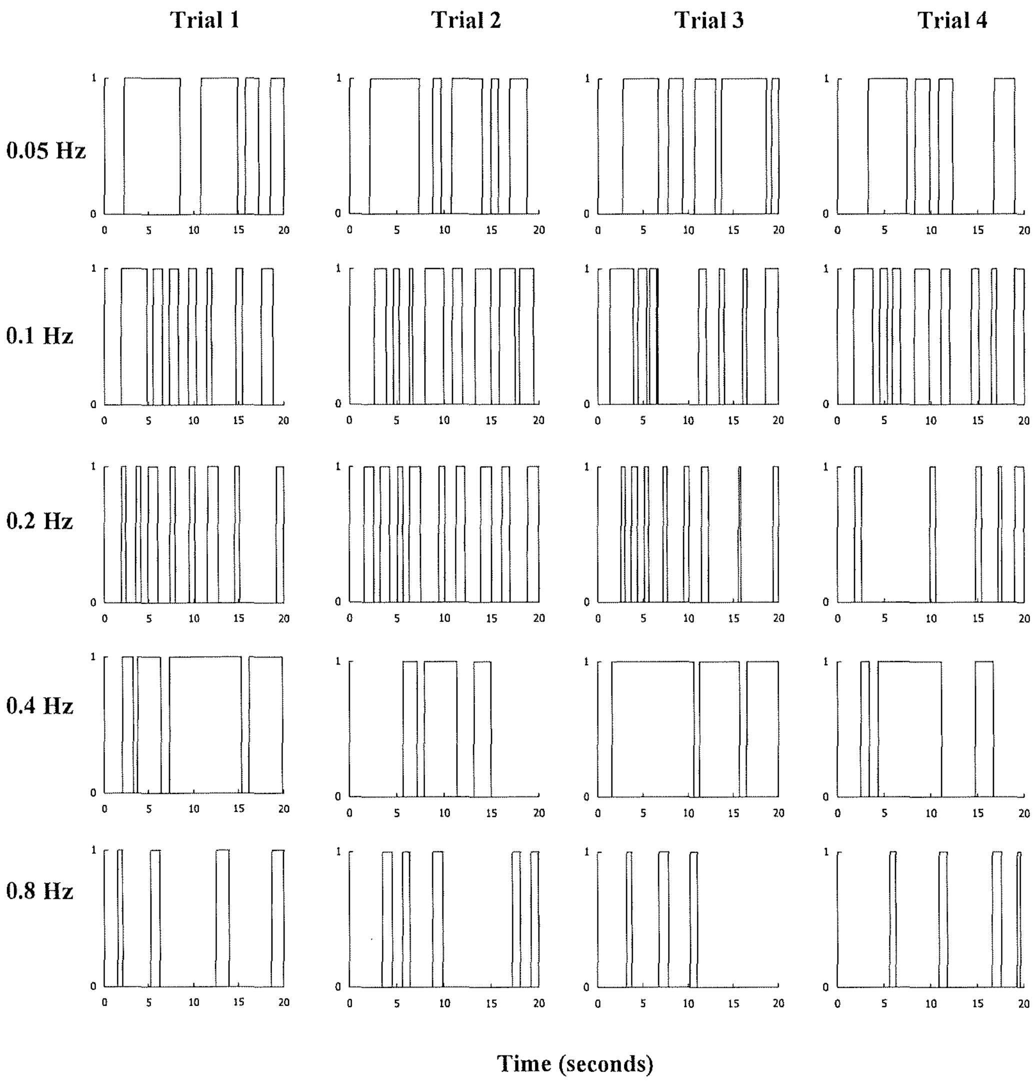


Subject: YUE (body movement trajectory)

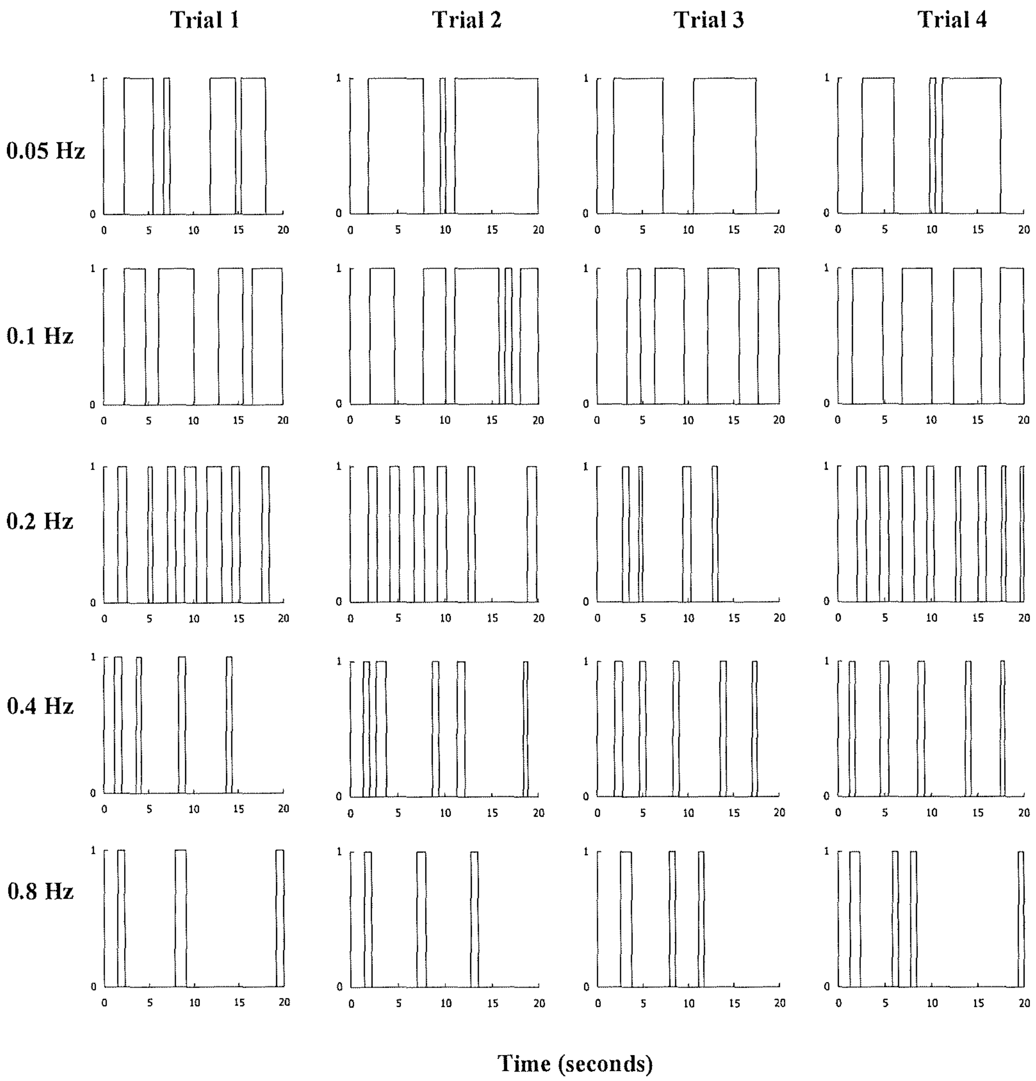


APPENDIX H: VECTION TIME-COURSE PLOTS (STUDY 1)

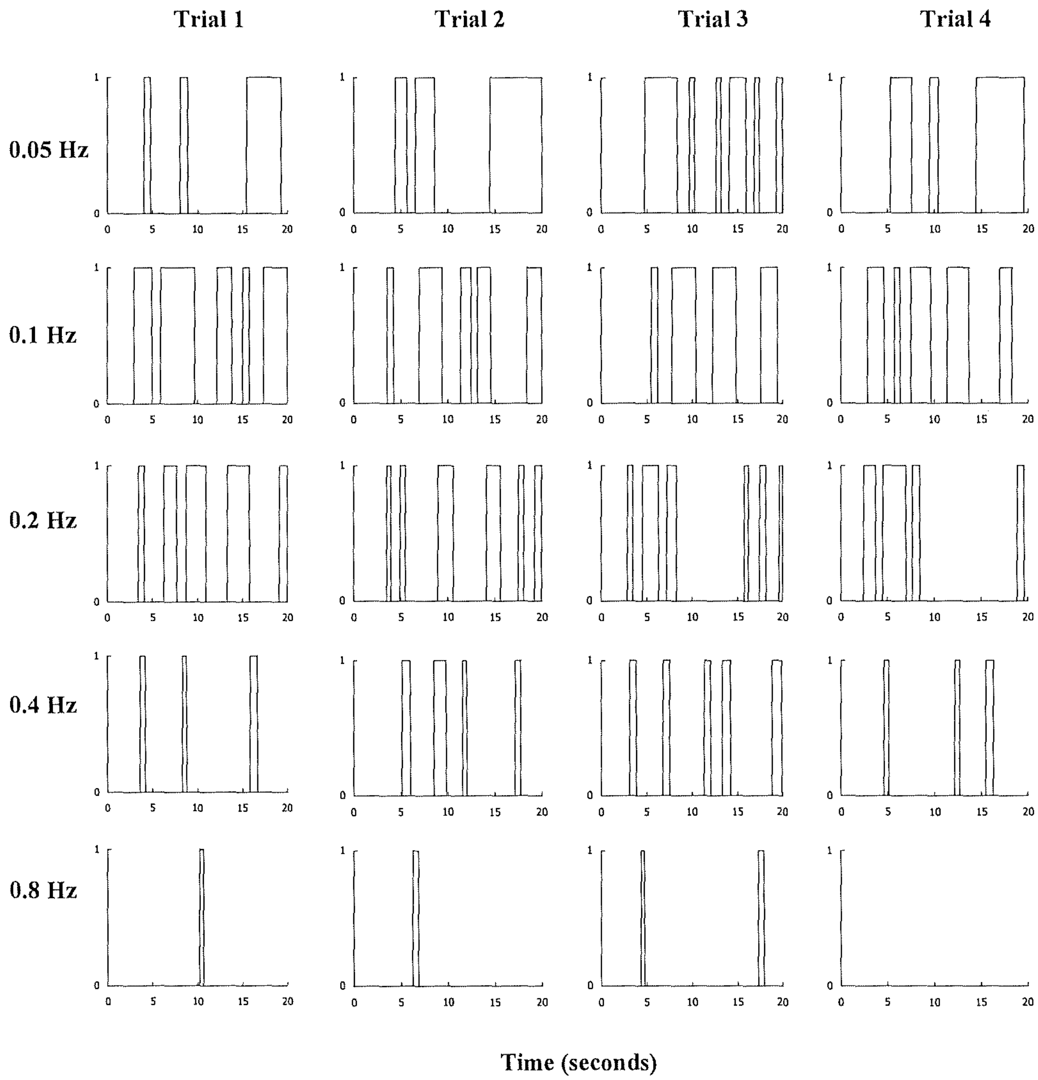
Subject: CYU (vection presence time course when viewing roll visual stimulus)



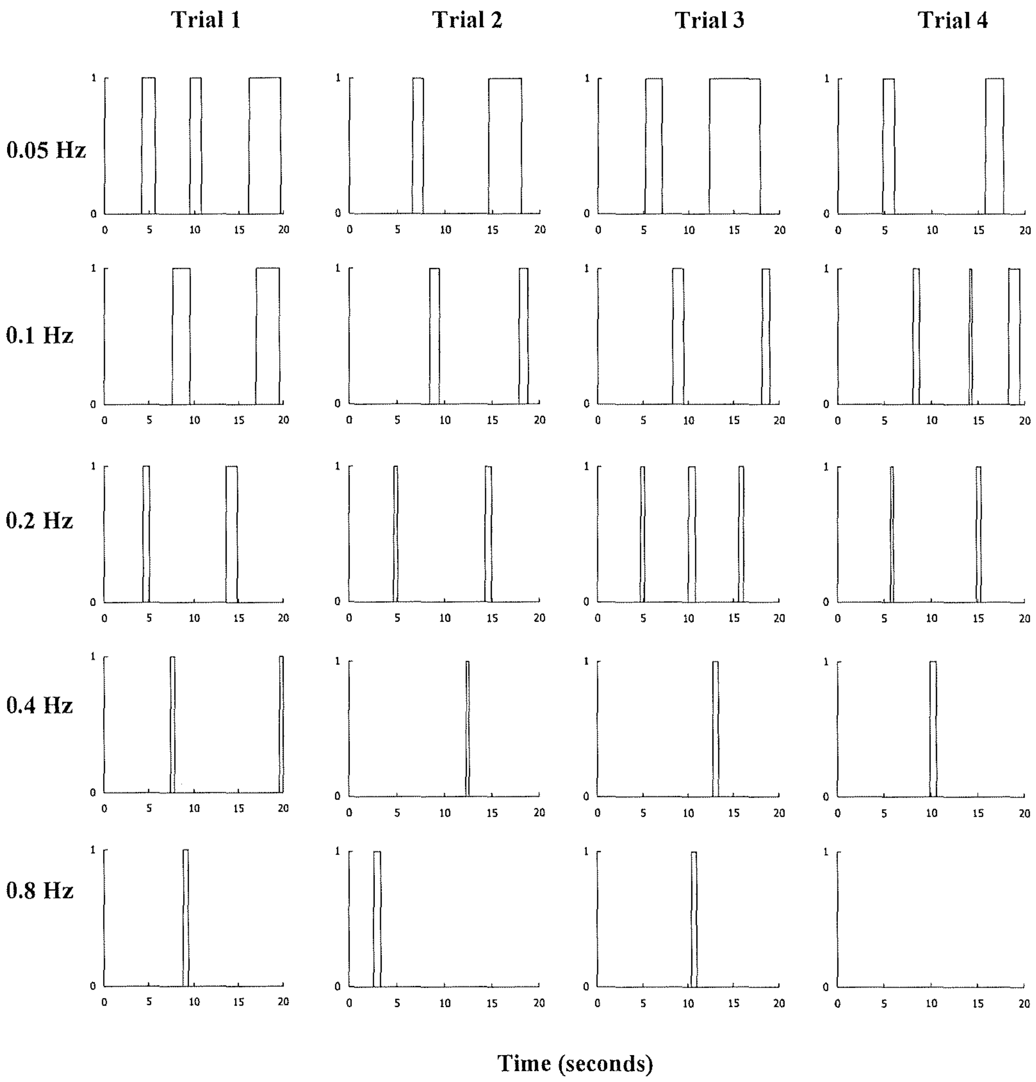
Subject: CYU (vection presence time course when viewing fore-and-aft visual stimulus)



