

Visual-motor Adaptation to Stabilize Perceptual World: Its Generality and Specificity

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Abstract

Though the retinal image changes drastically with the movement of our head or eyes, our perceptual world is stable. It is called visual stability or position constancy. When we observe a virtual-reality environment through a head-mounted display with moving our head, the perceptual world is stabilized by the appropriate visual-motor gain without significant system delay. It is known that when the gain is changed the visual stability adaptively changes. We aimed to know the generality and specificity of this adaptation to stabilize the perceptual world: What is limitation for the ability of our adaptive visual-motor system? We found that the visual-motor adaptation occurred irrespective of the amount of visual information or active/passive movement. Even though the eye for adapting and that for test were different, the adaptation was intact. When the retinal location (left or right hemi-field) for test was different from that for adaptation, the adaptation still occurred, but it was less than in the case of same retinal location. Thus, the visual-motor 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.

Key words: visual-motor adaptation, visual stability, head movement, eye transfer, retinal-location transfer, constancy.

1. Introduction to visual stability

We usually perceive the world with moving our head and eyes. Thus, observer's retinal image changes frequently and drastically as the jittering video image taken by a shaking video camera. While we tend to get sick with observing such a shaking video image, we never get sick with our natural visual input, or a shaking retinal image. Perceptual world is stable for the observer. This is called "position constancy" or "visual stability" in perceptual psychology.

Our brain has a compensation mechanism to stabilize the

perceptual representation against motion of head and eyes. This compensation process is driven by the vestibular information, the efferent copy of the motor command, or proprioceptive information [1]. Recently, for the small fixational eye-movement a new theory was proposed as follows [2-3]. The visual component of a coherent small visual motion on the retina must be induced by fixational eye-movement, thus it should be subtracted from the to-be-perceived representation. This is however limited to the small eye-driven motion component. When we are moving our head or whole body, the visual-motor system works to stabilize the perceptual world.

2. Adaptation to a new visual-motor world

It is well investigated whether the visual-motor system can be adaptively changed with an inter-sensory conflict situation. The most famous and traditional paradigm to investigate the adaptation of the visual-motor system is "inverted vision" with a prism scope [4-6]. 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" [7-8]. 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 visual-motor system is plastic and adaptive to a new environment.

In virtual reality studies some related studies are conducted [9-11]. Subjects were exposed to an inter-sensory conflict simulation for 45 min with a head-mounted display and a head-tracking device. When their chair rotates for 180 deg around vertical axis, the visual and virtual rotation was only 90 deg, (it is called the gain of 0.5). Then, in a test trial they were asked to

assess their rotation angle when they (their chairs) were passively rotated for 45-180 deg in a randomized session in darkness. In results, the estimated rotation was decreased at 10 – 30 % [10]. Thus, it is concluded that the adaptation of the visual-motor system to an inter-sensory discrepancy induces the change of the vestibular information.

This experimental paradigm “adaptation to a new visual-motor world” is a useful tool to investigate how the visual-motor system stabilizes our perceptual world [12-15]. The subjects experienced a prolonged exposure to visual-motor gain distortion: The head position and orientation was monitored and the visual image motion projected on the screen was manipulated by a gain with monitored information. Then, they were asked to judge which gain makes the visual stimulus most stable or constant. After only 10 min exposure, the gain to be perceived stable was changed into the direction of distorted gain [13]. The similar results were obtained in the virtual-reality environment with only 1 min adaptation [15]. We adopted a modified method of [15] in this present study.

The purpose of this study is to know the generality and specificity of the visual-motor adaptation to stabilize the perceptual world: What is limitation for the ability of our adaptive visual-motor system? Thus, we conducted psychophysical experiments to see if the amount of visual information (Experiment 1) and the activeness/passiveness of the head movement (Experiment 2) affect the adaptation or not, and to test eye transfer (Experiment 3) and retinal-location transfer (Experiment 4) of the adaptation.

3. Experiment 1: Amount of visual information

First, we investigated whether the amount of visual information affects the adaptation to a visual-motor conflict or not.

Methods:

Ten naive observers participated in the experiment. All of them were college students with normal or corrected-to-normal vision, who did not know the purpose of the experiment. We obtained written informed consent to participate in the experiment from all the participants.

