Proceedings of the Human Factors and Ergonomics Society Annual Meeting, v. 59, (1), September 2015, p. 1341-1345 (author final)

Heading Discrimination Thresholds and Lateral Heading Detection Thresholds When Exposed to Low-frequency Linear Motion

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This paper reports two experiments conducted to measure human heading discrimination performance. In the first experiment, we measured the minimum heading angle of a linear heading motion that can be discriminated from the straight ahead direction - ‘Heading Discrimination Threshold (HDT)’. Uni-directional linear sinusoidal motion was used. Effects of different combinations of peak acceleration (20, 25 and 30 cm/s^2) and frequencies (0.25, 0.5 and 1 Hz) were studied. In the second experiment, we also measured minimum peak acceleration needed for subjects to discriminate lateral heading motions and call it ‘Heading Detection Threshold (HDeT)’. We hypothesized that HDTs will be linearly correlated with HDeTs when measured in same frequency conditions. The preliminary result of first 7 subjects showed that peak acceleration magnitude was a significant factor on HDTs while frequency was not. A trend towards a significant correlation between HDTs and HDeTs was emerging for the 1 Hz condition.

INTRODUCTION

Discriminating heading of self-motion is a common task in people’s daily life. When people are driving, the passive accelerations could help people discriminate their self-motion headings. With the perceived heading information, drivers can adjust or maintain their heading directions. In previous inertial motion perception study (e.g., Benson, Spencer, & Stott, 1986; MacNeilage, Banks, DeAngelis, & Angelaki, 2010; Soyka, Giordano, Beykirch, & Bülthoff, 2011), frequency and peak acceleration of inertial motion were found to significantly influence subjects’ perception performance. Therefore, we would like to investigate the effect of frequency and magnitude on heading discrimination performance in this study. Past research in heading discrimination used heading motion less than 1Hz and we will narrow down the scope of our study to less than 1Hz as well (e.g., Fetsch, Turner, DeAngelis, & Angelaki, 2009; Butler, Smith, Campos, & Bülthoff, 2010; de Winkel, Weesie, Werkhoven, & Groen, 2010).

Heading Discrimination Threshold (HDT) has been widely used as an indicator of heading discrimination performance (e.g., Gu, DeAngelis, & Angelaki, 2007; Fetsch et al., 2009; MacNeilage et al., 2010; Butler et al., 2010). In this research, HDT is defined as the minimum heading angle θ (deviated from straight ahead position) of a linear heading motion that a subject can discriminate as different from the straight ahead heading with 84% correct rate. The stimulus is a linear inertial motion with certain peak acceleration magnitude M (Figure 1A). The experiment paradigm is like when a pilot is sitting in a motion simulator without outside view and the motion simulator moves forward with a small deviated heading angle θ from the pilot’s facing angle. After the motion, the pilot is required to report whether he/she was moved rightward or leftward. The motion-answer procedure was repeated with different deviation angles for many times in our study. The minimum deviation angle θ that allows each subject to have a correct rate of 84% is called HDT. We will use θ_{HDT} to denote the HDT in this paper. In order to make the result comparable with previous research (e.g., Gu et al., 2007; MacNeilage et al., 2010), we purposely choose 84% correct rate. The inertial motion was uni-directional and had a sinusoidal acceleration profile. All these were consistent with previous research (Gu et al., 2007; Fetsch et al., 2009; MacNeilage et al., 2010; Butler et al., 2010; de Winkel et al., 2010). In the past, different studies adopted different peak accelerations and frequencies. However, to the best of our knowledge, no one has studied the influence of frequency and peak acceleration magnitudes on human HDTs in the same experiment.

