Effects of retinal position on the visuo-motor adaptation of visual stability in a virtual environment

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Abstract. Although the retinal image changes a great deal with the movement of our head or eyes, we perceive a stable world (a phenomenon known as visual stability or position constancy). Visual stability adaptively changes for each new combination of vision and head motion, or to compensate for manipulated visuo-motor gain. This study aims to investigate the effects of retinal positions on visuo-motor adaptation and to discuss the neural mechanisms involved. I found that visuo-motor adaptation occurred, and was transferable from right to left visual fields (Experiment 1), between the upper and lower visual fields (Experiment 2), and between the central and peripheral visual fields (Experiment 4), and that for the left visual field (Experiment 1) and the large visual field (Experiment 3) visuo-motor adaptations were effective. The dominance of the central vision was found in Experiment 3 but not found in Experiment 4. These results suggest that the visuo-motor adaptation of visual stability was not specific to the retinal location, but is processed by a relatively high level of the perceptual system.

Keywords: position constancy, visuo-motor coordination, laterality, eccentricity.

1 Introduction

Since we observe our environment by moving our head and eyes, our retinal images change frequently, continuously, and abruptly. This retinal image motion is decomposed or interpreted into object motion, object structure, and self-motion by our perceptual processes (e.g. Kitazaki & Shimojo, 1998; Nakayama, 1985). When we see stationary environments while our head or eyes are in motion, our perceptual world is stable, even though the retinal image per se is in motion. This phenomenon is known as "position constancy" or "visual stability," and is based on a valid interpretation of object motion and self-motion using a combination of visual and motor (extra-retinal) information. This visuo-motor cross-modal system compensates for retinal image motions when our head or eyes are moving, and is extremely accurate and reliable. Healthy adults can detect environmental motions during head turning that amount to only 3% of the head motion, regardless of whether the environmental motion is against or in the same direction as the head rotation (Wallach, 1987).

This visuo-motor compensation system can adaptively change in response to inter-sensory conflict situations. When one wears a prism inversion goggle, the perceptual world is inverted, and he or she cannot help but stagger around. After a prolonged adaptation period (1–4 weeks), the perceptual world regains its proper orientation, and the individual becomes able to walk, run, and even ride a bicycle (e.g. Stratton, 1896, 1897a, 1897b). The neural mechanisms underlying this adaptive inverted vision have also been reported (Sekiyama, Miyauchi, Imaruoka, Egusa, & Tashiro, 2000). Adaptation also occurs over shorter periods of time; when one observes the environment through a distortion prism, manual pointing to a visual target fails and shifts to the distorted position. However, after a 15- to 60-min adaptation, individuals can correctly point to a target (Dolezal, 1982; Welch, 1969).

This visuo-motor adaptation of visual stability has been quantitatively investigated by varying "visuo-motor gain" (Becklen, Wallach, & Nitzberg, 1984; Wallach, 1987; Wallach & Canal, 1976; Wallach & Kravitz, 1965a, 1965b). The head position and orientation are monitored, and the visual image motion presented to participants is manipulated using a gain with monitored head motion. For example, when a visually simulated motion of 45° head rotation is presented to the participant, whose head rotates 90°, it is regarded as 0.5 visuo-motor gain. Then, after adaptation, the participant is asked to judge which gain makes the visual stimulus more stable or constant. The stable gain can be changed

into the direction of distorted gain with only a 10-min exposure (Wallach & Canal, 1976; Wallach & Kravitz, 1965b). Similar results were obtained in a virtual reality environment with only a 3-min adaptation period (Takahara, Okajima, & Takase, 1999). The visuo-motor adaptation of stable perception is gaining increased attention in virtual reality studies (Ivanenko, Viaud-Delmon, Siegler, Israel, & Berthoz, 1998; Viaud-Delmon, Ivanenko, Berthoz, & Jouvent, 1998; Viaud-Delmon, Ivanenko, Grasso, & Israel, 1999). Viaud-Delmon et al. (1998) report that the adaptation of the visuo-motor system to inter-sensory discrepancies induces a change in vestibular information; they also reported that the visuo-motor adaptation effect was larger for males than for females. However, there has been no research to date that reports the effects of retinal position and inter-visual field transfer.

The purpose of this study was, therefore, to explore the neural mechanisms responsible for the visuo-motor adaptation of visual stability, by investigating the effects of varying retinal positions on visuo-motor adaptation.

