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Modification of visual and vestibular control of posture by long-term adaptation to body-movement-yoked visual motion and galvanic vestibular stimulation

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Abstract

Human postural control is a multi-modal process with visual and vestibular information. Thus, postural sway is induced by visual motion as well as vestibular stimulation. The purpose of this study was to measure individual differences in weights on vision and vestibular senses to control posture, and to investigate if the individual weights could be modulated by long-term adaptation to visual motion or galvanic vestibular stimulation (GVS). GVS was applied through left and right mastoid processes (0.1-0.5mA, sinusoidal amplitude modulation). Both visual motion and GVS induced lateral (leftward-rightward) postural sway back and forth. Observers' body movement was measure by a force plate and a magnetic motion tracker. We measured observers' postural sway induced by visual motion or GVS before and after a 7-days adaptation task (n=24). We divided participants into 4 groups. In visual adaptation groups, visual motion was presented to enhance voluntary body movement for 5 participants, and to inhibit the movement for 6 participants (enhance/inhibit body-movement-yoked vision). In GVS adaptation groups, GVS was applied to enhance voluntary body movement for 6 participants, and to inhibit the movement for 7 participants (enhance/inhibit body-movement-yoked GVS). In results, the adaptation to the enhance body-movement-yoked visual motion decreased the GVS-induced postural sway and increased the visually-induced sway at a low motion frequency. The adaptation to the inhibit body-movement-yoked GVS increased the GVS-induced postural sway and decreased the visually-induced sway particularly at a high motion frequency. These results suggest that the long-term adaptation to body-movement-yoked GVS can modify weights on vision and vestibular senses to control posture. Our findings can be applied to training or rehabilitation of postural control or adaptive virtual-reality system.

Categories and Subject Descriptors (according to ACM CCS): H.1.2 [Models and Principles]: User/Machine Systems—human factors, human information processing

1. Introduction

Human posture is controlled by visual, vestibular, and proprioceptive information. Thus it is a multimodal process. Spontaneous postural sway decreases 50-60% with a stable visual environment [Tra45] [Edw46]. Visually induced postural sway has been investigated for many years. A moving room affects adults' and infants' posture [LL75] [LA74]. When a visual filed contains a large visual motion, observers' body sway occurs at the identical frequency of the visual motion [LSB77] [KKKI07]. The body sway occurs synchronously with the visual motion. Thus, when we use a cyclic visual motion, we find the sway at the same frequency of the visual motion.

Recently, galvanic vestibular stimulation is used to investigate vestibular induced postural sway. When a small current is applied to left and right mastoid processes, the observer inclines in the direction of anodal ear (eg [Day99]). When the GVS applies to a walking observer, his walking trajectory is affected [FWT99]. The GVS has been applied to the virtual reality. Virtual acceleration of self-motion was

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induced by the GVS as simultaneously presented with visual motion [MAS05][MAA*05]. The GVS was also applied to enhance a music experience in a field of the virtual-reality entertainment [NYS*06], and to transfer other's body balance as a vestibular tele-presence system [YAMW08]. Since the GVS is a small system and inexpensive, it has an advantage in comparison with some larger systems such as a motion platform, and will be getting popular in the field of the virtual reality.

It is known that perception-action coordination systems can adapt to a new situation rapidly. The most famous and traditional paradigm to investigate the adaptation of the perception-action system is 'inverted vision' with a prism scope [Str896]. When one wears the prism scope, the perceptual world is inverted and he/she cannot help staggering around. After prolonged adaptation (1-4 weeks), the perceptual world gets back to proper orientation, and he/she becomes able to walk, run, and ride a bicycle. More moderate version of it is 'distorted optical stimulation' [Wel69]. Manual pointing to a visual target is failed and shifted to the distorted position when one observes the world through the distortion prism. After adaptation, he/she can correctly point the target.