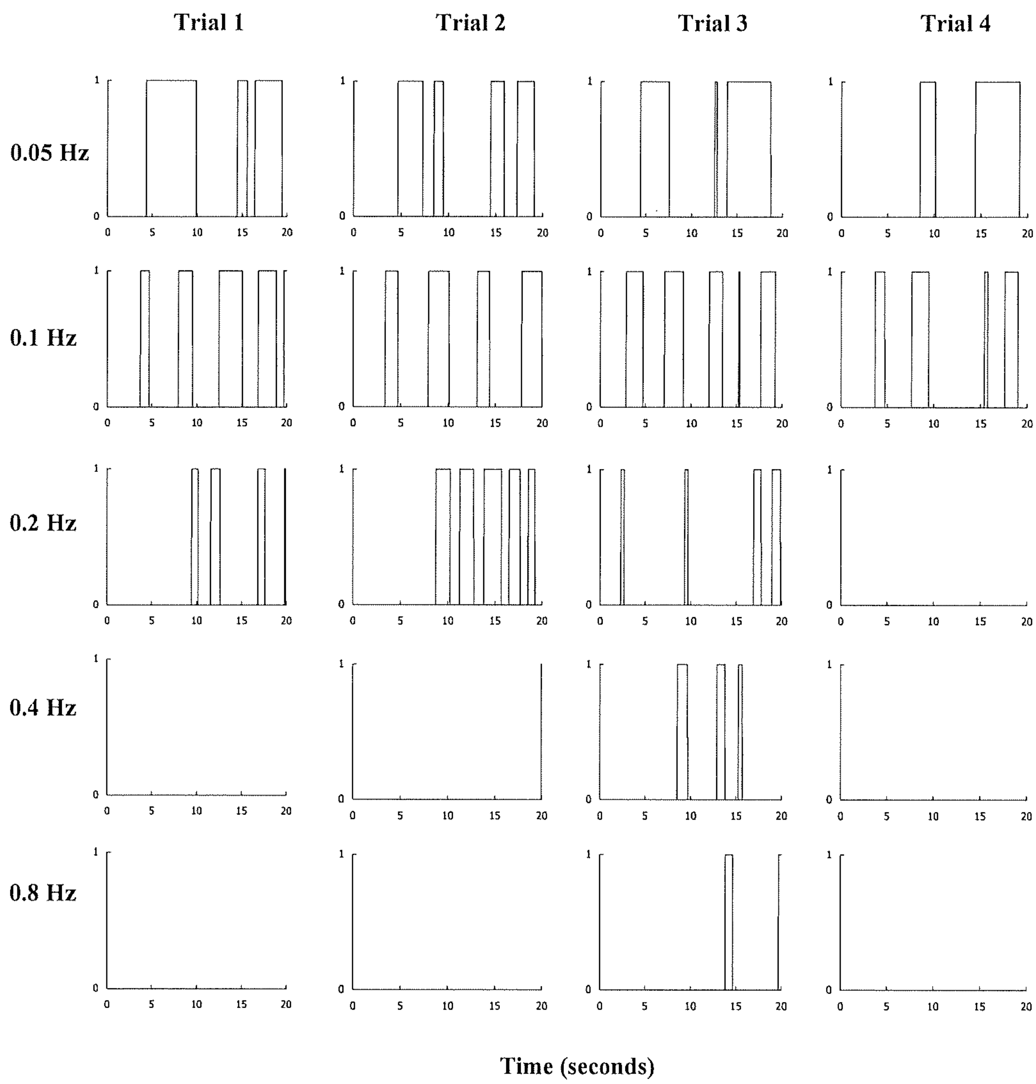
Subject: DAV (vection presence time course when viewing roll visual stimulus)



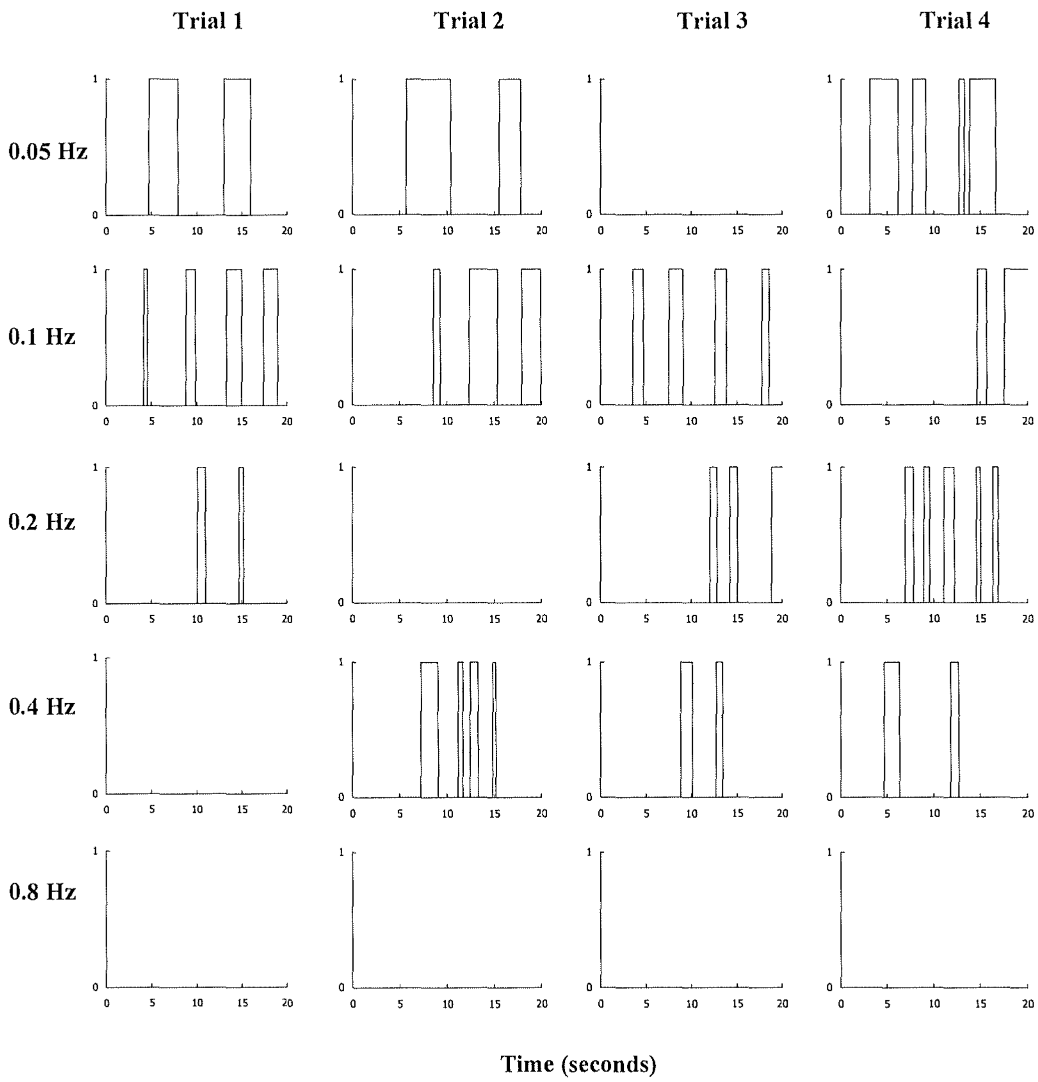
Subject: DAV (vection presence time course when viewing fore-and-aft visual stimulus)



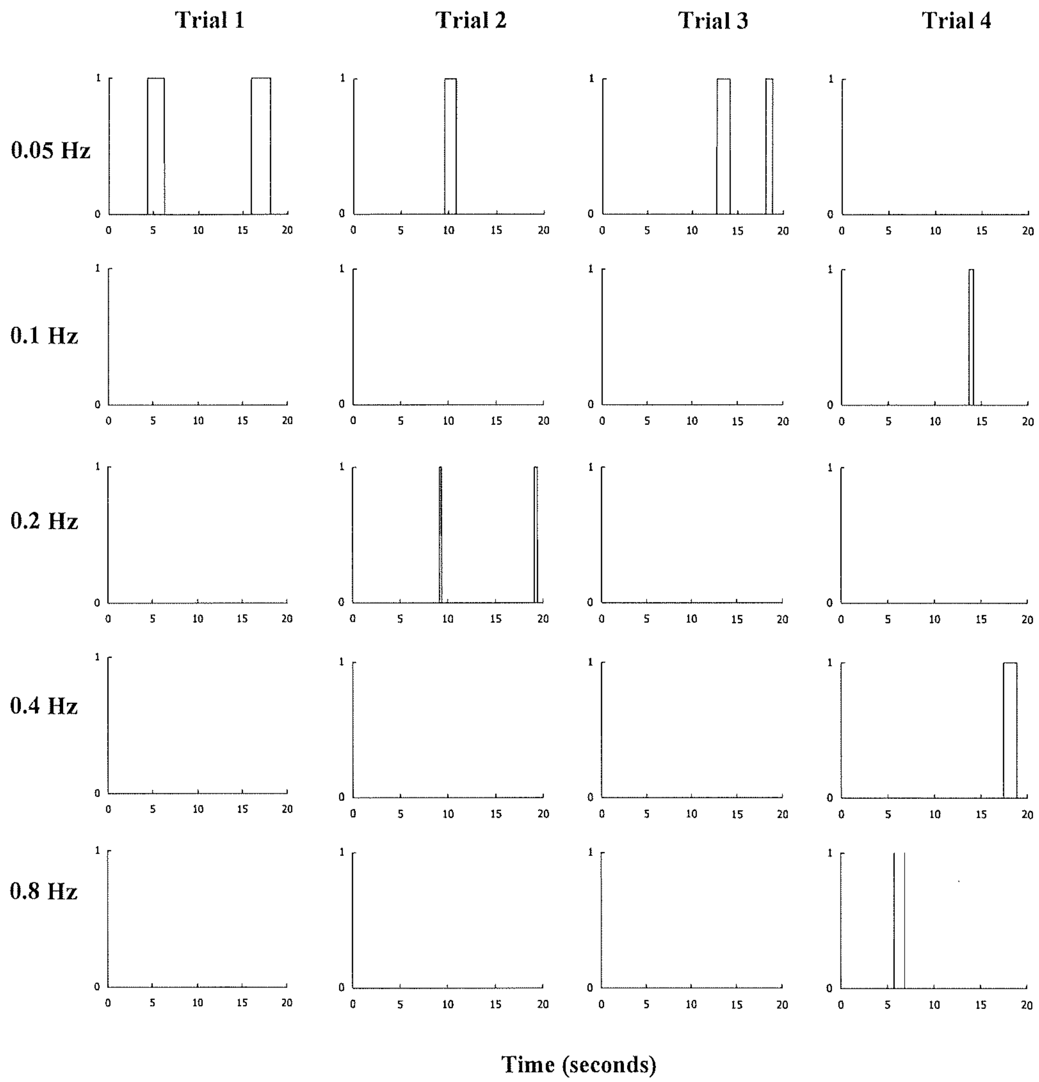
Subject: ECH (vection presence time course when viewing roll visual stimulus)