First, I conducted psychophysical experiments to ascertain whether visuo-motor adaptation can transfer between the left and right hemifields in Experiment 1 (preliminary data and analysis were previously presented at a conference by Kitazaki & Shimizu, 2005). The receptive fields of neurons in the early visual pathway, such as retinal ganglion cells, lateral geniculate nucleus (LGN), and V1 are smaller than those of neurons in the late visual pathways, such as MT, MST, and parieto-occipital cortex (Adelson & Movshon, 1982; Mikami, Newsome, & Wurtz, 1986). If there is no left–right visual field transfer of visuo-motor adaptation, this would imply that the adaptation is processed before the visual inputs of the left and right visual hemifields become integrated. In contrast, if results reveal a transfer between the left and right visual fields, then it is likely to be processed at a higher (post-integration) stage. Then, if we obtain an advantage in the left visual field, the adaptive visual stability seems to be processed in the right hemisphere of our cortex, which is more specialised for visuo-spatial processing than the left hemisphere (Bogen & Gazzaniga, 1965; Corballis, 2003).

Secondly, I investigated adaptation in the upper and lower visual fields, and its transfer, in Experiment 2. There is a functional asymmetry between the ventral and dorsal streams in the cortex; peripheral visual inputs from the lower hemifield are projected more to the dorsal streams (Danckert & Goodale, 2003; Maunsell & Van Essen, 1987). The dorsal stream projects to the parieto-occipital lobe from V1 and is referred to as the 'where' pathway for vision-for-action, while the ventral stream projects to the temporal cortex from V1, and is referred to as the 'what' pathway for vision-for-perception (Goodale & Milner, 1992; Milner & Goodale, 1995). Consistent with these anatomical facts, some visuo-motor control tasks such as pointing have an advantage when presented in the lower visual field (Danckert & Goodale, 2001; Previc, 1990). Moreover, attentional resolution is higher in the lower visual field than in the upper visual field (He, Cavanagh, & Intriligator, 1996, 1997; Intriligator & Cavanagh, 2001). This finding can be accounted for by the fact that the parieto-occipital cortex is strongly associated with spatial attentional control (Posner, Walker, Friedrich, & Rafal, 1987). If adaptation occurs to a greater extent in the lower visual field, the dorsal stream or the parieto-occipital cortex would be recruited for the visuo-motor adaptation of visual stability. By testing transferability between the upper and lower visual fields, we investigate interaction or independence between them for the visuo-motor adaptation of visual stability. If there is no or little transfer, the visual stability might be mainly processed in either the dorsal or ventral stream independently.

In the final two experiments (Experiments 3 and 4), the effects of central–peripheral relationships of retinal positions were investigated. Temporal resolution is known to be higher in the peripheral visual field than in the central visual field (e.g. Tyler, 1985). It has been argued that peripheral vision is critically important for visually induced self-motion perception (Brandt, Dichgans, & Koenig, 1973; Dichgans & Brandt, 1978; Held, Dichgans, & Bauer, 1975; Johansson, 1977). However, the advantage in the periphery disappears when stimulus size is equalised for the central and peripheral visual fields, and it is the size of the visual field rather than the eccentricity of the stimulus that is critical for visually induced self-motion perception (Howard & Heckmann, 1989; Post, 1988). On the contrary, the central visual field is dominant for heading perception (Crowell & Banks, 1993; Warren & Kurtz, 1992). Thus, we tested the effects of size and eccentricity of the stimulus on visuo-motor adaptation, in order to explore commonalities between visuo-motor adaptation, temporal resolution, and self-motion perception. By testing transferability between the central and peripheral visual fields, we investigate a possible hierarchical processing of the visuo-motor adaptation of visual stability. If the transfer is unidirectional that the peripheral adaptation with the central test is more effective than the central

adaptation with the peripheral test, the adaptive processing of visual stability requires peripheral-vision adaptation or exposure before the central-vision exposure.

2 Experiment 1

The transfer of visuo-motor gain adaptation between left-half and right-half retinal locations was investigated to see adaptation's specificity in retinal location and to test whether the right cortical hemisphere plays a critical role in this adaptation.