MacNeilage et al. (2010) hypothesized that the HDT between two forward motions were governed by subjects’ sensitivity to the difference between the two vectors of the heading motions (i.e., the ‘difference vector’. MacNeilage called this the ‘difference-vector hypothesis’).In current study, we adopt this hypothesis by redefining the ‘difference vector’ as the vector difference between the imagined straight forward direction (not represented by any motion) and the heading motion direction which deviated at an angle of θ_{HDT} (Figure 1B). We then hypothesized that this ‘difference vector’ is linearly correlated with lateral Heading Detection Thresholds (HDeT). The HDeT is defined as minimum peak acceleration A of a linear motion that a subject needed to detect lateral heading directions with 84% correct rate (Figure 1C). The experiment paradigm to measure HDeT is similar to HDT measurement. The only difference is that the peak acceleration of the movement was varied rather than the deviation angle θ which were restricted to be either -90° (left) or 90° (right).

The hypothesized linear correlation is as follows,

$$A_{HDeT} = \alpha \times M \times \sin(\theta_{HDT}) \quad (1)$$

Here, A_{HDeT} means the lateral Heading Detection Threshold, M means peak acceleration magnitude of stimuli used for measuring HDT, θ_{HDT} means HDT, α is a coefficient. The frequencies of stimuli used for measuring θ_{HDT} and A_{HDeT} are the same. For different peak acceleration M, there may be different α. The left hand of the equation is heading detection thresholds while the right hand is a coefficient multiply by the difference vector (i.e., M × sin (θ_{HDT})). We call this hypothesized linear relationship the modified 'Difference-vector Hypothesis' and tested this hypothesis with different peak acceleration *M* and frequency. If this hypothesis is supported, we could then use the existing data of heading detection threshold (Benson et al., 1986; Hlavacka, Mergner, & Bolha, 1996; Kingma, 2005; MacNeilage et al., 2010; Soyka et al., 2011) to predict the HDT.

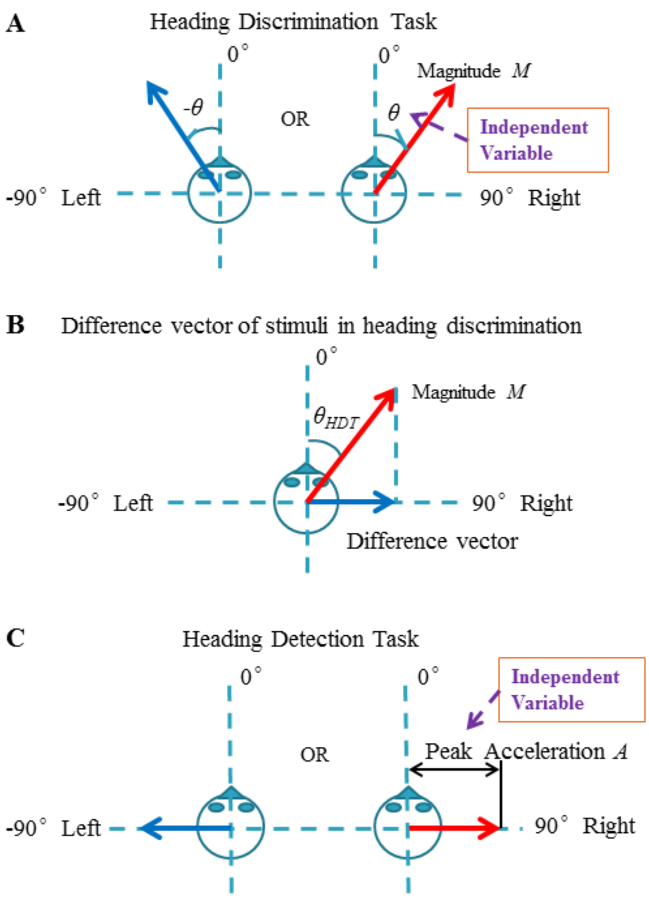

Figure 1. Illustrations of (A) the possible heading motions in HDT measurements; (B) difference vector; (C) the possible heading motions in HDeT measurements.

We have conducted two experiments to test the following hypotheses:

H1: human's inertial HDTs will be significantly changed with changing motion frequencies below 1 Hz.