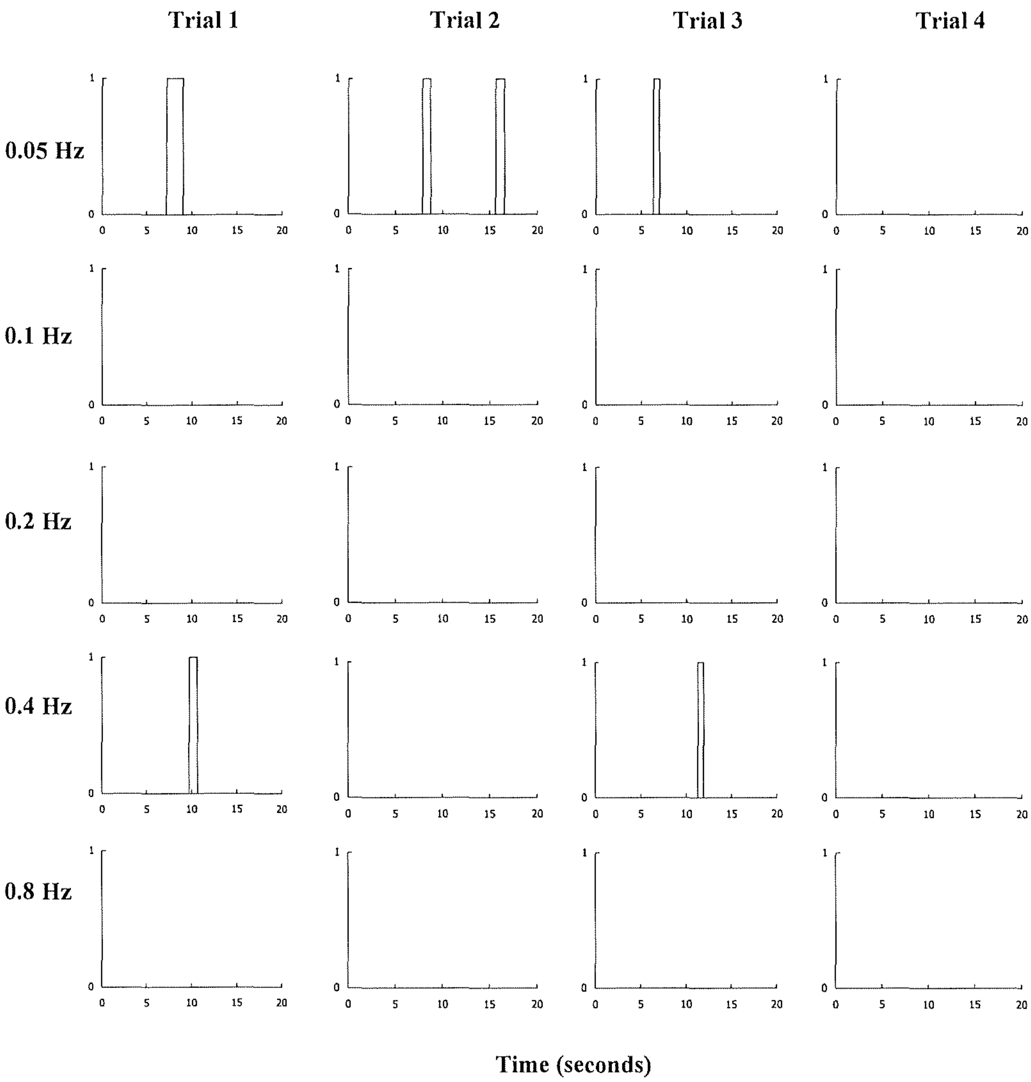
Subject: ECH (vection presence time course when viewing fore-and-aft visual stimulus)



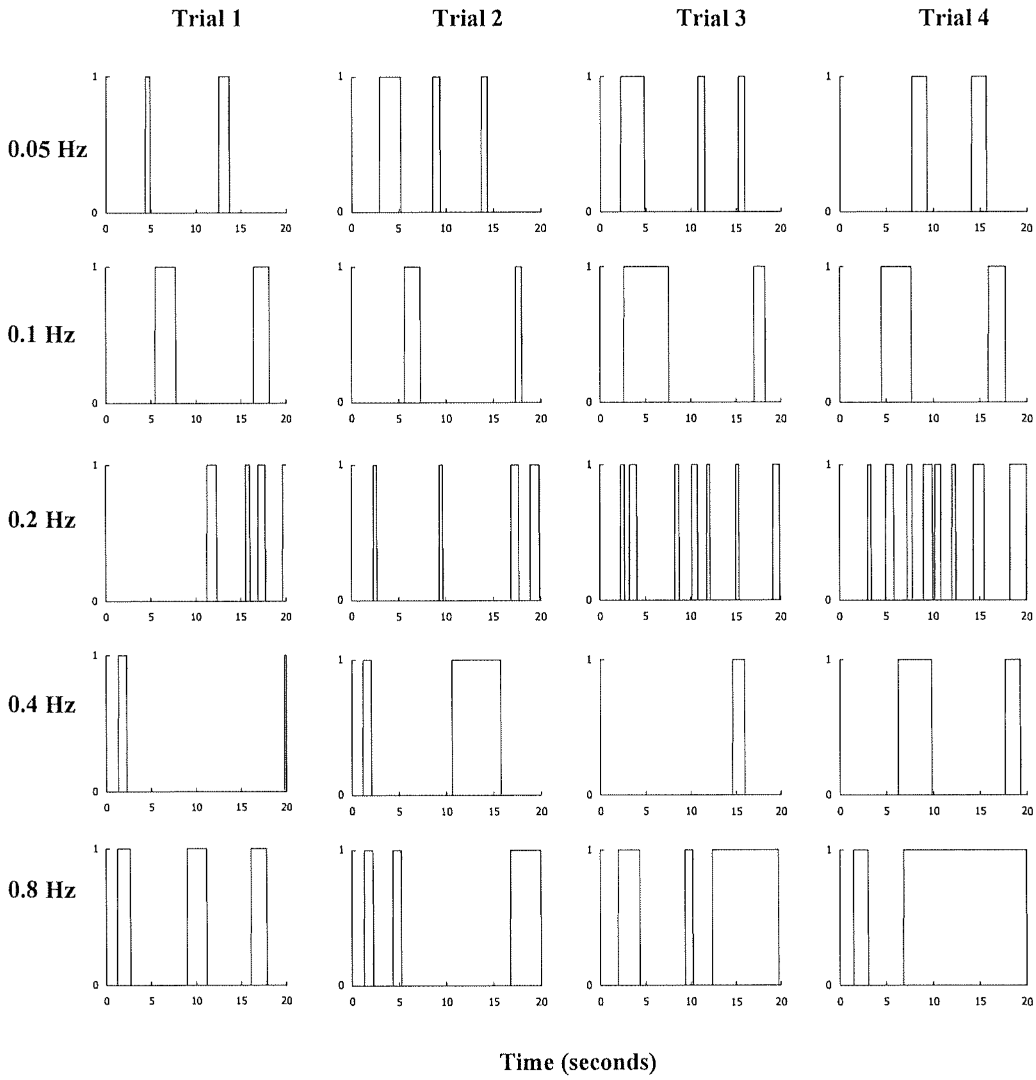
Subject: FSK (vection presence time course when viewing roll visual stimulus)



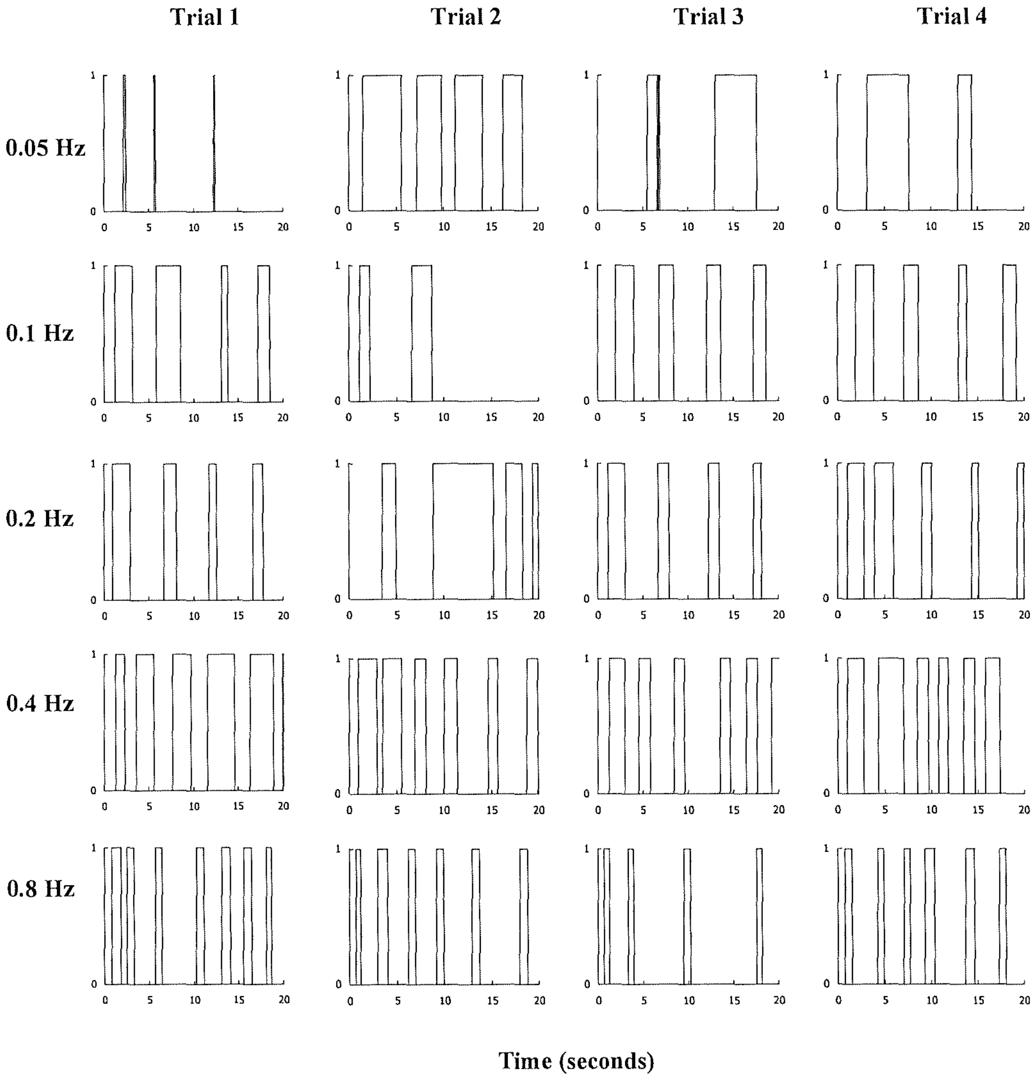
Subject: FSK (vection presence time course when viewing fore-and-aft visual stimulus)



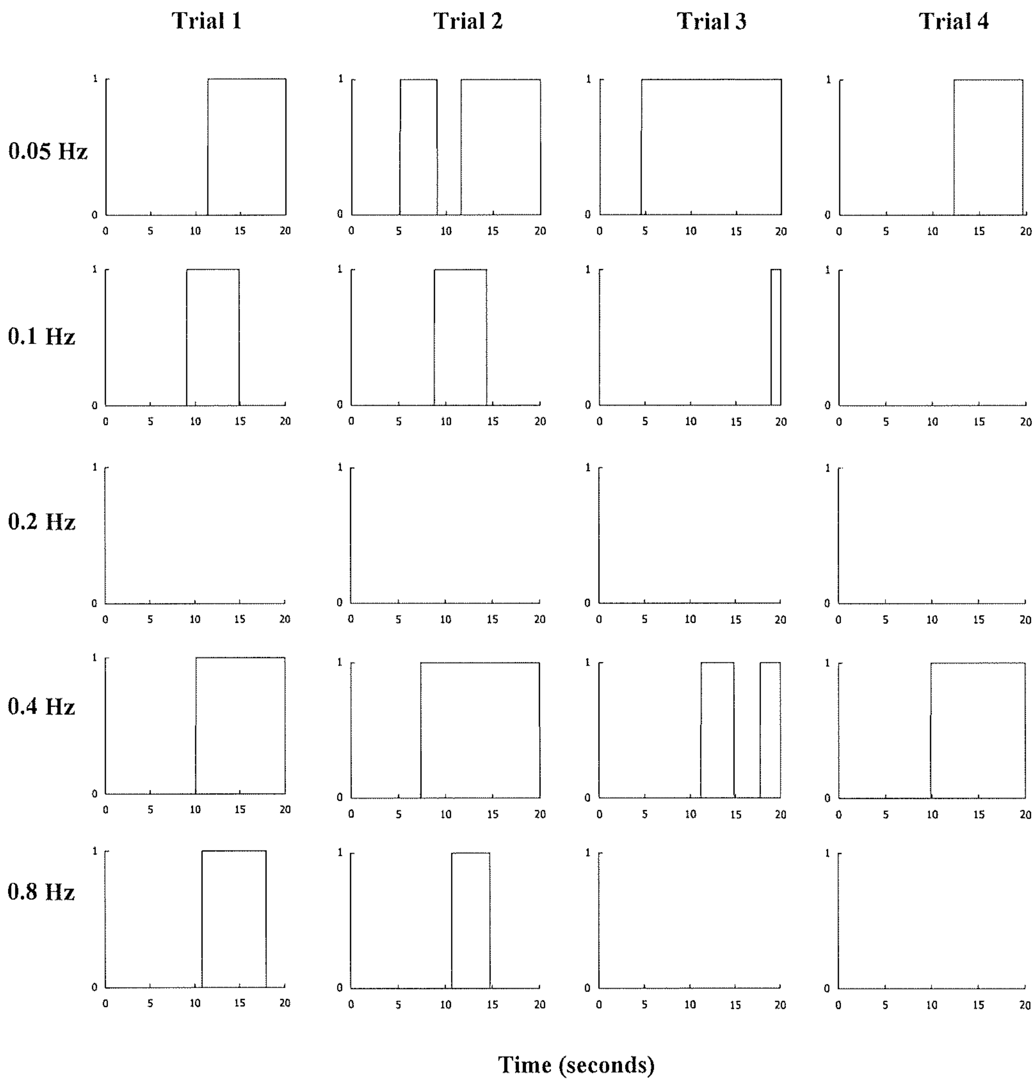
Subject: HAZ (vection presence time course when viewing roll visual stimulus)