2.1 Methods

2.1.1 Subjects

Six naive subjects participated in the experiment; all provided written informed consent prior to participation. All were university students, with normal or corrected-to-normal vision, and they were blind to the purpose of the experiment. The committee of 'Human subject studies' of the Toyohashi University of Technology approved all experimental protocols in this study.

2.1.2 Apparatus

Participants' head position and orientation were monitored by a magnetic motion tracker (Polhemus Fastrak). A computer (DELL Precision Workstation 530, Xeon 2.4 GHz, 1.0 GB RAM, NVIDIA Quadro4-900XGL, MS-Windows 2000, Open GL 1.0, GLUT 3.2) generated and controlled visual stimuli, using the monitored head positions and orientations. Head tracking was sampled at 60 Hz, and visual stimuli were updated at a rate of 60 Hz (orientation accuracy: 0.15°, latency: 4 ms). The delay of motor information to visual information was 1 frame (1/60 s). Visual stimuli were presented on an HMD (iO Display Systems i-glasses SVGA, 800 (wide) × 600 (high) pixels, 21.2° × 15.9° visual angle, refresh rate 60 Hz).

2.1.3 Stimuli, conditions, and procedures

A virtual world containing 3,000 wireframe balls (radius 10 cm) was simulated around the observer's head. The area containing the balls was a sphere of 6.0-m radius, but an inner spherical region of 1.0-m radius was excluded (Figure 1).

The visual stimulus was always presented to both eyes (binocularly identical image), but the image region was limited to the left or right hemifield (43.75% of the whole field), and the other hemifield was kept black (see Figure 2). The subject was asked to fixate their gaze on the central fixation cross throughout the experiment. This fixation inhibited both smooth pursuit eye movements and the vestibulo-ocular reflex.

A single experimental trial consisted of an adaptation phase and a test phase. In the adaptation phase, the visual stimulus of balls was positioned either left or right within the visual field, and
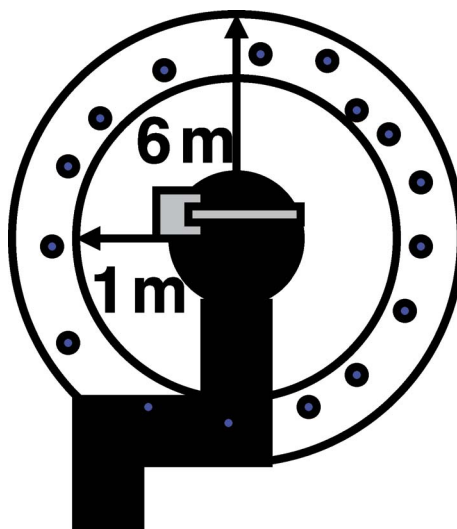

Figure 1. Simulated virtual world. Participants' viewpoint is located at the centre of the virtual area containing 3,000 wireframe balls.
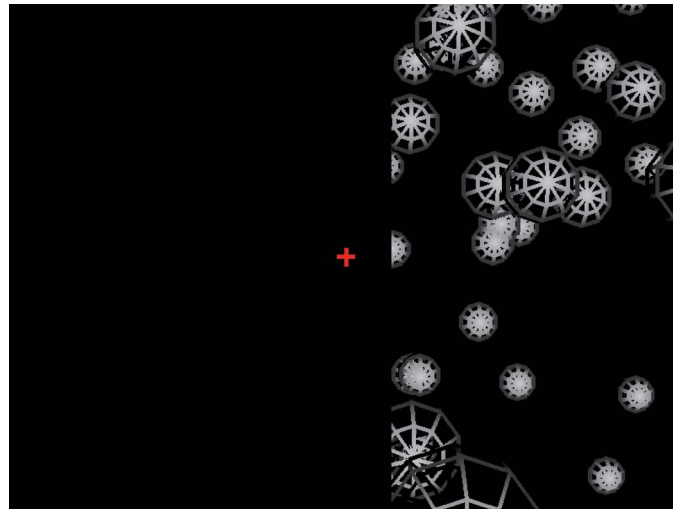
Figure 2. Example of stimulus (right visual field) with fixation point in the centre.

visuo-motor gain was set at either 0.5 or 1.0. Visuo-motor gain was defined as follows: gain = virtual rotation of head in the visual simulation/actual rotation of the observer's head. Thus, with the gain at 0.5, when the observer rotates their head 60° to the left, the virtual head rotates 30°, and the visual image motion is thus half of the ideal motion. With the gain set at 1.0, the simulated motion is identical to the real-world head motion. During the adaptation phase, participants were exposed to the stimulus while moving (rotating) their head actively left and right in a range of 120° at approximately 0.2 Hz for 2 min. Before the experiment, all participants underwent a training period and could move their head correctly over 120° laterally, at 0.2 Hz. During the experiment they were asked to move their head over the same range and at the same speed.