H2: human's inertial HDTs will be significantly changed with changing peak accelerations of low-frequency (< 1Hz) motions.

H3 (Modified Difference-Vector Hypothesis): The difference vectors in heading discrimination task will be correlated to the HDeTs of the same subject with stimuli of same frequency.

H1 and H2 were tested in Experiment A and H3 was tested in Experiment B. In Experiment A, we measured HDTs with stimuli of different combinations of frequencies and peak accelerations. In Experiment B, we measured HDeTs with stimuli of the same frequencies as Experiment A.

METHOD

Subjects

Up to now, 7 subjects (4 male and 3 female) with age from 21 to 28 participated the experiments. All subjects had no history of vestibular defects. They were not receiving any medical treatment and were naïve to the experiment. The experiment was approved by the Human Subject and Research Ethics Committee at the university.

Apparatus and Stimuli

A dual-axis motion simulator was used to generate inertial heading motions. The motion simulator is basically a room which can move linearly in the horizontal plane. In the current experiment, the generated inertial heading motions were linear and uni-directional. Its acceleration profile follows a one-cycle sinusoidal function. A sample motion profile is shown in Figure 2. The acceleration profile has a frequency of 0.5 Hz and a peak acceleration of 30 cm/s^2. In every trial, the subject was exposed to the stimulus first. Then there was a 3s stationary answering period. After that, motion simulator moved back to the starting point. The backward motion has the same motion profile as the stimulus except in reversed heading direction. The subject was not prompted to give answer during the backward motion nor could they change their previous answers.

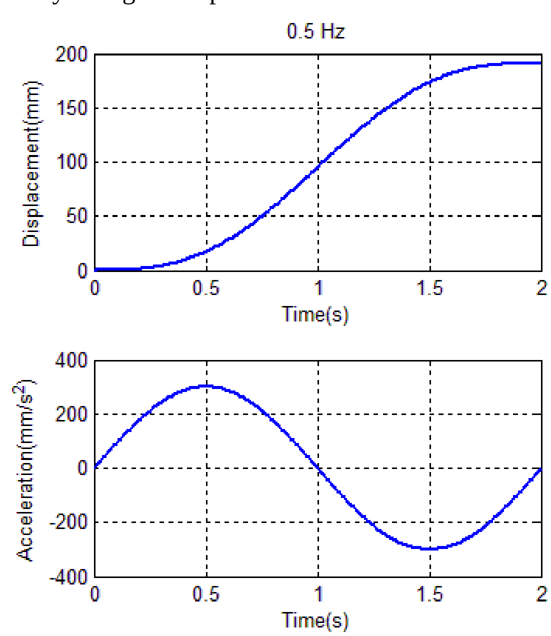

Figure 2. Displacement and acceleration time histories of a typical heading motion.

A chair and 46 inches LCD TV was placed inside the motion simulator. During the experiment, the subject sat in the chair and looked at the LCD in front of him/her. A four-point-harness, a head-restraint and a chin rest were used to control subjects' body and head movement. The subject wore a pair of ear plug to reduce the influence of auditory cues related to the movement of the motion simulator. The red fixation cross, instruction words and subject's answer were displayed by the 46 inches LCD TV which was placed at 80 cm away from the subject's eyes. In order to reduce environment influence, the TV and subject(s) was enclosed by a black curtain. All control and display programs used in the experiment were coded with OpenGL 2.3, C++.

In Experiment A, three levels of peak acceleration magnitude (20, 25, and 30 cm/s^2) and three levels of frequencies (0.25, 0.5 and 1 Hz) were studied. Since different subjects have different sensitivities to heading motions, we prepared 7 pairs of direction stimuli (± 3/5/8/13/18/23/28°) for all subjects. In the formal experiment, each subject only experienced 5 pairs of headings closest to their thresholds observed during their training sessions. The facing direction of the subject was defined as 0° and positive angle refers to rightward deviated heading directions.