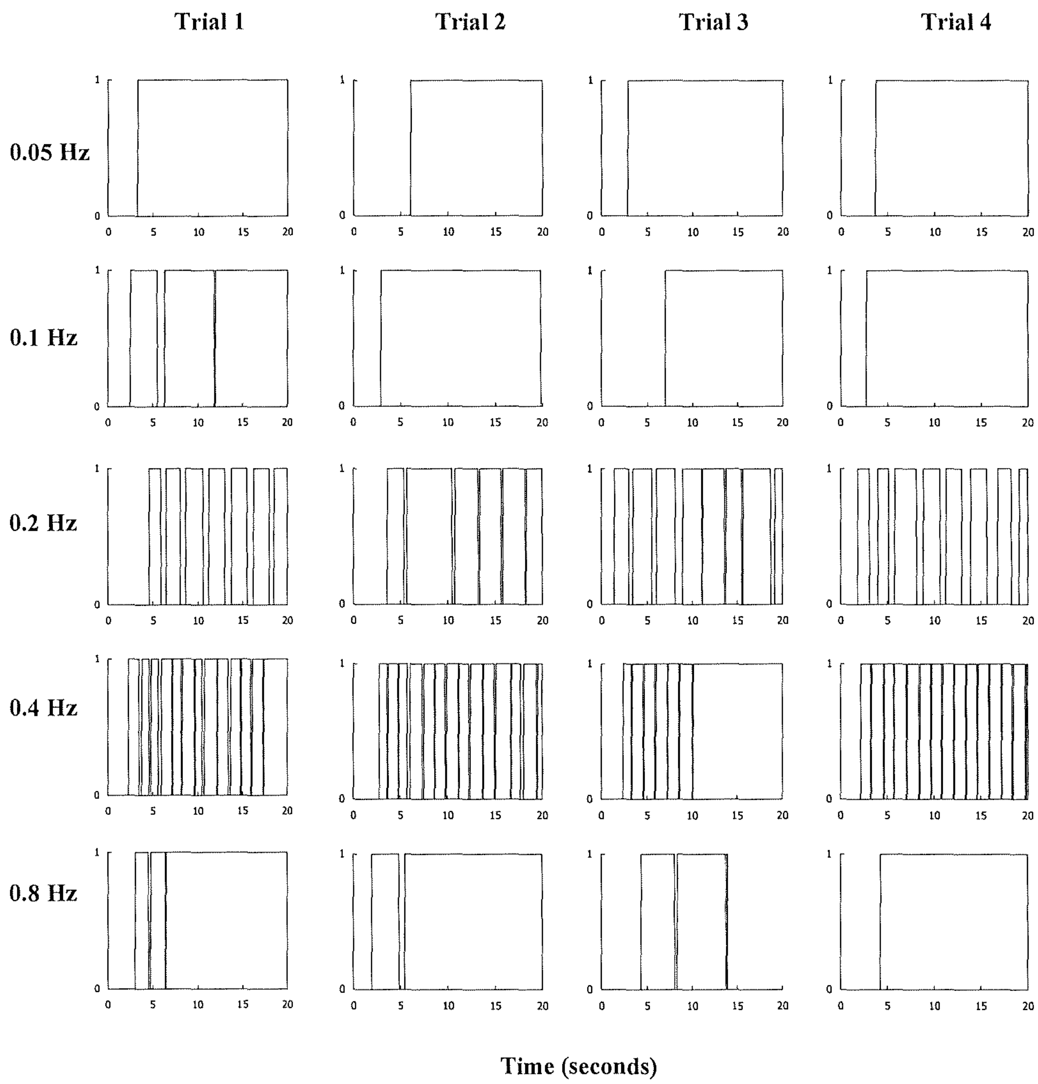
Subject: HAZ (vection presence time course when viewing fore-and-aft visual stimulus)



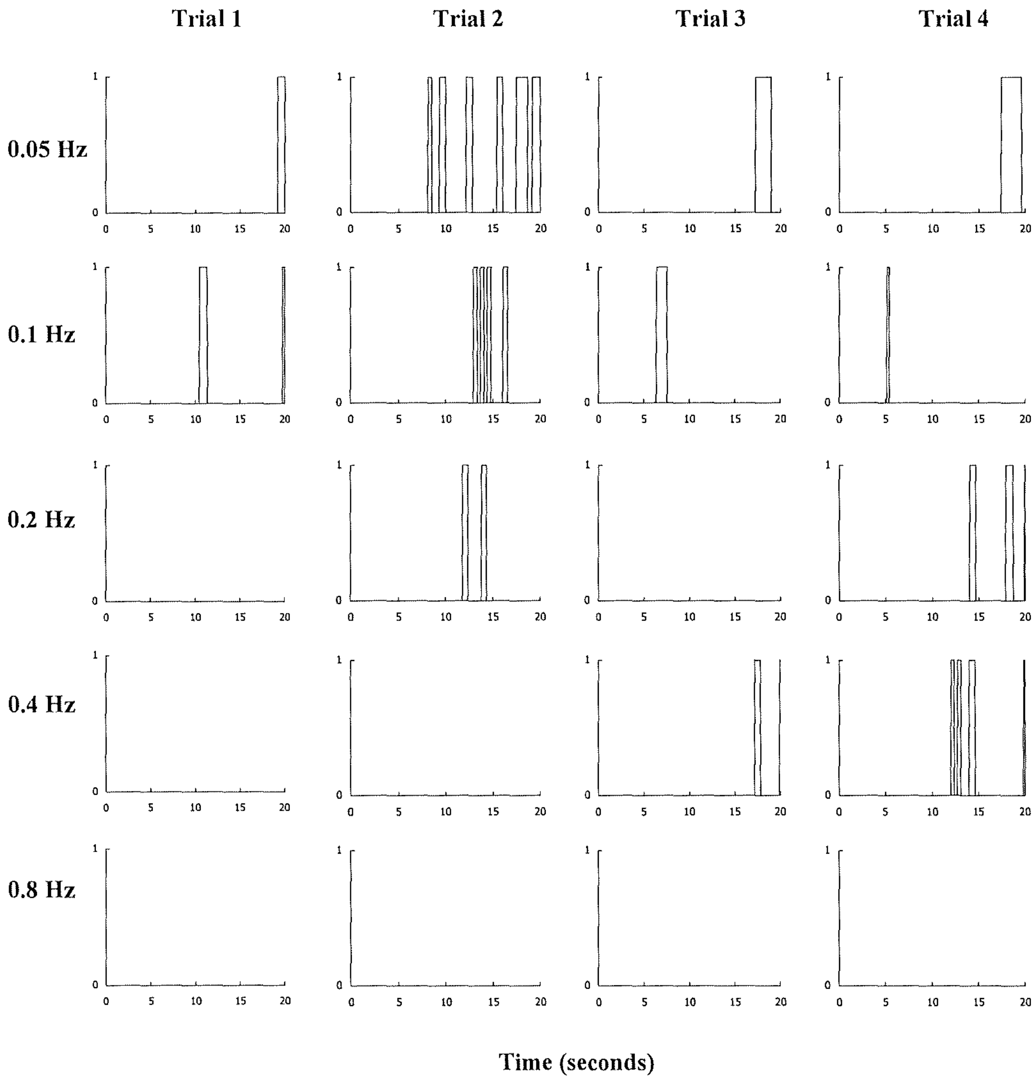
Subject: JON (vection presence time course when viewing roll visual stimulus)



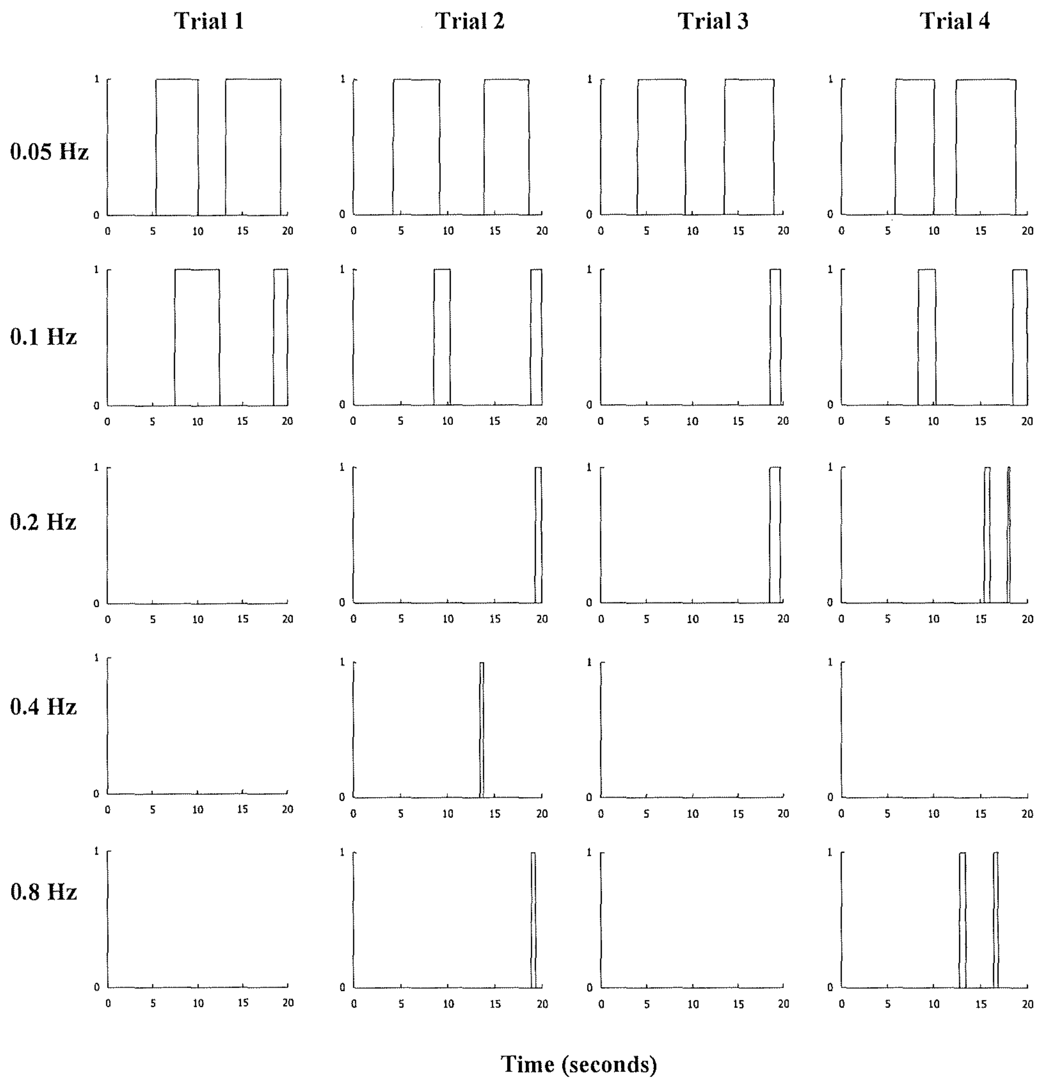
Subject: JON (vection presence time course when viewing fore-and-aft visual stimulus)



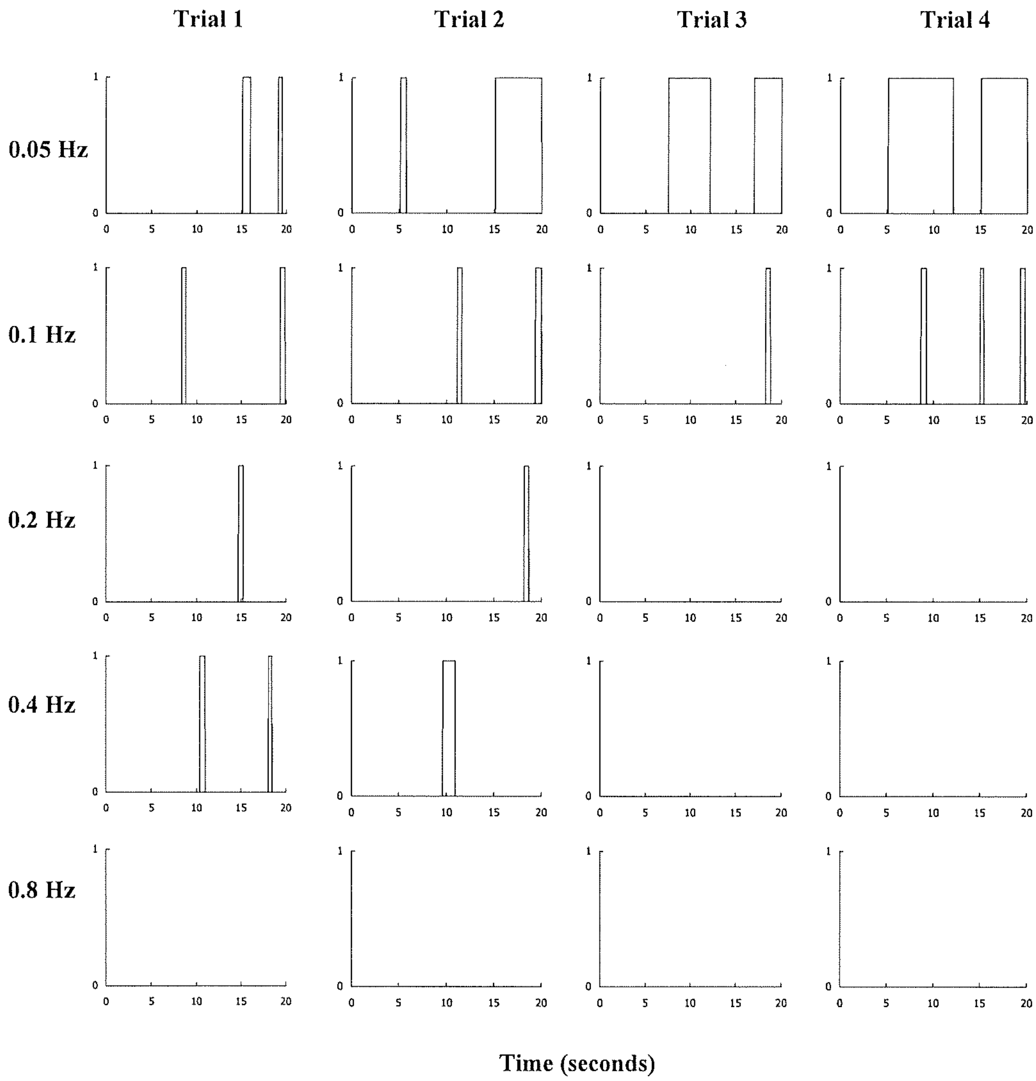
Subject: MAG (vection presence time course when viewing roll visual stimulus)