The adaptation phase was followed by a test phase after a 1-min rest in darkness. In the test phase, the visual field of balls was either the same as or different from the adaptation phase, and the initial visuo-motor gain was randomly set within the range of 0.25–1.75. Participants were able to manipulate the gain during the test phase, and were asked to adjust the gain so they perceived the visual world to be constant/stable, while they were observing the stimulus with their head moving laterally. The duration of the test phase was 1 min. In this manner, we determined the visuo-motor gain required to stabilise an inter-sensory discrepant virtual world. Each session consisted of 2 adaptation–visuo-motor gain conditions (0.5, 1.0) × 2 adaptation–visual field conditions (left, right) × 2 adaptation-test–visual-field consistency conditions (same, different), presented in random order, giving eight trials in total. Each participant conducted three sessions (repetitions).

Immediately prior to starting each session, the participant conducted 20 trials of pre-testing, measuring each participant's standard gain in the experimental setup. The pre-test trials were identical to the test phase.

2.2 Results and discussion

First, each participant's standard gain for a stable visual world was calculated by averaging the last 10 trials of pre-tests for each session. Their adjusted gain in the (post) test phase was normalised (divided) by the standard gain in the pre-test phase for each session, and for each participant. Then, the medians of three repetitions of each condition for each subject were calculated. Averaged data of all the participants are plotted in [Figure 3](#). A three-way repeated-measures ANOVA was conducted. The main effect of adaptation gain ($F(1, 5) = 28.191$, $\eta_p^2 = 0.849$, $p = 0.0032$), the interaction of adaptation gain and adaptation-test consistency ($F(1, 5) = 13.488$, $\eta_p^2 = 0.839$, $p = 0.0144$), and the interaction of adaptation gain, adaptation–visual field and adaptation-test consistency ($F(1, 5) = 9.029$, $\eta_p^2 = 0.643$, $p = 0.0299$) were all found to be significant. The main effect of adaptation gain indicated that adjusted visuo-motor gain after adaptation was correlated with the gain at adaptation, and this finding supports the visuo-motor adaptive change.

To explore the details of these interactions, we conducted statistical tests on simple–simple effects. Simple–simple effects of adaptation gain were significant under the conditions of left hemifield adaptation and left hemifield test ($F(1, 20) = 37.174$, $p < 0.0001$), under the conditions of right hemi-
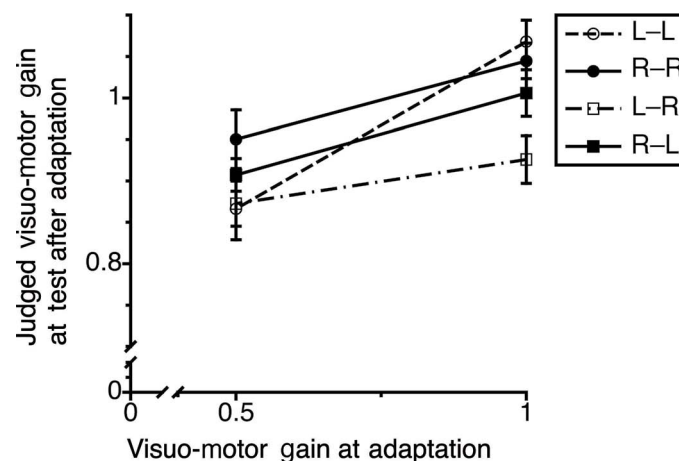
Figure 3. Results of Experiment 1. The horizontal axis represents visuo-motor gain at the adaptation phase, and the vertical axis shows adjusted gain at the test phase, after normalization to pre-test data. Vertical error bars represent SEM for six participants. Each line indicates one of the conditions of retinal location for adaptation and test; L is the left field and R is the right field.

field adaptation and right hemifield test ($F(1, 20) = 7.289$, $p = 0.0138$), and the conditions of right hemifield adaptation and left hemifield test ($F(1, 20) = 5.184$, $p = 0.0339$), but not under the conditions of left hemifield adaptation and right hemifield test ($F(1, 20) = 3.217$, $p = 0.0880$). The effect size of the gain effect under the condition of left hemifield adaptation and left hemifield test was higher ($d = 1.897$) than under the condition of either right hemifield adaptation and right hemifield test ($d = 1.174$) or right hemifield adaptation and left hemifield test ($d = 1.370$). These interactions indicate that visuo-motor adaptation increased when the retinal locations were the same for the adaptation and test periods, and particularly when both the adaptation and test visual fields were on the left.