These studies showed that our perception-action system is plastic and adaptive to a new environment. When observers are moving, they sense both visual and vestibular sensations. In the daily life the visual information and the vestibular information are consistent. For example, when we walk 5 m, the visual information and the vestibular information are equivalent and have a value of 5 m. Some researchers manipulated a gain of visual motion when an observer actually moved, and showed that the prolonged adaptation to a new gain modified the perceptually stable gain in the direction of the adapted gain [WC76][BWN84][Wal87]. Using virtual-reality techniques, it is reported that adapting to a visual-vestibular conflict for 45 min modified the vestibular sensation, but not the vestibulo-ocluar reflex (VOR) [IVS*98][VIGI99]. The degree of this adaptation is stronger for males than females [VIBJ98]. In our previous study, we manipulated a gain of visual motion when an observer rotates his head with wearing a head-mounted display, and investigated whether the gain that the observer perceives as most stable adaptively changed [KS05]. We found that the stable gain adaptively changed after just 2-min active adaptation and that the adaptation for visual stability is concerned with relatively higher information processing, at least after the fusion of binocular sources, but is specific to or modulated by the retinal location. In clinical studies, Jenkins and his colleagues reported that the VOR gradually changes for 120 days after vestibular ablation [JCK00][Jen85].

The purpose of this study was to measure individual differences in weights on vision and vestibular senses to control posture, and to investigate if the individual weights could be modulated by a long-term active adaptation to visual motion and galvanic vestibular stimulation.

2. General Methods

2.1. Participants

24 graduate and undergraduate students participated in the experiment with a written informed consent. This research was approved by the Committee for Human-Subject Studies of the Toyohashi University of Technology.

2.2. Apparatus

The experiments were conducted in a semi-dark room (Figure 1). Visual stimulus was presented to a rear-projection screen (width 2.43 x height 1.82 m) by a 3-CRT projector (Barco Cine7/II. 1024 x 768 pixel, 60 Hz refresh). Galvanic vestibular stimulation (GVS) was generated by a DA device board (National Instruments PCI-6704), and applied through left and right mastoid processes with a pair of disposable Ag/AgCI electrode (Ambu Blue Sensor P-00-S, Figure 2).

Figure 1: *Experiment apparatus in a dark room*

Figure 2: *Disposable electrode at right mastoid*

We measured participants' head movement and center of gravity for the indexes of postural sway. The head motion

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was measured by a magnetic motion tracker (Polhemus FASTRAK) at 60 Hz. The center of gravity was measured by a force plate (NEC EB1101) and recorded through a AD device board (National Instruments PCI-6024) to a computer (DELL, Pentium4 2.8GHz CPU, 512MB RAM, nVIDIA-Quadro-FX1000 Graphics, MS-Windows 2000). The computer controlled visual stimuli and GVS as well as measured both the head motion and the center of gravity. Thus, the timings of stimulus presentation and recording postural data were synchronized.

2.3. Experimental Design

We employed a typical experimental paradigm to investigate adaptation/learning: pre- and post-tests with adaptation. Firstly, all 24 participants performed an experiment to measure postural sways induced by visual stimulus and GVS (pre-test). Then, they adapted to one of 4 perception-action combinations for 7 days. For 5 participants, visual motion was presented to enhance voluntary body movement. For 6 participants, visual motion was presented to inhibit the movement (enhance/inhibit body-movement-yoked visual motion). For 6 participants, GVS was applied to enhance voluntary body movement. For the other 7 participants, GVS was applied to inhibit the movement (enhance/inhibit body-movement-yoked GVS). After the adaptation period, all participants performed again the postural-sway experiment identical to the first one to see the effect of adaptation (post-test). The change of visually- and GVS-induced postural sways before and after the adaptation will reflect the effect of adaptation and the plasticity of multi-modal postural control system.

3. Experiments for visually- and GVS-induced postural sways (pre-test)

3.1. Visual and GVS Stimuli

Modality of motion stimulus was the most critical independent variable. Either visual stimulus or GVS was presented to a participant for each trial.

For visual stimulus, we presented lateral motion of random dots on the front-parallel screen (width 58.3 x height 50.5 deg in visual angle) at 1.5 m visual distance. 5000 random dots moved laterally (leftward and rightward) back and forth with sinusoidal speed modulation (travel distance: 11.6 deg, up to 5.8 deg left and right from the center). Each dot was a square (0.45 x 0.45 deg) and red (0.76cd/m^2) on a black background. Density of the random dots on the background was 15.9% (Figure 3).