Visual stimulus was generated and controlled by a computer (DELL Precision Workstation 530, Xeon 2.4GHz, 1.0GB RAM, NVIDIA Quadro4-900XGL, MS-Windows 2000, Open GL, GLUT). Subject’s head position and orientation were monitored by a motion tracker (Polhemus Fastrak) and the visual stimulus was updated at 30Hz. Visual stimulus was presented on a

head-mounted display (HMD, Personal Display Systems i-visor DH-4400VP, 800x600 pixel, 31x23 deg visual angle, refresh rate 60Hz, binocular but non-stereo presentation).

In a virtual world, we put a lot of balls (1000, 3000, or 9000, radius 10 cm) around the observer’s head. The area of balls was a sphere of 700 cm radius but an inner spherical region of 200 cm radius was excluded (Figure 1). A light source was located 20 m above the head, and balls were rendered in smooth shading.

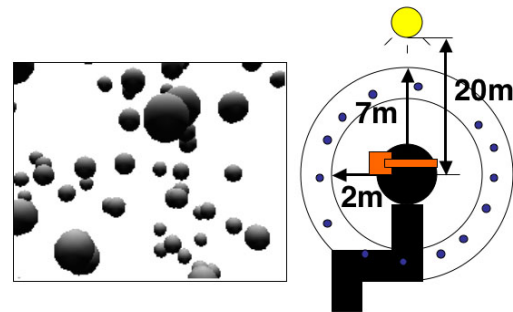


Figure 1: Simulated virtual world and the stimulus

One trial consisted of an adaptation phase followed by a test phase. In the adaptation phase, we set 3 x 3 experimental conditions. One was the “visual-motor gain” condition, which was 0.5, 1.0, or 1.5. We defined the visual-motor gain: $\text{Gain} = \text{Virtual rotation of head in the visual simulation} / \text{Actual rotation of the observer's head}$. In the case of the gain 0.5, when the observer rotates the head at 60 deg to left, the virtual head orientation rotates at 30 deg and the visual image motion is half of the ideal motion. In the case of the gain 1.0, the simulated motion is identical to that in the real world. In the case of the gain 1.5, the visual motion was much faster than the ideal motion in the real world. The other condition is the number of balls (1000, 3000, or 9000), which is assumed to be quantitative amount of visual information.

In the adaptation phase, the observer was exposed to the stimulus with moving (rotating) the head actively left and right at the range of 120 deg at about 0.2 Hz for 2 min. Before the experiment all of the subjects received enough training to move their head correctly for 120 deg laterally at 0.2 Hz. During the experiment they were asked to move the head for the same range at the same speed. One session consisted of 3 x 3 conditions in random order, thus 9 trials in total. Each subject conducted three sessions. Just before starting each session, the subject conducted 10 times of pre-test (which is identical to test trial) for pre-measurement of the judgment.

An adaptation phase was followed by a test phase after 1 min rest in darkness. In the test phase, the number of balls was always 3000, and the initial visual-motor gain

was randomly selected at the range of 0.25 to 1.75. The subject was able to manipulate the gain during test phase. The subject was asked to adjust the gain as he/she perceives the visual world to be most constant / stable, while he/she were observing the stimulus with moving the head laterally. In this way, we obtained the visual-motor gain to stabilize an inter-sensory discrepant virtual world.

Results:

We calculated the median of three repetitions of each condition for each subject, and averaged the data for all the subjects (Figure 2). Judged visual-motor gain after adaptation was correlated with the gain at the adaptation. But, its change was less than the gain at the adaptation (resulted gain was 0.84, 0.93, and 1.02 for adaptation gain 0.5, 1.0, and 1.5, respectively). These results suggest that the observer’s visual-motor system for position constancy adaptively changed, but it is partial; at most 30 % of the distortion.

There was no effect of the number of balls in adaptation. Thus, the mount of visual information is irrespective to change the visual-motor system, or it has little effect.

We conducted a repeated-measures ANOVA (ANalysis Of VAriance) to test the results statistically. The main effect of the adaptation gain was significant ($p < .001$), but the main effect of the number of balls ($p = .78$) or the interaction ($p = .65$) was not significant. Thus, the results were confirmed with the statistical tests.

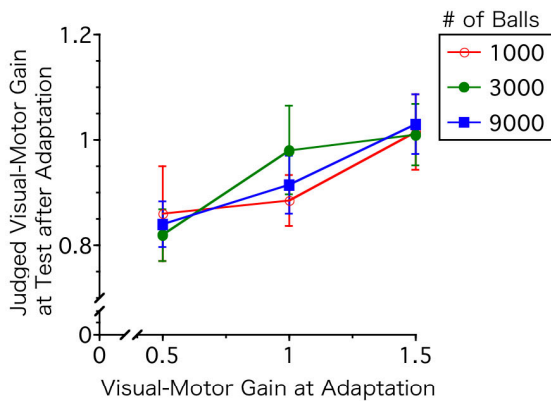


Figure 2: Results of Experiment 1.