These results suggest that the visuo-motor adaptation effect can transfer from the right to the left hemifields, but it is larger when the adaptation and the test both occur in the left visual field. Thus, the processing is not at the level of the early visual pathways strictly specific to retinal locations. It may be dominant in the right hemisphere than in the left hemisphere of the cortex, and the right hemisphere might play an important role in the visuo-motor adaptation and the visual-stability perception. However, the left visual field projects to the right hemisphere, and its information transferred to the right hemisphere is transported to the left hemisphere through the corpus callosum. Both hemispheres can process information from the left visual field. Thus, the left visual field's advantage of visuo-motor adaptation would not directly mean that the right hemisphere is responsible for the visual-stability adaptation processing. It is a limitation of this speculation on the neural processing. The fact that we did not find significant adaptation transfer from the left hemifield adaptation to the right hemifield test also discounts the speculation. Thus, it is required to investigate carefully in future studies.

The adaptation effect was approximately only 20% of perfect adaptation: the adjusted gain after adapting to the gain of 0.5 ranged from 0.85 to 0.95. This may be because the adaptation duration was only 2 min and we have been exposed to the natural gain for the stable visual world (1.0) throughout our daily life.

3 Experiment 2

The visuo-motor gain adaptation of the upper-half and lower-half retinal locations and its transfer were investigated in order to see potential involvement of the dorsal stream, which is dominant in the lower visual hemifield.

3.1 Methods

Eight naive participants performed the experiment, after providing written informed consent. All were university students with normal or corrected-to-normal vision, and did not know the purpose of the experiment. Methods were identical to those used in Experiment 1, except for the visual field conditions. In this experiment, the image region was limited to either the upper or lower hemifield (43.75% of the whole field), and the other hemifield was kept black.
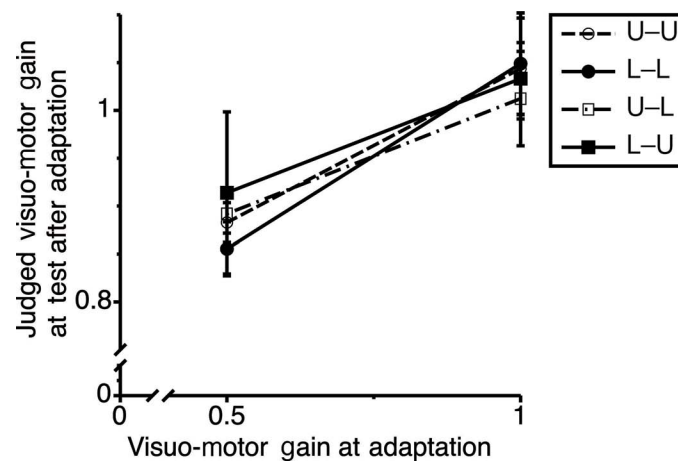
Figure 4. Results of Experiment 2. The horizontal axis represents visuo-motor gain at the adaptation phase, and the vertical axis shows adjusted gain at the test phase, after normalization to pre-test data. Vertical error bars represent SEM for the eight participants. Each line indicates one of the conditions of retinal locations for adaptation and test; U is the upper field and L is the lower field.

3.2 Results and discussion

The analyses conducted were the same as in Experiment 1. Averaged data of all the participants are plotted in Figure 4. A three-way repeated-measures ANOVA was performed. The main effect of adaptation gain ($F(1, 7) = 70.237$, $\eta_p^2 = 0.909$, $p < 0.0001$) was significant, but none of the other main effects or interactions were significant (for example, the interaction between adaptation gain and adaptation-test consistency: $F(1, 7) = 1.949$, $\eta_p^2 = 0.218$, $p = 0.2054$; the interaction between adaptation gain, adaptation–visual field, and adaptation-test consistency: $F(1, 7) = 0.147$, $\eta_p^2 = 0.021$, $p = 0.7132$). The main effect of adaptation gain in this experiment indicates that visuo-motor adaptation can occur under any conditions.