For GVS, we presented a weak current (minimum 0.1 mA - Maximum 0.5 mA) through left and right mastoids. Its modulation was sinusoidal and similar to the visual motion. Though the resolution of current modulation was limited to 0.1 mA step by the apparatus, the postural sway of participants was smooth and natural.

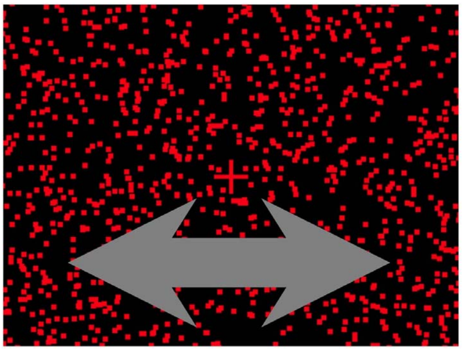

Figure 3: *(a) Schematic stimulus of random-dots visual motion*

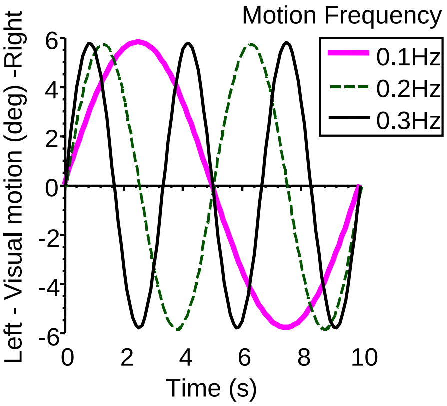

Figure 3: *(b) Visual motions varied with motion frequency*

We manipulated the motion frequencies of visual motion and GVS as an independent variable: 0.1, 0.2, and 0.3 Hz. Since the duration of a trial was always 90 s, the 9, 18, and 27 cycles of visual or GVS motion were presented for 0.1, 0.2, and 0.3 Hz conditions, respectively. We put a fixation point (a cross, 4.6 x 4.6 deg) at the center of the display, and asked participants to fixate their eyes on it. In visual motion condition, the moving random dots were presented around the fixation point, and in the GVS condition, only the fixation point was presented on the black background.

3.2. Procedure

We made a session with condition combination of 2 stimulus modalities (Vision or GVS) and 3 motion frequencies (0.1, 0.2, or 0.3 Hz), where these 6 conditions/trials were presented in a random order. Each participant conducted 10 sessions, thus every condition was repeated 10 times.

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3.3. Results

All participants showed induced sways by visual and GVS motions (Figure 4). We applied FFT to each trial data, and extracted postural-sway powers at the frequency of visual or GVS motion. This is a typical analysis of induced postural sway. Since absolute values of postural sway were large, we normalized the data by using the individual average. The normalized data (relative value to the individual average) were plotted in Figure 5. The data were averages of all 24 participants with error bars of the standard errors. We obtained 2 types of indexes for postural sway: center of gravity and head motion. Since the results of these 2 indexes were similar, we show the data of center of gravity only in figures. GVS-induce postural sway was larger than visually-induced postural sway, particularly in low frequencies. GVS-induced sway decreased with high frequency.