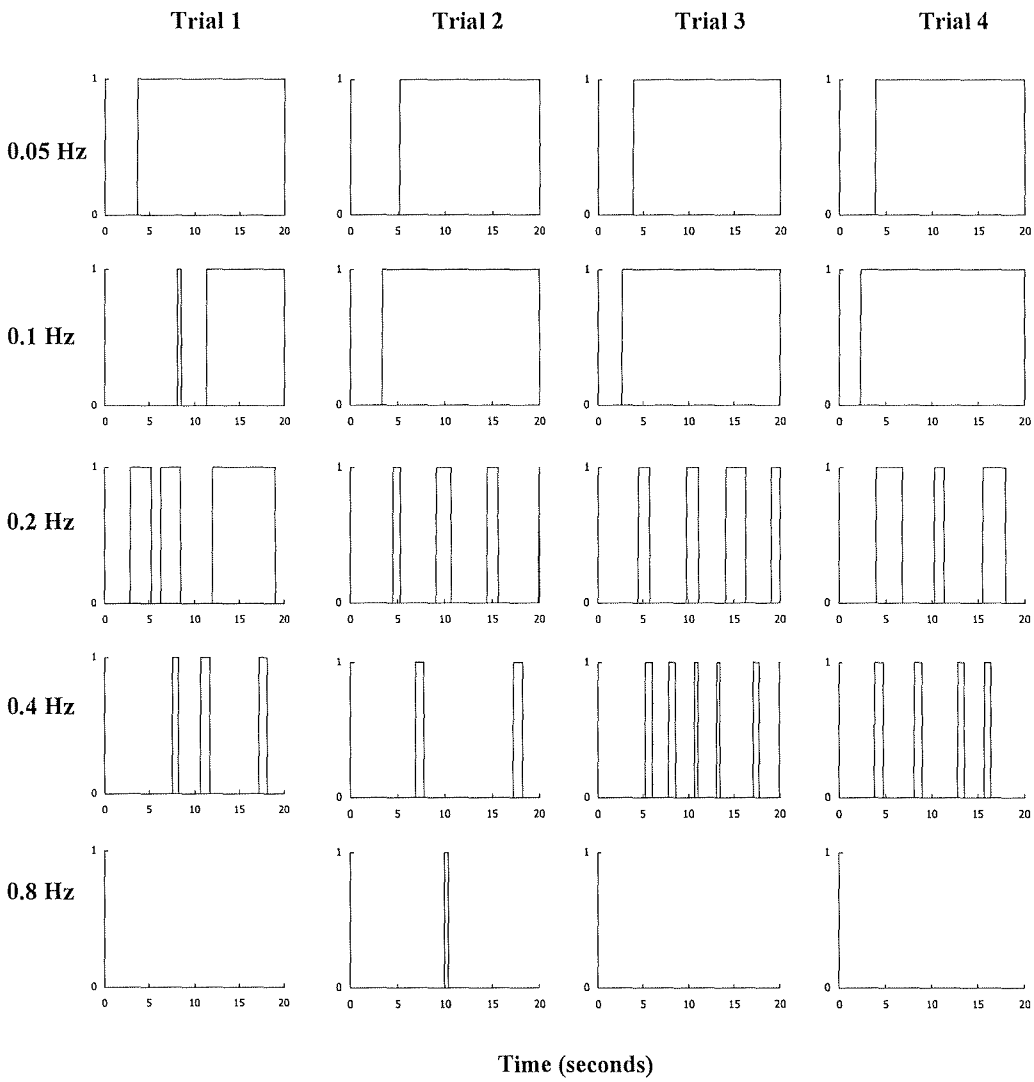
Subject: MAG (vection presence time course when viewing fore-and-aft visual stimulus)



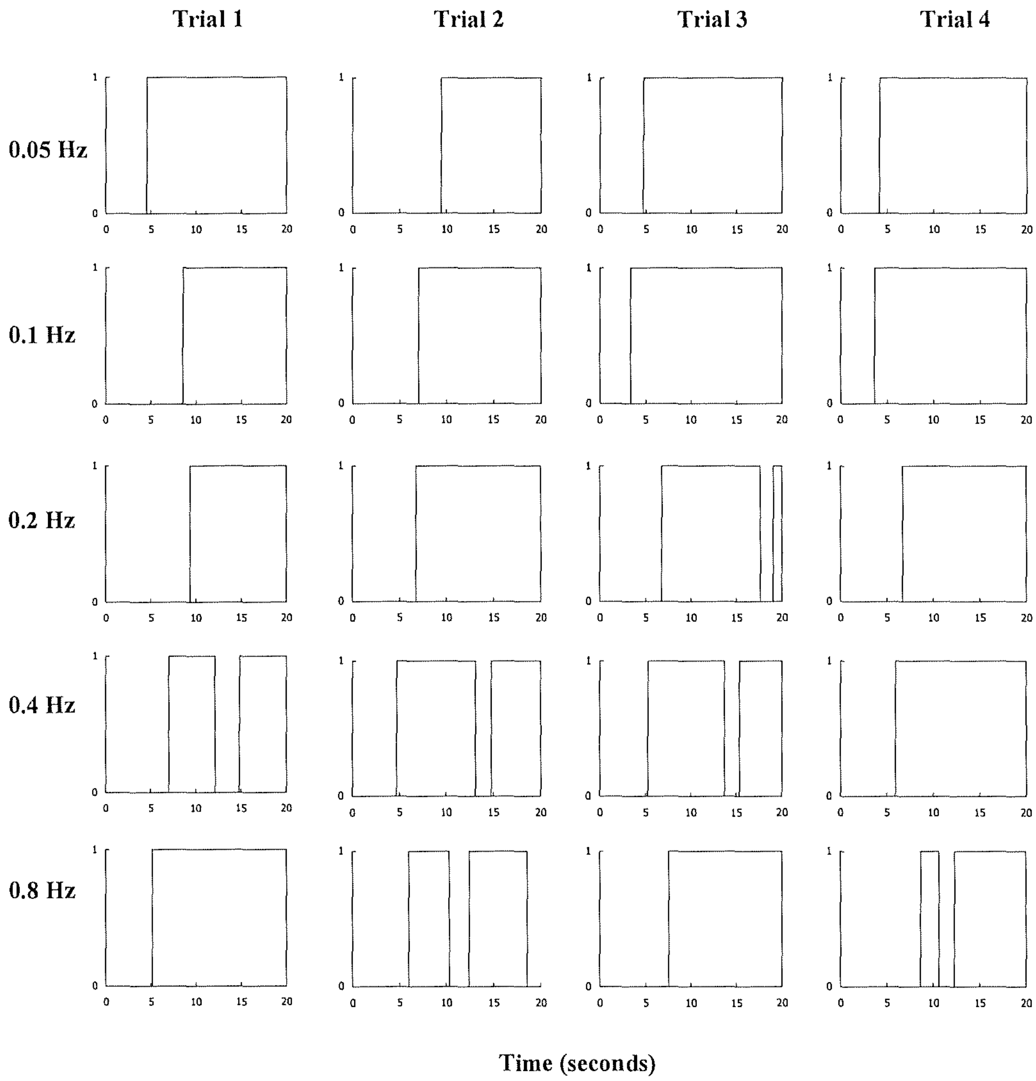
Subject: RTA (vection presence time course when viewing roll visual stimulus)



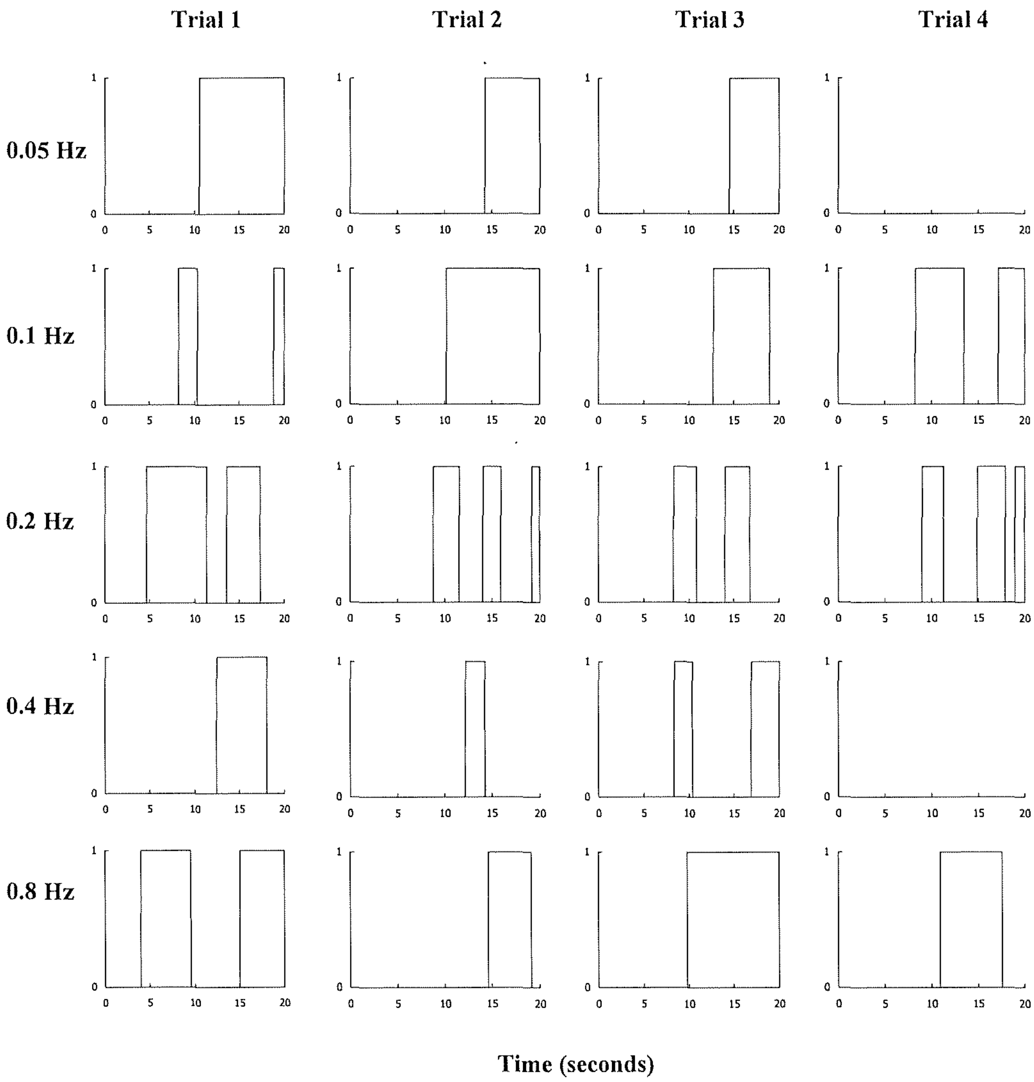
Subject: RTA (vection presence time course when viewing fore-and-aft visual stimulus)



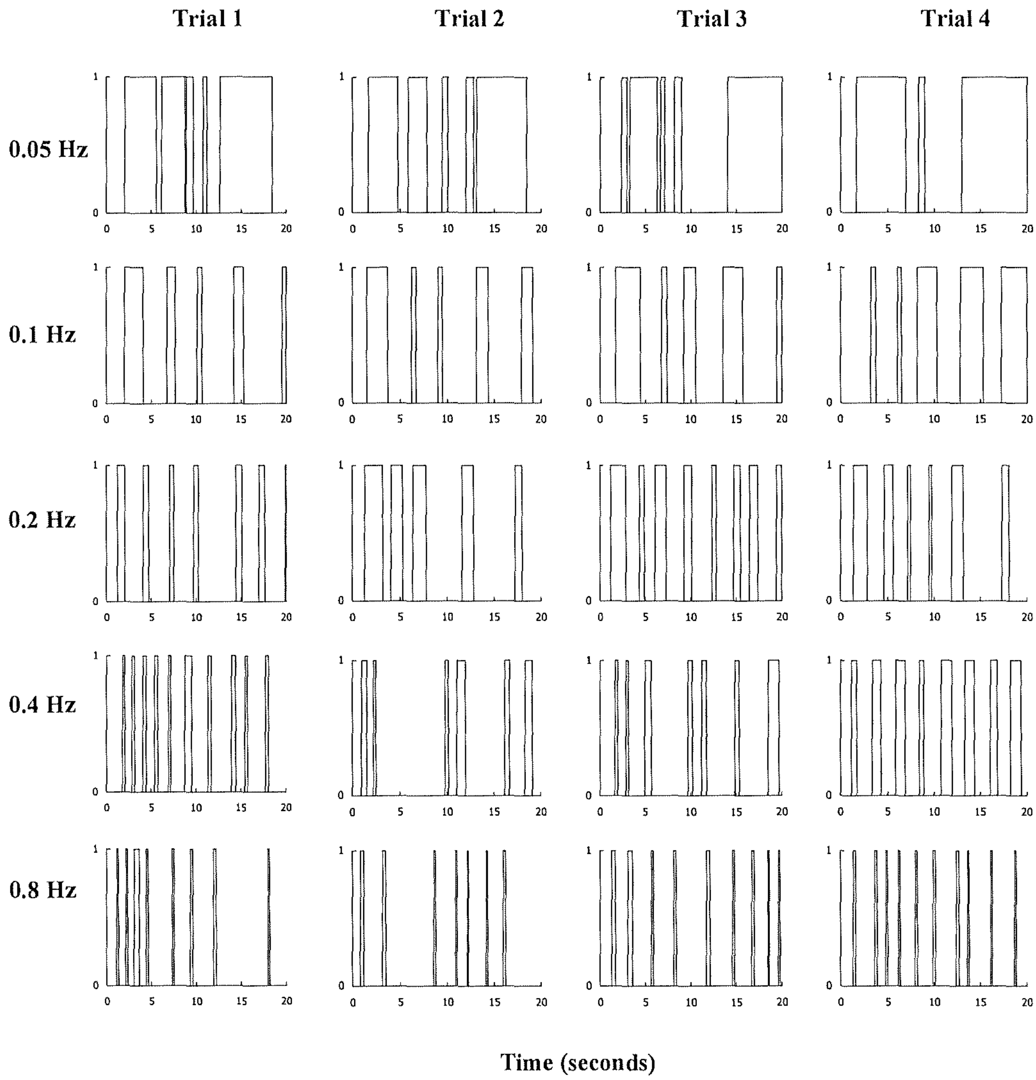
Subject: VIN (vection presence time course when viewing roll visual stimulus)