These results suggest that the visuo-motor adaptation effect can transfer between the upper and lower hemifields, and has no advantage in the lower visual field. Thus, the distinction of dorsal and ventral streams in the cortex is not important for the visuo-motor adaptation of visual stability.

4 Experiment 3

To investigate the effects of retinal positions on central–peripheral relationships, visuo-motor adaptation was investigated using varying sizes of stimuli and eccentricity. I aimed to investigate a possible link between visual-motor adaptation, temporal resolution, and self-motion perception.

4.1 Methods

Eight naive participants performed the experiment, after providing their written informed consent. All were university students with normal or corrected-to-normal vision, and did not know the purpose of the experiment. Methods were identical to those used in Experiment 1, but the stimuli and conditions were different.

The adaptation visual gain was either 0.5 or 1.5. In Experiments 1 and 2, we used the gain 0.5 and 1.0, and found that visuo-motor adaptation occurred significantly at gain 0.5, which is lower than the natural gain of 1.0. Here, we employed the gain 1.5 instead of 1.0, so the gain was either 0.5 or 1.5. This is because I aimed to prevent a floor effect of the adaptation, using limited visual fields that are much smaller than those used in Experiments 1 and 2.

The retinal eccentricity of the visual field was either central or peripheral, and the field size was small (11.11% of the whole screen: either inside of a 3.8° radius or outside of a 10.2° radius), medium (50.00%: inside or outside of a 7.2° radius), or large (88.89%: inside or outside of a 10.2° radius or outside of a 3.8° radius). The fixation point was located in the centre, and black–white polarity was reversed from the previous experiments in order to clarify the centre–periphery border (Figure 5). The visual field conditions of eccentricity and size were identical across the adaptation phase and the subsequent test phase. The procedure was identical to that described for Experiment 1. All participants conducted three repetitions (sessions) of a combination of two adaptation gain conditions, two eccentricity conditions, and three size conditions, with pre-tests.
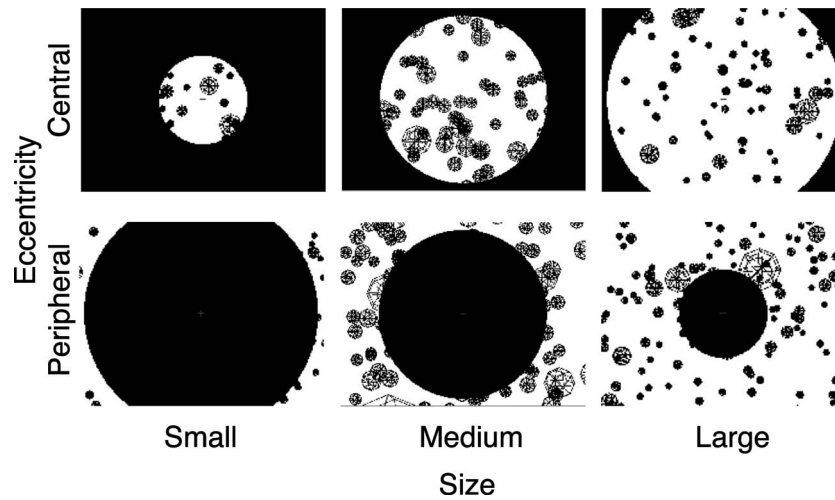
Figure 5. Stimulus conditions for Experiment 3.

4.2 Results and discussion

The same analyses were performed as for the previous experiments. Averaged data of all participants are plotted in Figure 6. A three-way repeated-measures ANOVA was performed. The main effect of adaptation gain ($F(1, 7) = 43.556$, $\eta_p^2 = 0.862$, $p = 0.0003$), the interaction of gain and eccentricity ($F(1, 7) = 6.825$, $\eta_p^2 = 0.494$, $p = 0.0348$), and the interaction of gain and size ($F(2, 14) = 4.341$, $\eta_p^2 = 0.383$, $p = 0.0341$) were all found to be significant. The other main effects or interactions were not significant (for example, the interaction of gain, eccentricity, and size: $F(2, 14) = 0.656$, $\eta_p^2 = 0.086$, $p = 0.5339$). The main effect of the adaptation gain indicates that visuo-motor adaptation occurred.