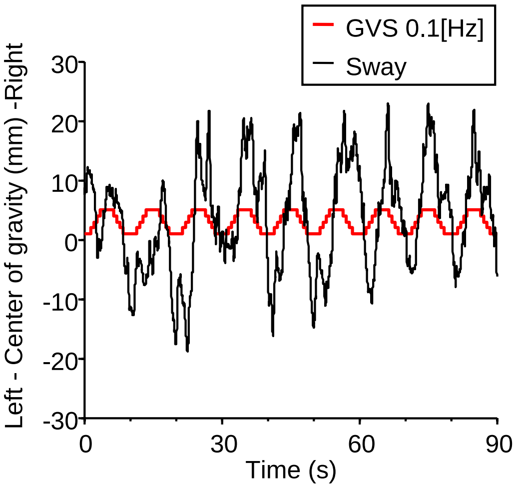

Figure 4: *Sample data of postural sway*

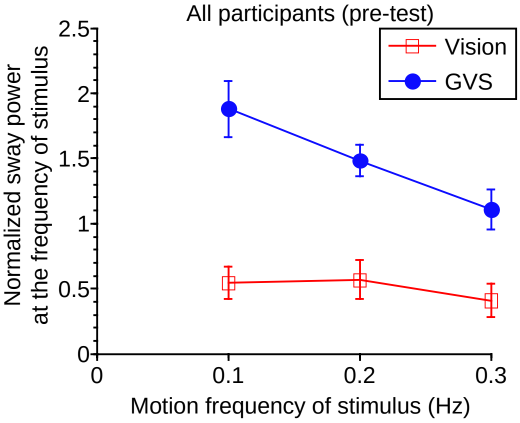

Figure 5: *Results of visually- and GVS-induced postural sways (pre-tests)*

As a statistical test, we conducted a repeated measures ANOVA (2 ways: 2 modalities x 3 frequencies). We found significant main effects of the modality (p=.0002) and the frequency (p=.0087), and an interaction of them (p=.0211). These results were identical to our previous data [KK08]. In this paper, we use these data as standards before adaptation.

4. Long-term adaptation

4.1. Adaptation groups

We divided participants into 4 groups randomly: the inhibit body-movement-yoked vision group (5 participants), and the enhance body-movement-yoked vision group (6 participants), the inhibit body-movement-yoked GVS group (7 participants), and the enhance body-movement-yoked GVS group (6 participants).

4.2. Methods

Apparatus was identical to the pre-tests except that the force plate was excluded. We monitored the motion of participants' head by a motion tracker (Polhemus FASTRAK), and manipulated visual motion or GVS continuously (on-line) depending on their motion at 60 Hz.

In the 'enhance vision' adaptation, when the participant inclined rightward the random dots moved rightward to induce more rightward postural sway, vice versa. In the 'inhibit vision' adaptation, when the participant inclined rightward the random dots moved leftward. For these 2 conditions, the manipulation of visual motion was just opposite.

In the 'enhance GVS' adaptation, when the participant inclined rightward the GVS induced the rightward postural sway. In the 'inhibit GVS' adaptation, when the participant inclined leftward the GVS induced the rightward postural sway. For these 2 conditions, the manipulation of GVS was just opposite.

We asked participants to sway their body laterally back and forth with 30 cm travel distance (15 cm left and right from the center) at 0.2 Hz. To guide this body motion, we presented 2 vertical bars in red and green on the screen (Figure 6). The red bar moved leftward and rightward with sinusoidal speed modulation at 0.2 Hz. The green bar represented the current (on-line) position of the participant's head. We asked participants to move the green bar on the red bar as possible as accurately. A trial continued for 60 s. Each subject performed 10 trials a day, and continued for 7 days. Thus, every participant performed 70 trials in total.

5. Experiments to see effects of long-term adaptation on induced postural sway (post-test)

5.1. Methods

Methods were identical to the first one (pre-test). All participants performed the same experiment.

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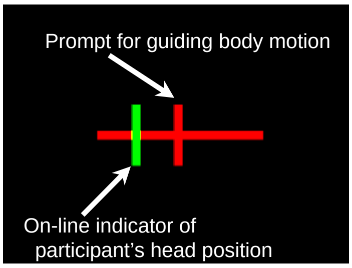

Figure 6: *Display for the adaptation experiment*

5.2. Results

We conducted the identical analysis to the pre-test, and plotted the data separately in inhibit and enhance vision groups in Figure 7, and inhibit and enhance GVS groups in Figure 8, respectively. Generally, the GVS-induced sway was larger than the visually-induced sway, but the differences depended on the adaptation groups.

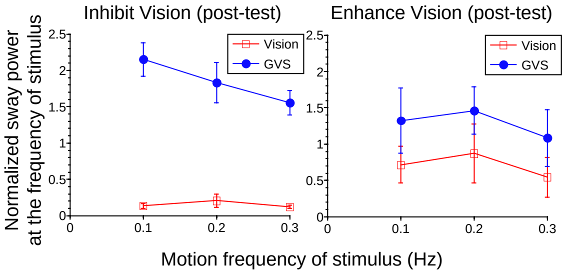

Figure 7: *Results of post test in inhibit and enhance vision groups*

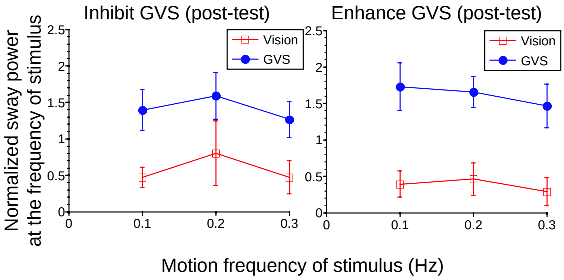

Figure 8: *Results of post test in inhibit and enhance GVS groups*

To investigate individual change before and after the adaptation, we calculated the difference of the induced postural sway before and after the adaptation by subtracting the pre-test data from the post-test data (Figure 9 and 10).