In Experiment B, there were three levels of frequencies (0.25, 0.5 and 1 Hz). For the same reason, we also prepared 7 candidates (3/4/6/9/12/15/20 cm/s^2) of peak accelerations. The heading directions were ± 90°. In the formal experiment, each subject experienced 5 peak accelerations out of 7 candidates according to their performance during the training sessions.

Procedure

Before Experiment A, all subjects received at least two hours of training. The training stimuli have similar motion profile with the formal experiment, but were of different frequencies (0.4 and 0.8 Hz), peak accelerations (18 cm/s^2) and heading directions (± 5, 9, 18, 36°).

At the beginning of every session, the subject sat in a chair and wore a pair of ear plug. Their body and head was fixed with four-point-harness, a head-restraint and a chin rest. A keyboard was provided for reporting perceived heading directions. In front of the subject, a LCD TV was used to show the eye fixation point and instruction words. The chair and LCD TV was enclosed by a black curtain and the light inside the motion simulator were turned off during the experiment. Subjects were instructed to look at the fixation cross on the screen after a loud 'beep' alarm. A stimulus would then be presented about 1.5s later. Right after the stimulus, subject was required to report their perceived heading directions (left or right) within 3s. Their response was shown on the screen and can be changed within the answering time. They were forced to give an answer even if they cannot discriminate the heading directions of stimulus. After that, the motion simulator would move back to the starting point and stay stationary for a while. The subject was not able to change their responses after the 3s answering period.

The proportion of rightward response for each heading would be used to calculate HDTs of different conditions (see results for detail). The dependent variable of Experiment A is HDT. The independent variables are frequency and magnitudes. The design of Experiment A is a two-factor full-factorial design. In Experiment A, there were 6 sessions for every subject. The 6 sessions were conducted in similar time of different days. In each session, there were 6 blocks. We inserted a 2-3 minutes short break between every 2 blocks and the break between block 3 and block 4 (midpoint of the session) was extended to 5-10 minutes. During the pilot tests, some subjects missed the short duration stimuli (1 Hz) frequently when we mixed stimuli of different frequencies. Thus, we separated stimuli of different frequencies into different blocks. One block lasted 4-7 minutes. The block order was randomized and counterbalanced. The 5 pairs of headings were performed within every block. In short, one block consists of 30 trials of stimuli (1 frequency * 3 magnitude * 10 headings * 1 repetition). In total, there were 12 repetitions for each stimulus type.

Before Experiment B, all subjects took part in a 20-minute training session. Experiments B contained 2 sessions for every subject and were conducted in similar time on different days. The block setup was similar to Experiment A. Five levels of peak accelerations were chosen from the prepared 7 candidates according to the result of training. One block consists of 30 trials (1 frequency * 5 magnitudes * 2 headings * 3 repetitions). In total, there were 12 repetitions for each stimulus type. The procedure was similar to Experiment A. The dependent variable was HDeT and the independent variable was frequency.

RESULTS AND DISCUSSION

The rightward response proportions of all heading directions were calculated for each condition. They were then fitted with cumulative normal distribution to get the HDTs by Matlab Psignifit 3.0 toolbox (Fründ et al., 2011). In Figure 3, the rightward proportion data and the corresponding cumulative normal distribution of one subject was plotted as an example. Further analysis of HDTs and HDeTs will be presented in the following discussion. The analysis was performed by MATLAB R2012a and SPSS 21.

Heading Discrimination Threshold (HDT). The partial calculated HDTs of the first 7 subjects were shown in Figure 4. In order to identify the influence of motion frequency and peak acceleration, a repeated-measure ANOVA was performed. For peak acceleration, a significant influence was found ($p < 0.01$) while for frequency no significant result was found ($p > 0.1$). No significant interaction between frequency and peak acceleration were found ($p > 0.1$). In post hoc tests using Bonferroni correction, the result of peak acceleration comparison showed that there were significant difference in 20 cm/s^2 VS 25 cm/s^2, 20 cm/s^2 VS 30 cm/s^2 ($p < 0.05$), but not in 25 cm/s^2 VS 30 cm/s^2 ($p > 0.1$).