To explore the details of the interactions, we conducted statistical tests on the simple main effects. The simple effects of gain were significant under both conditions of eccentricity (central vision: $F(1, 14) = 13.559$, $p = 0.0025$; peripheral vision: $F(1, 14) = 46.756$, $p < 0.0001$). The effect size of gain was larger for central vision ($d = 1.610$) than for peripheral vision ($d = 1.135$). The simple effect of eccentricity was significant with a gain of 1.5 ($F(1, 14) = 7.391$, $p = 0.0166$), but was not significant with a gain of 0.5 ($F(1, 14) = 2.572$, $p = 0.1311$). Thus, visuo-motor adaptation with central vision was explicit at a high gain. This result suggests that high-speed motion on the central retina facilitates visuo-motor adaptation. The simple effects of gain were significant under all conditions of field size (small: $F(1, 21) = 14.244$, $p = 0.0011$; medium: $F(1, 21) = 30.148$, $p < 0.0001$; large: $F(1, 21) = 45.699$, $p < 0.0001$). The effect size of gain was larger for the large visual field ($d = 1.7838$) than for either the medium and small visual fields (medium: $d = 1.2361$; small: $d = 1.1032$).

The simple effects of size were not significant under any gain conditions (gain 0.5: $F(1, 21) = 1.132$, $p = 0.3367$; gain 1.5: $F(1, 21) = 2.123$, $p = 0.1385$).

These results suggest that central vision is dominant for visuo-motor adaptation, and a large field is more effective for it. This effect of size is consistent with previous findings on visually induced
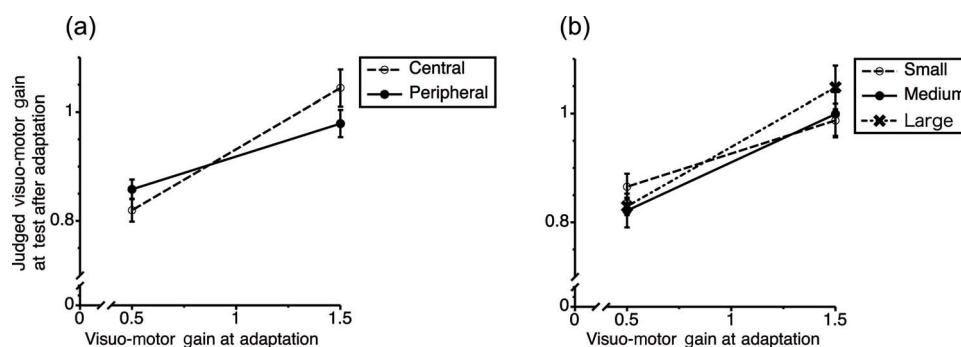

Figure 6. Results of Experiment 3. Effects of (a) eccentricity and (b) size. The horizontal axis represents visuo-motor gain at the adaptation phase, and the vertical axis shows adjusted gain at the test phase, after normalization to pre-test data. Vertical error bars represent SEM for the eight participants.

self-motion perception, but the central-vision advantage is inconsistent with these findings, and is not related to high temporal resolution in the periphery.

5 Experiment 4

The transfer of visuo-motor gain adaptation between the central-half and peripheral-half retinal locations was investigated in order to investigate potential central–peripheral hierarchical relationships, by separating out the adaptation and test phases.

5.1 Methods

Eight naive participants performed the experiment after providing their written informed consent. All were university students with normal or corrected-to-normal vision, and did not know the purpose of the experiment. Methods were identical to those described for Experiments 1 and 2, except for the visual field conditions and the adaptation gain conditions. For this experiment, the image region was limited to either the central or peripheral half-field (50% of the whole field: inside or outside of a 7.2° radius), and the other hemifield was kept black. The adaptation gain was set at either 0.5 or 1.5.