4. Experiment 2: Active/passive self-motion

In Experiment 1, the observer actively moved the head. In Experiment 2, we focused on the difference of active and passive motion of the self-body.

Methods:

Six naive observers participated in the experiment. All of

them were college students with normal or corrected-to-normal vision, who did not know the purpose of the experiment

The methods and procedure were identical to those in Experiment 1 except for the following points. In the adaptation phase, we set 2 x 2 conditions. One was the visual-motor gain, which was 0.5 or 1.0. The other was the type of self-motion, which was active or passive. In the passive condition, the experimenter rotated the chair on which the subject was sitting. The number of balls was fixed at 3000. In the test phase, the self-motion was always active.

Results:

We conducted the same analysis as in the previous experiment (Figure 3). Judged visual-motor gain after adaptation was correlated with the gain at the adaptation as in Experiment 1. There was no effect of the type of self-motion in adaptation. Thus, both active motion and passive motion can change the visual-motor system. These results suggest that the perception of self-motion or vestibular information is more important to the adaptive visual-motor system than the efferent copy of motor command.

We conducted a repeated-measures ANOVA to test the results statistically. The main effect of the adaptation gain was significant ($p < .011$), but the main effect of the type of motion ($p = .47$) or the interaction ($p = .99$) was not significant. Thus, the results were confirmed with the statistical tests.

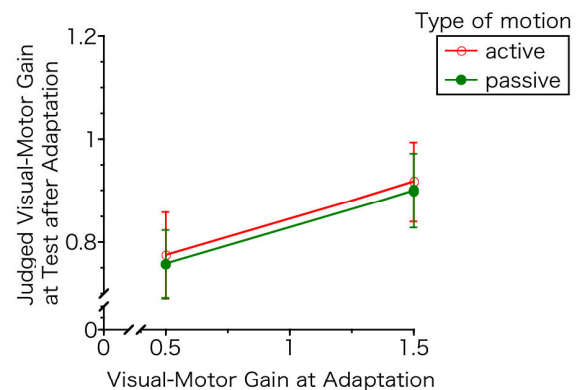


Figure 3: Results of Experiment 2.

5. Experiment 3: Eye transfer

We tested whether the adaptation of one eye can transfer to the other eye in test phase. This experimental paradigm “eye-transfer” can tell us the pathway or loci of the visual-motor adaptation in the brain.

Methods:

Nine naive observers participated in the experiment. All of them were college students with normal or corrected-to-normal vision, who did not know the purpose of the experiment

The methods and procedure were identical to those in the previous experiments except for the following points. We replaced the HMD with a stereo-capable HMD for dichoptic presentation (iO Display Systems i-glasses SVGA, 800x600 pixel, 21.2x15.9 deg visual angle, refresh rate 60Hz, dichoptic presentation at 30Hz for each eye). The balls were rendered as wire-frame model in gray scale on the black background, in order to inhibit the binocular rivalry. For both adaptation phase and test phase, the visual stimulus was presented at only one eye either left or right, while the display for the other eye was kept in black.

The experiment was designed as 2 x 2 x 2 conditions. One was the visual-motor gain for adaptation (0.5, 1.0). The second condition was the adaptation eye on which the stimulus was presented in the adaptation phase (left eye, right eye). The third condition was the correspondence of the adaptation eye and the test eye: same or different. The area of sphere filled with balls was changed to 600 cm radius without inner 100 cm radius sphere, but the number of balls was identical (3000). The initial gain at the test phase was at random from 0.25 to 1.25.

Results:

We conducted the same analysis as in the previous experiments (Figure 4). Judged visual-motor gain after adaptation was again correlated with the gain at the adaptation. There was no effect of the adaptation eye or the correspondence of adaptation and test eyes.

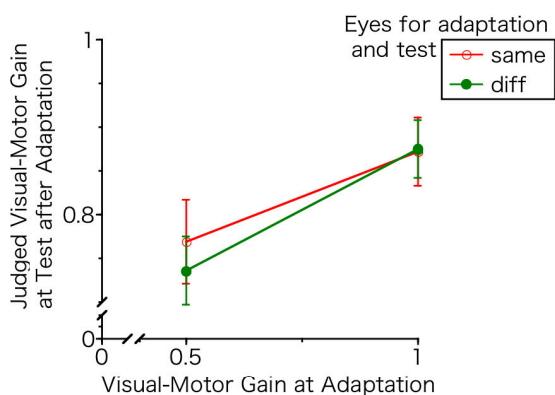


Figure 4: Results of Experiment 3.