For the 'inhibit Vision' adaptation condition, we did not find any effects of the adaptation (Figure 9a). For the 'enhance Vision' adaptation condition, the visually-induced sway slightly increased and the GVS-induced sway decreased at the low frequency, 0.1 Hz (Figure 9b).

As statistical tests of the effects of the adaptation, we conducted repeated measures ANOVA for the data of Figure 9a and 9b (3 ways: 2 adaptation groups x 2 modalities x 3 frequencies). We found a significant 3-way interaction: adaptation (inhibit/enhance) x modality x frequency (p=.0491). This statistically supports the fact that the 'enhance Vision' adaptation decreased GVS-induced sway and increased visually-induced sway only at the low frequency. Then we conducted paired t-tests to test the difference between GVS-induced sway and visually-induced sway for each frequency condition, but we found only a weak tendency of the difference between GVS- and visually-induced sways with the 'enhance Vision' adaptation at 0.3 Hz (p=.1441).

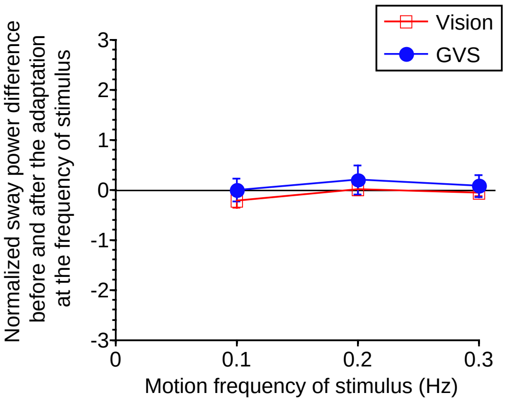

Figure 9: *(a)Effects of the adaptation (post test - pre test) in inhibit Vision group*

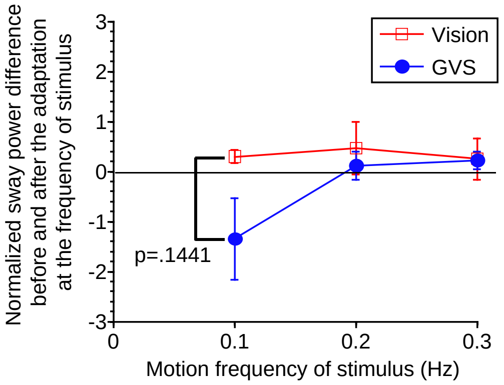

Figure 9: *(b)Effects of the adaptation (post test - pre test) in enhance Vision group*

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For the ’inhibit GVS’ adaptation condition, the GVS-induced sway increased particularly at the high frequency (0.3 Hz), and the visually-induced sway slightly decreased (Figure 10a). For the ’enhance GVS’ adaptation condition, the GVS-induced sway slightly increased and the visually-induced sway decreased at the low frequency (Figure 10b).

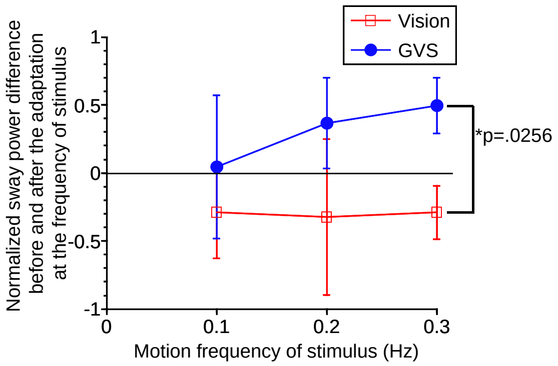

Figure 10: *(a)Effects of the adaptation (post test - pre test) in inhibit GVS group*