5.2 Results and discussion

The same analyses were performed as for previous experiments. Averaged data of all the participants are plotted in Figure 7. A three-way repeated-measures ANOVA was performed. The main effects of adaptation gain ($F(1, 7) = 23.163$, $\eta_p^2 = 0.7680$, $p = 0.0019$) and adaptation visual field ($F(1, 7) = 8.743$, $\eta_p^2 = 0.5559$, $p = 0.0212$) were found to be significant, but no other main effects or interactions were significant (for example, the interaction between gain and adaptation visual field: $F(1, 7) = 1.097$, $\eta_p^2 = 0.1355$, $p = 0.3298$; the interaction between gain and adaptation-test consistency: $F(1, 7) = 0.006$, $\eta_p^2 = 0.0008$, $p = 0.9402$). The main effect of adaptation gain indicates that visuo-motor adaptation occurred under all conditions. The main effect of eccentricity indicates that the adjusted gain was higher for peripheral adaptation than for central adaptation. This may be due to the difference in perceptual speed. If the peripheral stimuli were perceived as faster than stimuli presented in the central field, participants would be expected to adapt to a virtually higher gain. However, this is merely speculation, and inconsistent with results in Experiment 3, where there was no main effect of the eccentricity. In contrast to Experiment 3, we did not observe any significant dominance of the central visual field for visuo-motor adaptation in this experiment. These discrepancies currently cannot be explained, but the difference in experimental design between Experiments 3 and 4 may have affected these results. For the advantage of the central visual field to become significant, a larger visual field may be necessary. These would be interesting aspects to be investigated in a future study.

These results suggest that the visuo-motor adaptation effect can transfer between the central and peripheral half-fields. Thus, a cortical area, and not a lower processing level such as retina or LGN, is predicted to be responsible for its processing.
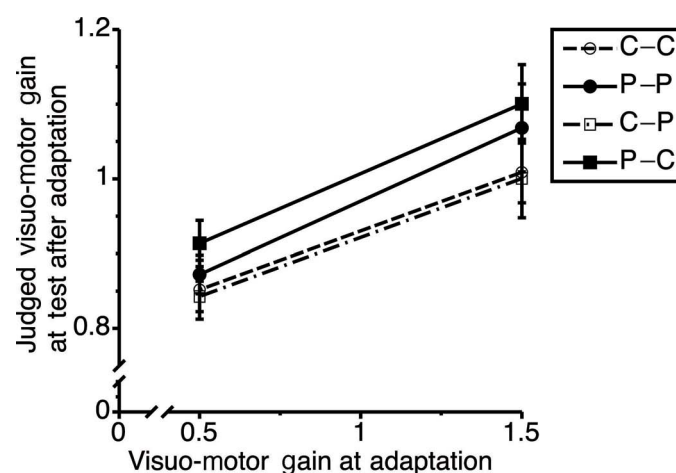

Figure 7. Results of Experiment 4. The horizontal axis represents visuo-motor gain at the adaptation phase, and the vertical axis shows adjusted gain at the test phase, after normalization to pre-test data. Vertical error bars represent SEM for the eight participants. Each line indicates one of the conditions of retinal location for adaptation and test; C refers to the central field and P to the peripheral field.

6 General discussion

In summary, in this study I have demonstrated that visuo-motor adaptation occurs and is transferable from the right to left visual fields (Experiment 1), between upper and lower visual fields (Experiment 2), and between central and peripheral visual fields (Experiment 4), and that the left visual field (Experiment 1) and the large visual field (Experiment 3) increase the effectiveness of the adaptation. The dominance of the central vision was found in Experiment 3, but not found in Experiment 4.

When both visuo-motor adaptation and test were performed on the left visual field, the adaptation changed the visual-stability gain more than the other combinations of the left and right hemifields. It might reflect a potentially dominant involvement of a visuo-spatial processing specialized for the left visual field in the human cortex, but further studies are required.

We obtained adaptation effects at only 20% of perfect or full adaptation. Previous studies report that an adaptation of 6 h produces half of full adaptation (Wallach & Kravitz, 1965a), while an adaptation of 10 min produces 27% of full adaptation, using head rotation, in a manner similar to the present research (Wallach & Kravitz, 1965b). Thus, the size of the adaptation effect in this study seems reasonable, because the adaptation period was only 2 min.

Humans show a flexible ability to adapt to new environments. In this study, I showed that participants adapted to a new visuo-motor gain after only a 2-min exposure of relatively poor visual information, and that this was not strictly specific to retinal position. Therefore, although many of the virtual reality systems in use today have system delays or inaccuracies, users are able to adapt to the system. From our findings, the left visual field appears to be more weighted to present visual information for effective adaptation than the other fields, and its field size is expected to be large. Our findings may contribute to the design of effective adaptive virtual reality systems.

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