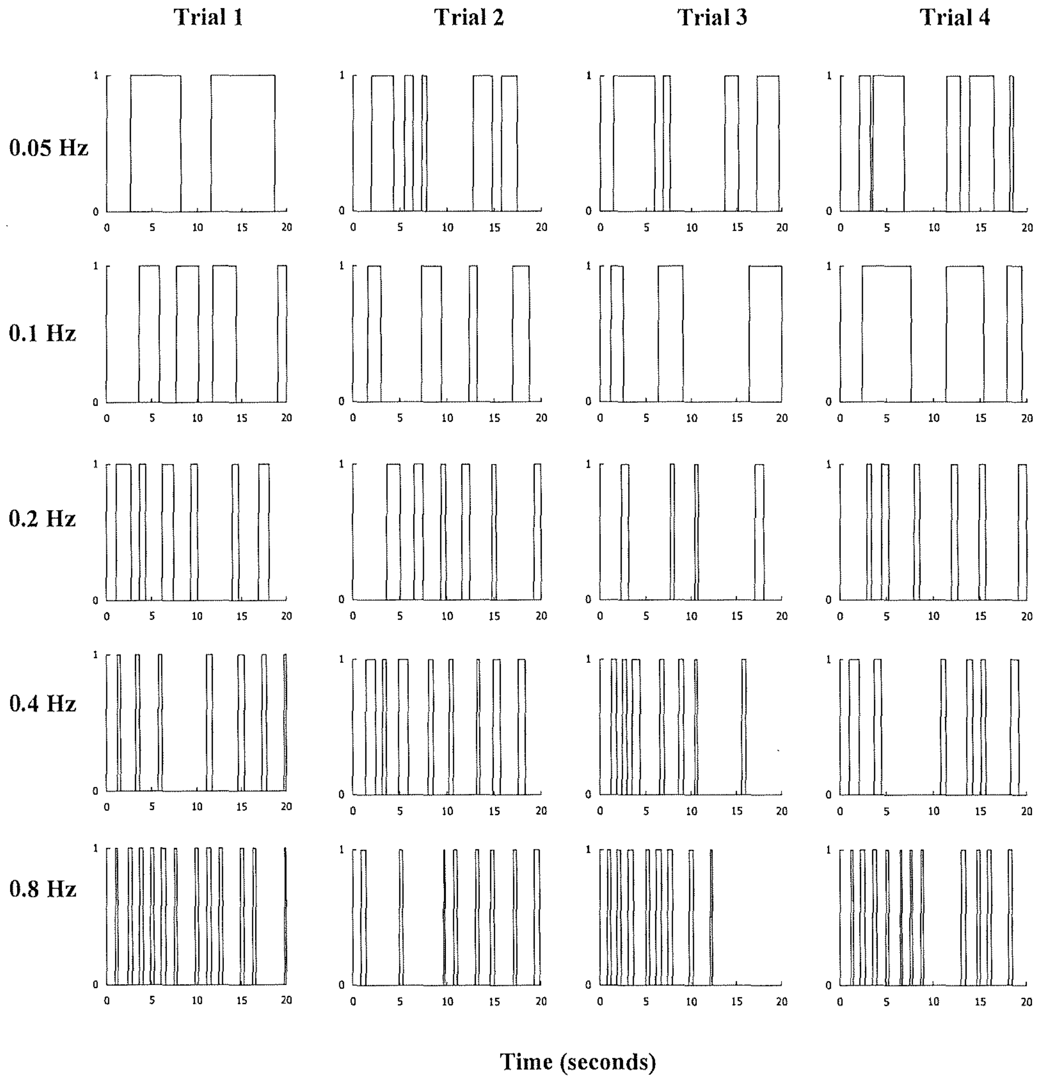
Subject: VIN (vection presence time course when viewing fore-and-aft visual stimulus)



Subject: XYU (vection presence time course when viewing roll visual stimulus)

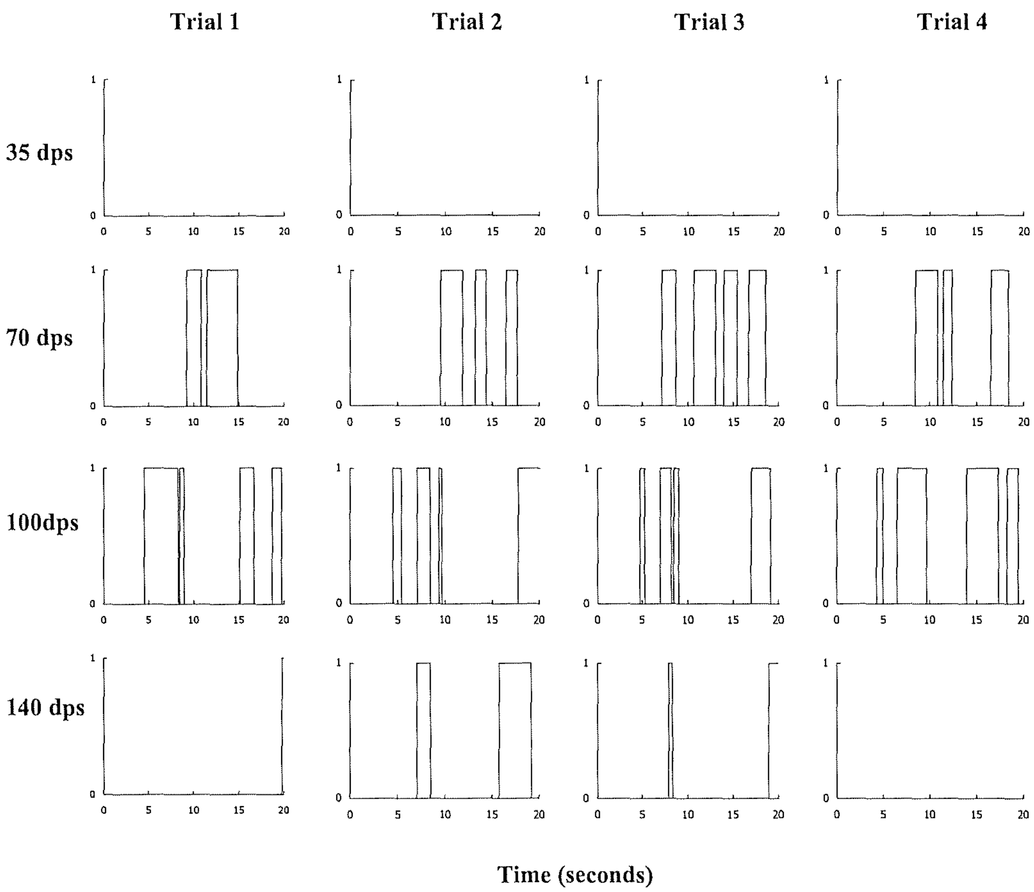


Subject: XYU (vection presence time course when viewing fore-and-aft visual stimulus)

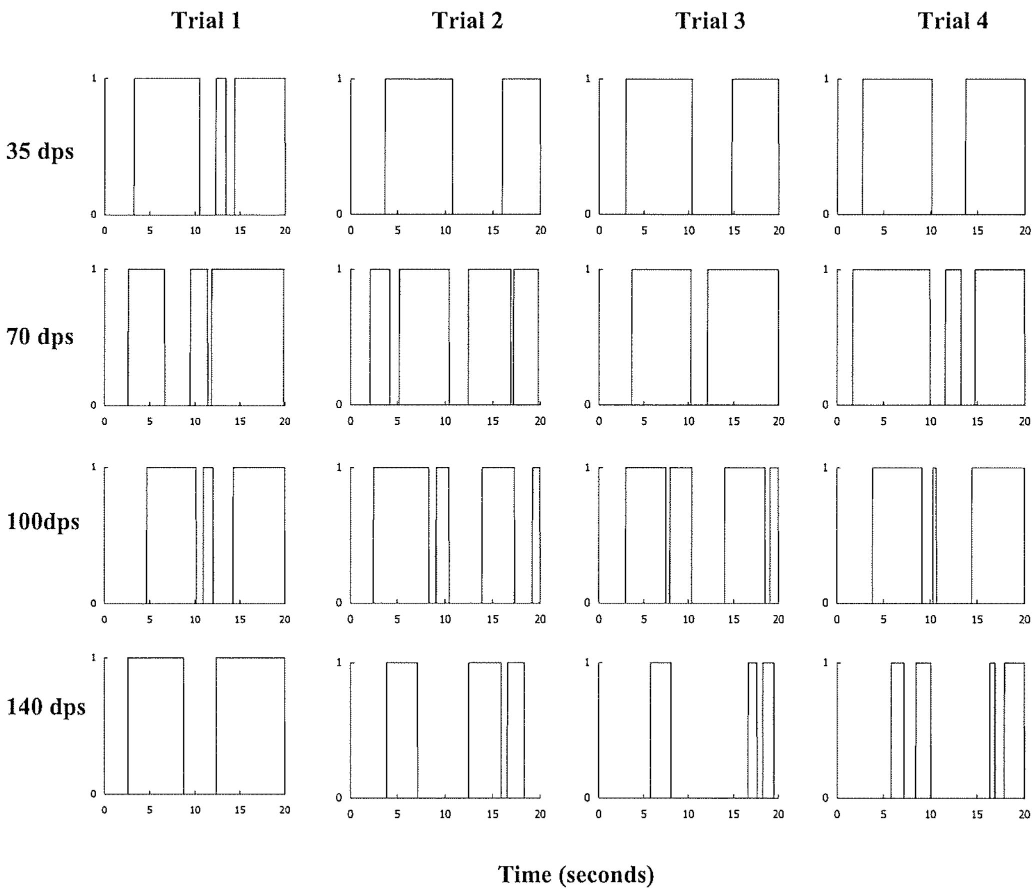


APPENDIX I: VECTION TIME-COURSE PLOTS (STUDY 2)

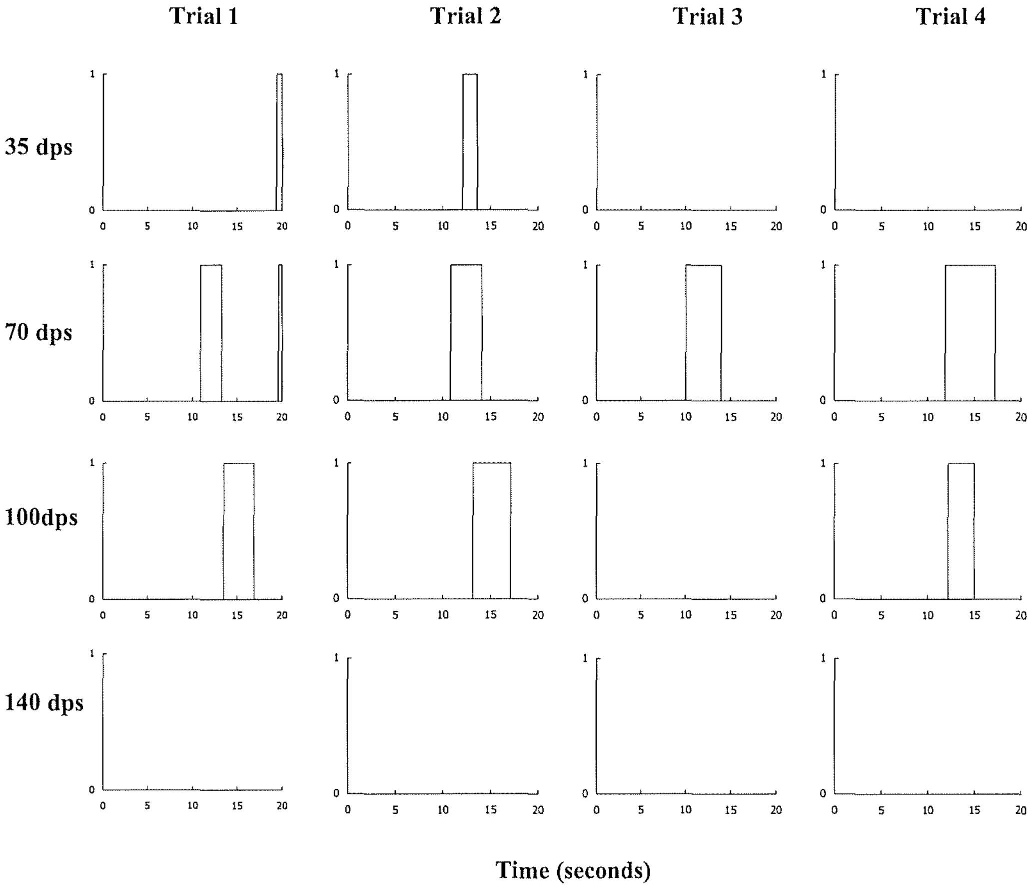
Subject: CHC (vection presence time course when viewing roll visual stimulus)