The result indicates that HDTs was reduced when we increased peak acceleration magnitude of stimuli. However, there is no significant influence of stimuli frequency. From Figure 4, we noticed that the frequency had different types of influence on HDTs for different magnitudes. In lower magnitudes, the HDTs decreased insignificantly as frequency increased. But in higher magnitudes, HDTs of 1 Hz seemed to reach a limit and were not reduced significantly while HDTs of

0.25/0.5 Hz kept decreasing with increasing magnitudes. In 30 cm/s^2 condition, the smallest HDT was achieved in 0.5 Hz although the result is not significant (0.25 Hz VS 0.5 Hz, paired t-test, p = 0.08; 0.5 Hz VS 1 Hz, paired t-test, p = 0.06). More data were being collected to see whether people are more sensitive to 0.5 Hz motions than 1 Hz motions with 30 cm/s^2 peak acceleration magnitudes. The result also indicates that there was a limit for HDTs and the limits are different for different frequencies. A similar limit of monkey's HDT was observed in previous research (supplementary material, Gu et al., 2007). In the current experiment, the frequency factor confounded with stimuli duration. HDTs of 0.25 Hz might have been underestimated while HDTs of 1 Hz were overestimated due to the duration influence. The separate effect of frequency and duration should be explored in future research.

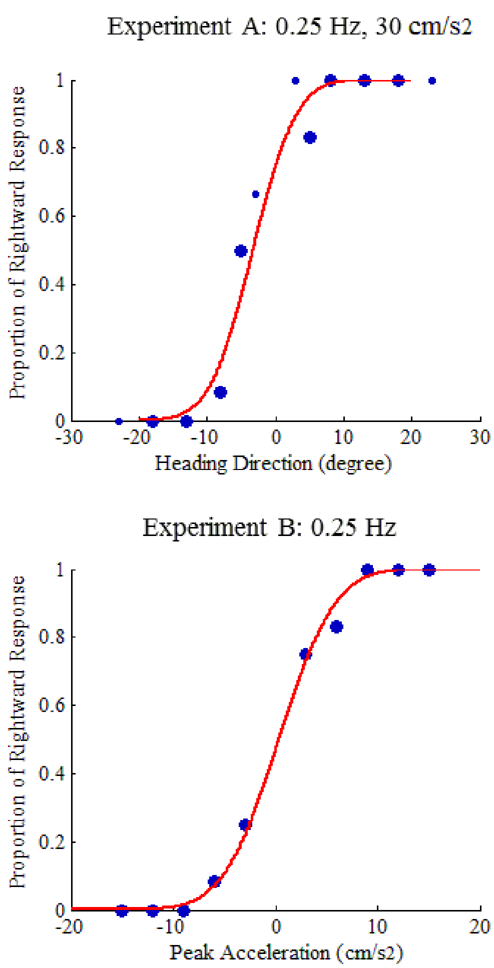

Figure 3. The plot of rightward proportion data and the corresponding cumulative normal distribution of one subject.

Heading detection threshold. The preliminary calculated heading detection thresholds were shown in Fig. 5. We also performed a repeated-measure ANOVA to test the influence of frequency factor. A significant result were found (p<0.01). Post-hoc tests with Bonferroni correction revealed that heading detection thresholds of 0.25 Hz were significantly higher than other 2 frequencies (p < 0.05), but there was no significant difference between heading detection thresholds of 0.5 Hz and 1Hz (p > 0.1).