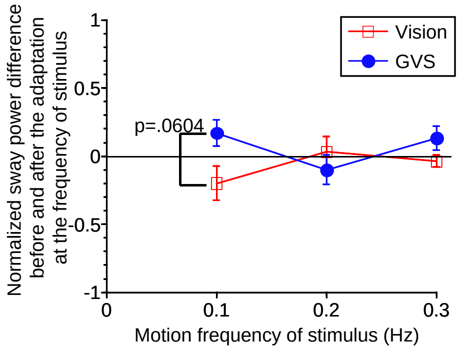

Figure 10: *(b)Effects of the adaptation (post test - pre test) in enhance GVS group*

As statistical tests of the effects of the adaptation, we conducted repeated measures ANOVA for the data of Figure 10a and 10b (3 ways: 2 adaptation groups x 2 modalities x 3 frequencies). However, we did not find any significant effect because the individual difference was large. Then we conducted paired t-tests to test the difference between GVS-induced sway and visually-induced sway for each frequency condition. For the ’inhibit GVS’ condition, we found a significant effect of the adaptation (p=.0256) at 0.3 Hz, that the GVS-induced sway increased significantly more than the visually-increased sway. For the ’enhance GVS’ condition, we found a near significant effect of the adaptation (p=.0604) at 0.1 Hz, that the GVS-induced sway increased more than the visually-increased sway. These results of t-tests support the above findings shown in Figure 10a and 10b.

6. Discussion

We conducted a 7-days long-term adaptation experiment using a body-movement-yoked visual motion and GVS. Participants were applied visual motion or GVS, which either inhibited their voluntary sway or enhanced it. In results, the ’enhance Vision’ adaptation decreased GVS-induced sway and increased visually-induced sway only at the low frequency. The adaptation to the ’inhibit GVS’ increased the GVS-induced postural sway and decreased the visually-induced sway particularly at a high motion frequency (0.3Hz). The adaptation to the enhance body-movement-yoked GVS slightly increased the GVS-induced postural sway and decreased the visually-induced sway particularly at a low motion frequency (0.1Hz).

The ’enhance Vision’ adaptation increased the weight of the visual control of posture relatively to that of the vestibular control. It is reasonable because the ’enhance Vision’ adaptation seemed to make visual information more reliable to control postures. Why is the effect limited to the lower frequency? We think that the difference of the weights of vision and vestibular senses are large at the low frequency (see Figure 5), so that it could be easy to be affected by the adaptation.

The ’inhibit GVS’ adaptation increased the weight of the vestibular control of posture relatively to that of the visual control at a high motion frequency. It is controversial. As a speculation, it may be related to that our visual and vestibular postural control is not good at higher frequency [Sto86] [vAGdG88] [KKKI07] [KK08]. By exposure to inhibiting GVS, a kind of negative aftereffect might occur at the frequency vulnerable to posture controls, then GVS-induced sway would increase after adaptation. The ’enhance GVS’ adaptation increased the weight of the vestibular control of posture relatively to that of the visual control at 0.1 Hz. It is reasonable similarly to the above finding of the ’enhance Vision’ adaptation.

These results suggest that the long-term adaptation to body-movement-yoked visual motion and GVS can anyhow modify weights on vision and vestibular senses to control posture. It reflects a great plasticity of our perception-action system. Our findings can be applied to training or rehabilitation of postural control or adaptive virtual-reality system in a future. For example, we can propose an adaptive tele-presence system for mobile observers. Though the tele-presence system needs to send multi-modal information such as vision and vestibular sensation, one of them may not be sent with a high resolution. If the quality of vision is lower than the vestibular information, the amplitude of the vestibular information should be increased with the GVS. For a long-term usage/adaptation, users would be relying more on the vestibular information gradually, and the degraded visual information would not deteriorate the performance. If our vestibular sensitivity is getting worse than vision as aging, we should use the visual information to control posture more than the vestibular information. We can propose an AR application to enhance optic flow to increase the visual weight for the postural control. Using this system for a period, we will more rely on the visual information rather than the vestibular information. It is also applicable to a disorder of vestibular organs. However, our findings are still basic, and we need further experiments with a large number of participants.

7. Acknowledgements

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