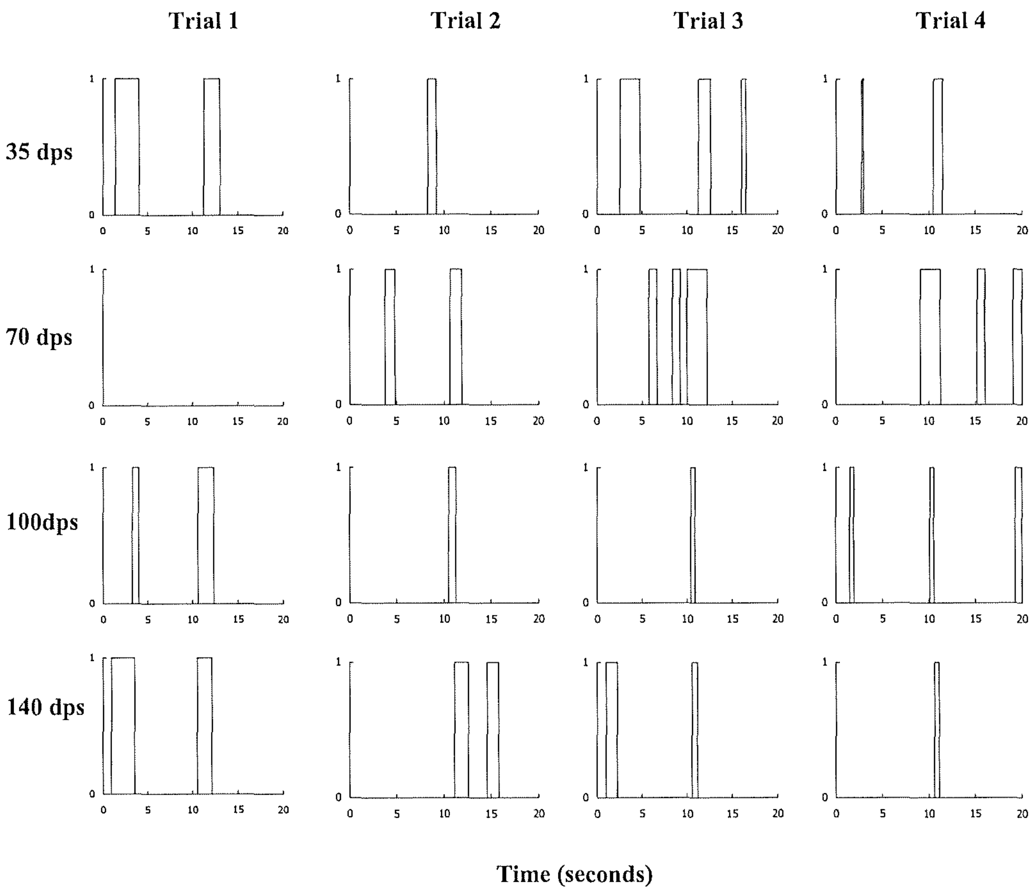
Subject: CHE (vection presence time course when viewing roll visual stimulus)



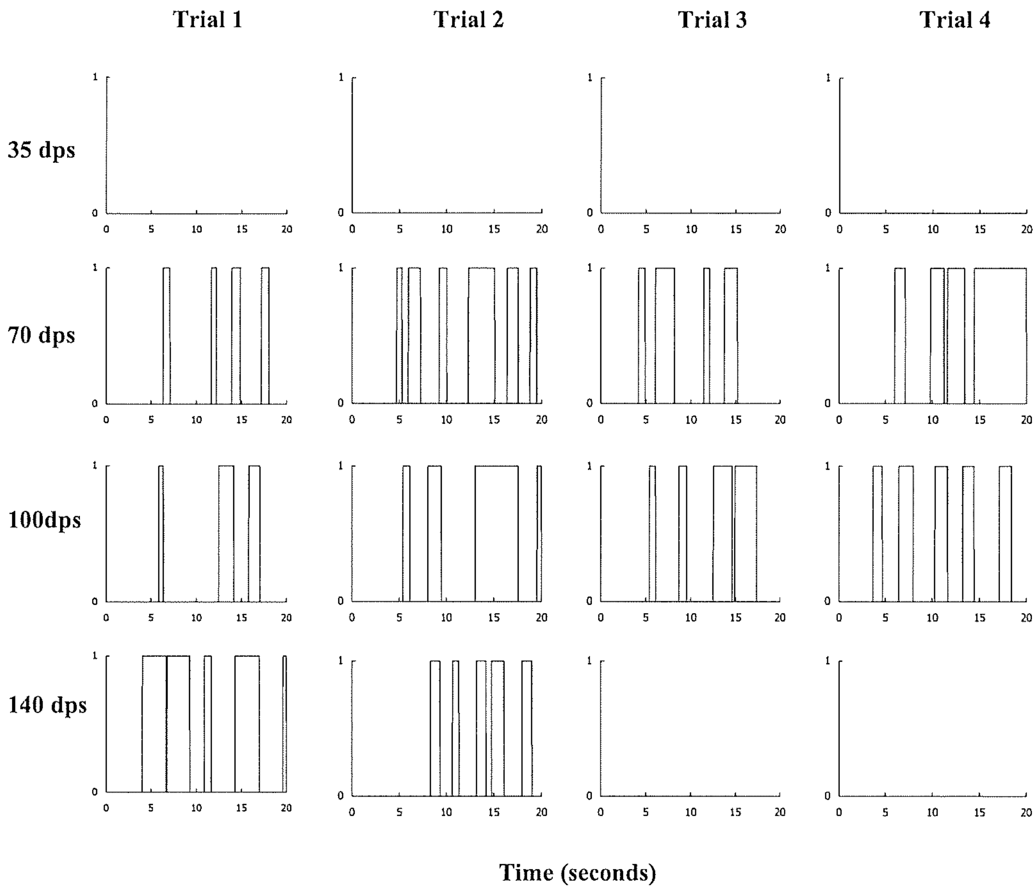
Subject: CIN (vection presence time course when viewing roll visual stimulus)



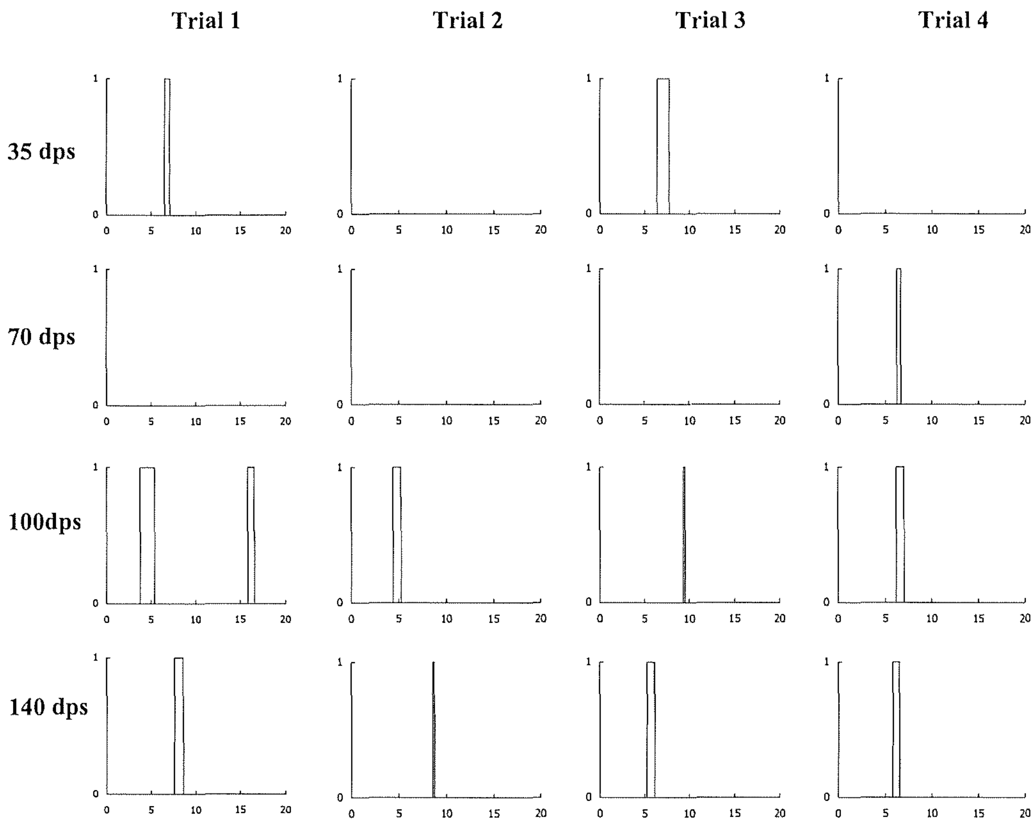
Subject: CUI (vection presence time course when viewing roll visual stimulus)



Subject: DAV (vection presence time course when viewing roll visual stimulus)

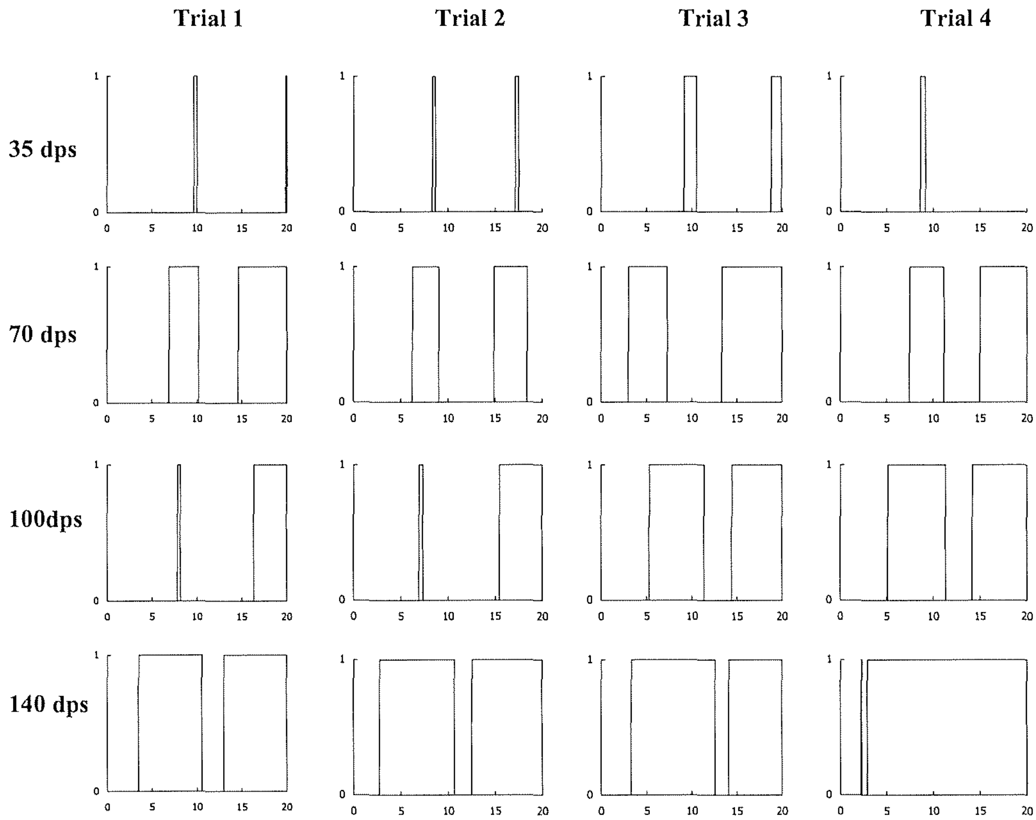


Subject: JAS (vection presence time course when viewing roll visual stimulus)