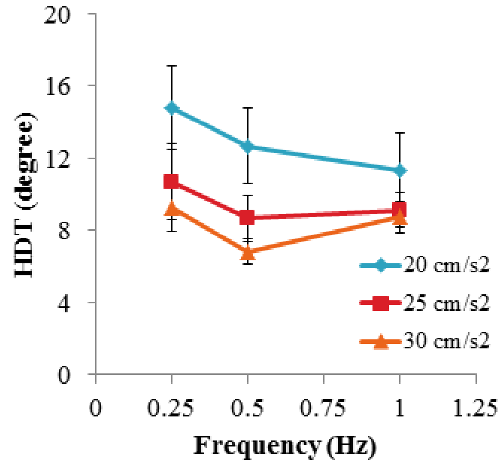

Figure 4. HDTs as functions of peak accelerations and frequency of heading motions (7 subjects' data).

Modified Difference-Vector Hypothesis. Pearson correlations between difference vectors and heading detection thresholds were calculated. In 0.25 Hz and 0.5 Hz condition, there were no significant correlations. In 1 Hz, we found significant correlation in all condition (20 cm/s^2: r = 0.8, p < 0.02; 25 cm/s^2: r = 0.78, p < 0.03; 30 cm/s^2: r = 0.78; p < 0.03). A possible explanation for the frequency difference is that subjects' sensitivity to lateral acceleration governed the limits of HDTs in each frequency instead of HDTs itself. Because only HDTs of 1Hz was around the limit, a significant correlation was thus observed.

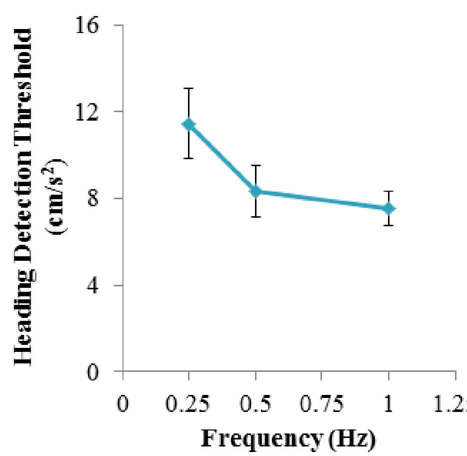

Figure 5. HDeTs of heading motions of different frequencies (7 subjects' data)

The equation (1) was fitted with 1 Hz data by linear regression. The coefficients α are 0.7 (20 cm/s^2), 0.39 (25 cm/s^2) and 0.42 (30 cm/s^2). The result implied that, for different peak acceleration of heading discrimination task, the coefficients are different, and all coefficient are smaller than 1.

Inspired by the significant correlation results, we conducted paired t-tests on Difference Vector VS HDeT in conditions of different combination of peak acceleration and frequency. The result showed that difference vectors were significantly smaller than corresponding HDeT of the same subject ($p < 0.01$). This indicates that subject's sensitivity to lateral acceleration was improved when an extra forward acceleration was presented simultaneously. We are excited about the preliminary results. With more data to be collected, we believe the findings will be more significant.

CONCLUSIONS

The result here suggest that Heading Discrimination Thresholds (HDTs) changes significantly with stimuli of different peak acceleration in low-frequency range (<1 Hz). The improvement was getting smaller as the peak acceleration increases. We believe that the HDTs are getting close to a limit as peak acceleration increases and the limits are different for different frequencies. Motion frequency has been shown not to be a significant factor on HDTs.

Heading detection thresholds (HDeTs) decreased when stimuli frequency increased in low frequency. This result is consistent with the previous reported data (Benson et al., 1986). The heading detection thresholds were significantly correlated with the difference vectors only in the 1Hz conditions. One possible reason is that HDTs of 1Hz conditions were closer to the HDT limit of 1Hz.

More data should be collected to consolidate the current findings. In future, the effect of frequency and duration should be explored separately. Why 'Modified Difference-vector Hypothesis' didn't hold in 0.25 and 0.5 Hz is another problem need to be studied in the future.

ACKNOWLEDGEMENTS

This research is partially supported by the Hong Kong Research Grants Council through 620009 and 618812.

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