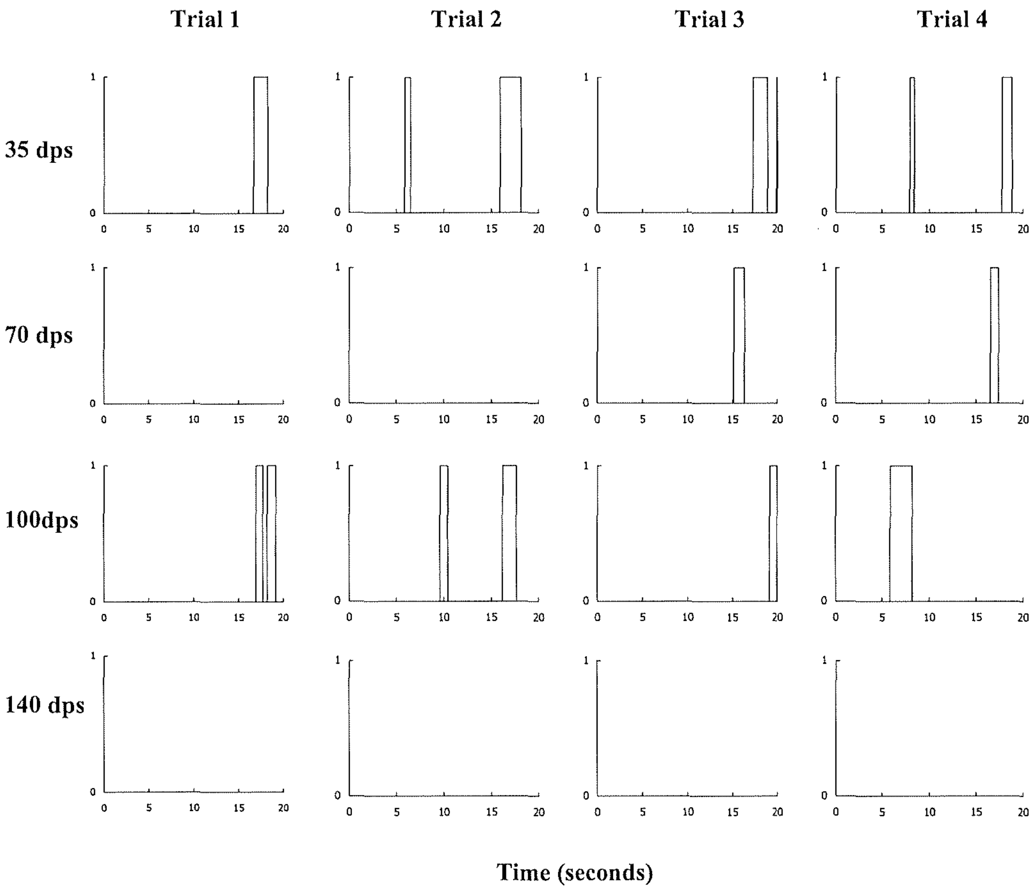
Time (seconds)

Subject: LHY (vection presence time course when viewing roll visual stimulus)

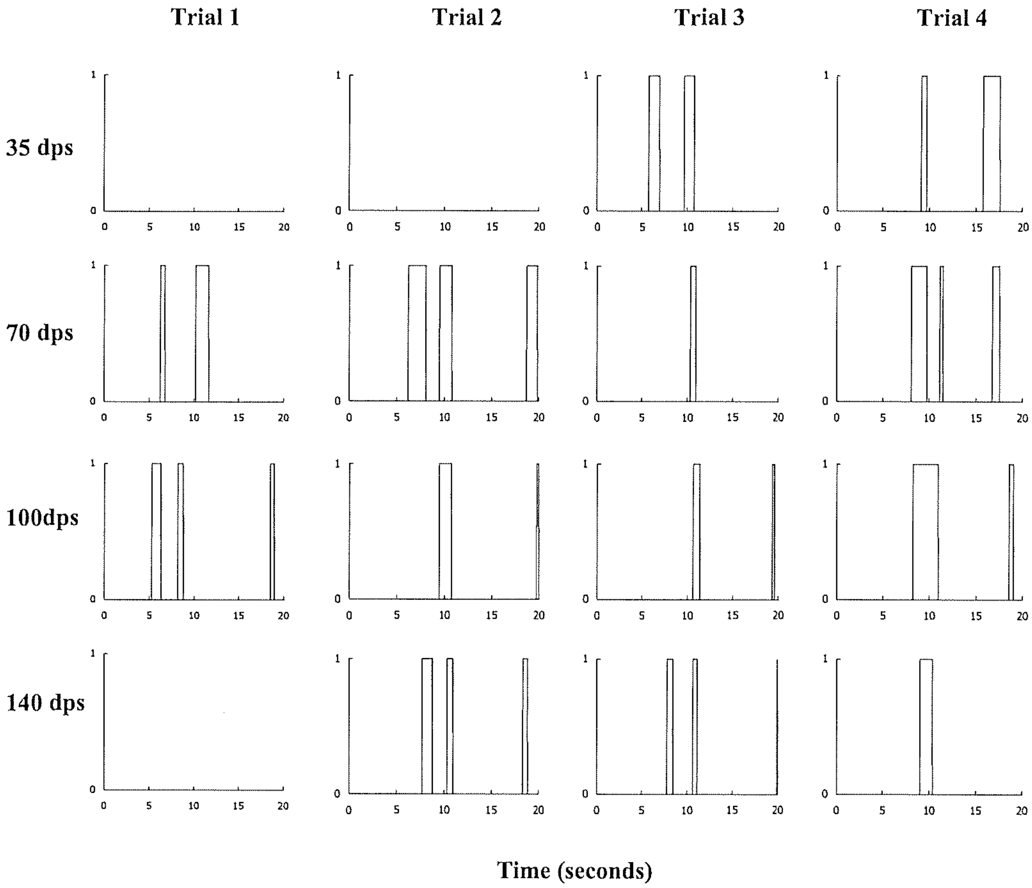


Time (seconds)

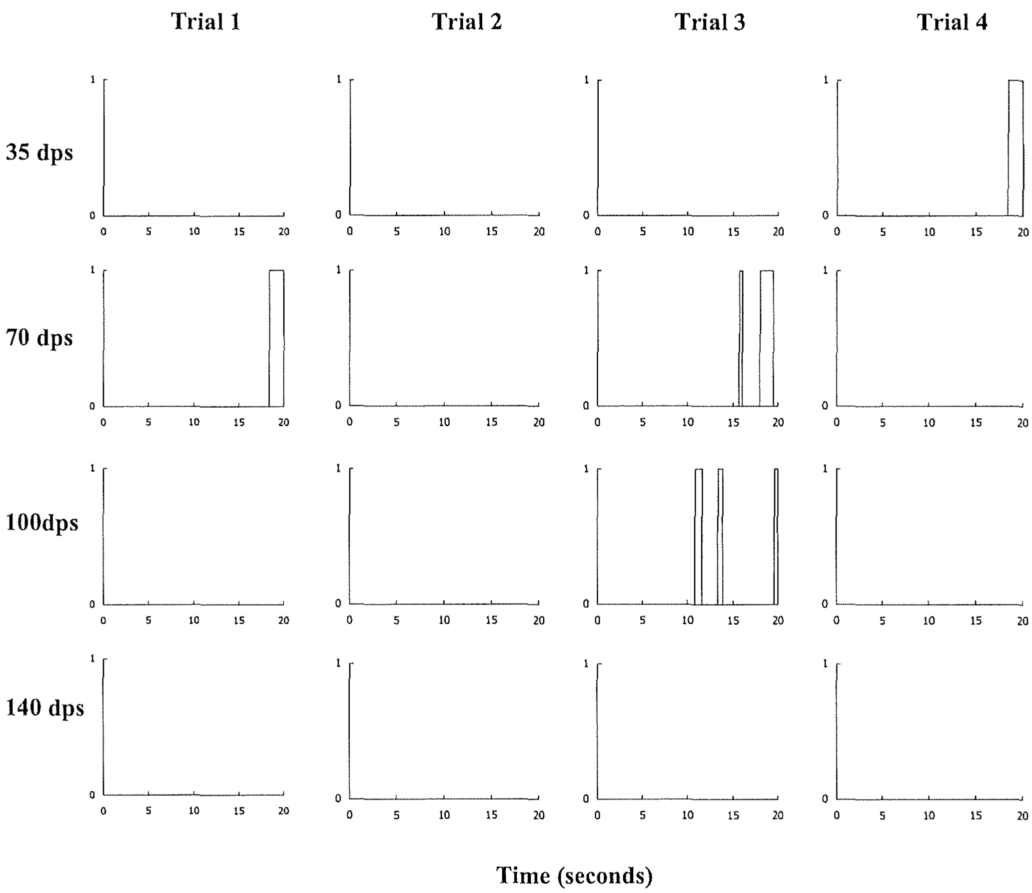
Subject: MAN (vection presence time course when viewing roll visual stimulus)



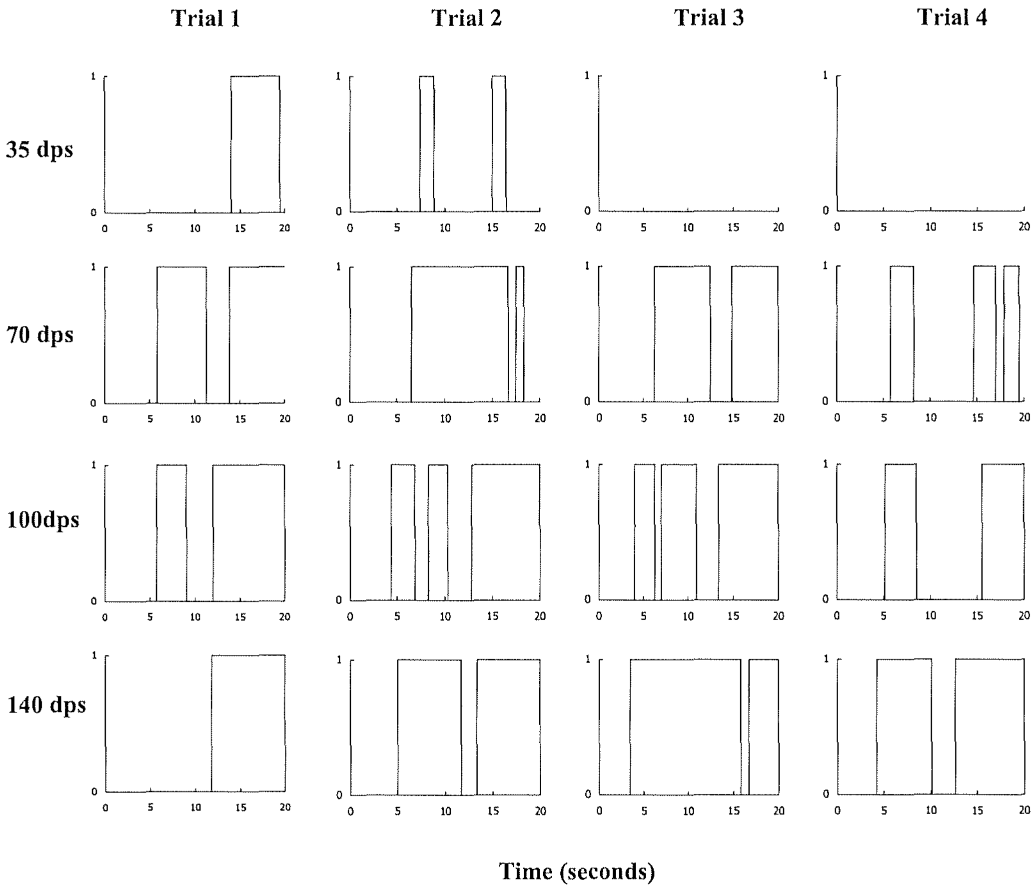
Subject: PAN (vection presence time course when viewing roll visual stimulus)



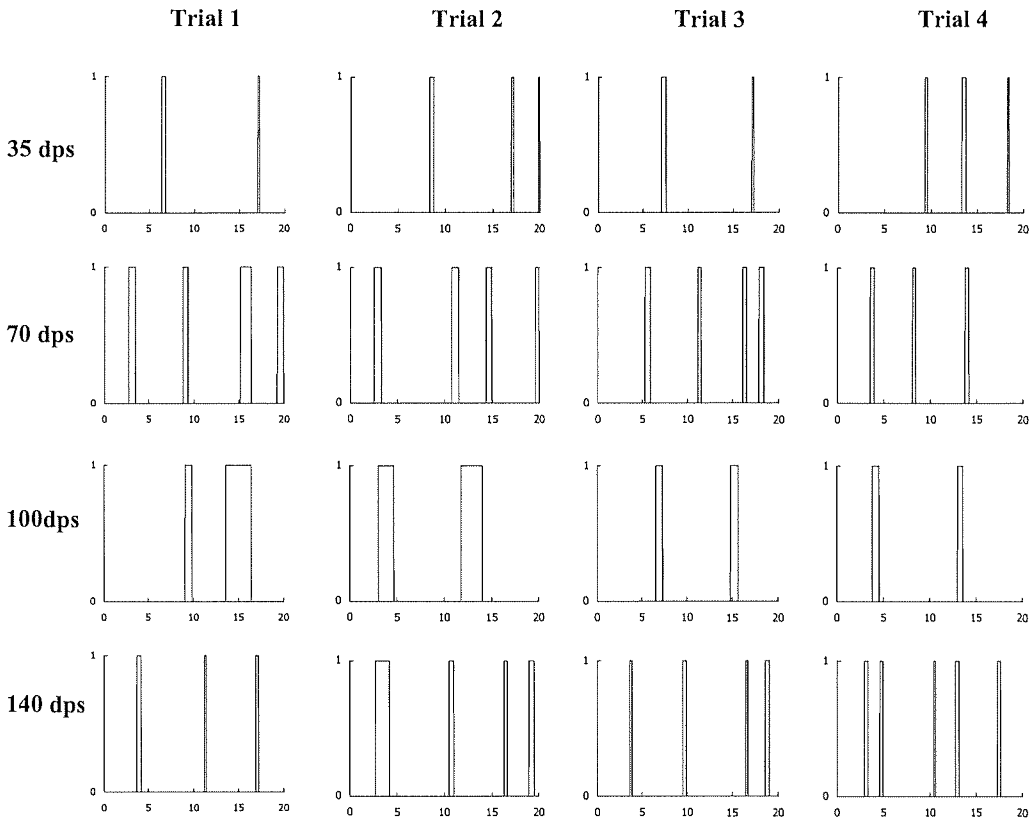
Subject: PHO (vection presence time course when viewing roll visual stimulus)



Subject: WCC (vection presence time course when viewing roll visual stimulus)



Subject: YUE (vection presence time course when viewing roll visual stimulus)



Time (seconds)