If the eye-transfer was limited the effect of the adaptation gain should have been decreased when adaptation and test eyes were different. However, the effect of the adaptation gain did not significantly changed by the correspondence of adaptation and test eyes. These results suggest that the adaptation effect can transfer perfectly

between left and right eyes, thus it is processed after binocular fusion.

We conducted a repeated-measures ANOVA to test the results statistically. The main effect of the adaptation gain was significant ($p < .001$), but the main effect of the adaptation eye ($p = .70$), that of the eye correspondence ($p = .55$), the interaction of the gain and the eye correspondence ($p = .31$) or any interaction was not significant. Thus, the statistical tests supported the results.

6. Experiment 4: Retinal-location transfer

Next, we focused on the transfer of the adaptation between the left-half and right-half retinal locations.

Methods:

Six naive observers participated in the experiment. All of them were college students with normal or corrected-to-normal vision, who did not know the purpose of the experiment

The methods and procedure were identical to those in Experiment 3 except for the following points. The visual stimulus was always presented for both eyes (binocularly same image), but the image region was limited into left or right hemi-field (43.75% of the whole field to avoid the possibility of the eye-movement), and the other hemi-field was kept in black. The subject was asked to fixate the eyes on the central fixation point during the experiment.

The design of experiment was 2 x 2 x 2 conditions. One was the visual-motor gain for adaptation (0.5, 1.0). The second condition was the adaptation location on which the stimulus was presented in the adaptation phase (left, right). The third condition was the correspondence of the adaptation and the test locations: same or different.

Results:

We conducted the same analysis as in the previous experiments (Figure 5). Judged visual-motor gain after adaptation was again correlated with the gain at the adaptation. The effect of the adaptation gain (slope in the graph) decreased when adaptation and test locations were different. These results suggest that the adaptation effect can transfer between left and right hemi-fields, but it is somewhat limited (partial transfer). Thus the visual-motor adaptation is partly specific to the retinal hemi-field.

A repeated-measures ANOVA was conducted to test the results statistically. The main effect of the adaptation gain ($p < .016$), and that of the adaptation location were ($p < .05$) significant, but the main effect of the

correspondence of the adaptation and the test locations was not significant ($p=.16$). The main effect of the adaptation gain supports the visual-motor adaptive change. The main effect of adaptation location indicates the judged gain was less in the left hemi-field adaptation. As for interactions, we found only one significant interaction of the adaptation gain and the correspondence of the adaptation and the test locations ($p<.002$). This indicates the visual-motor adaptation decreases when the retinal locations are different for adaptation and test (partly location specific).

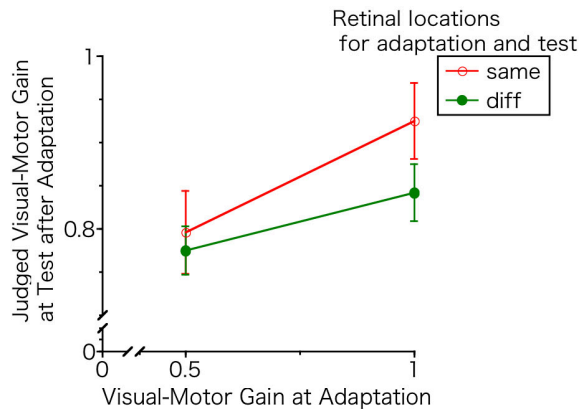


Figure 5: Results of Experiment 4.

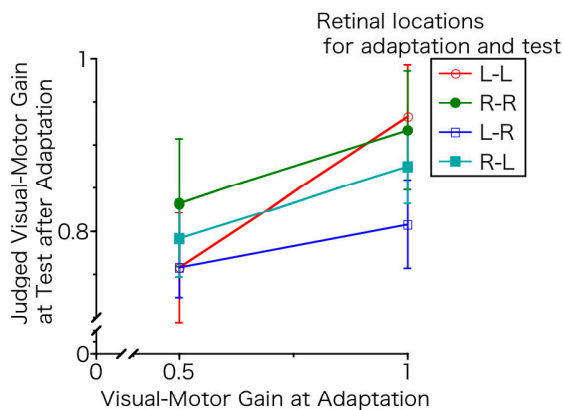


Figure 6: Re-plotted results of Experiment 4.

To investigate in detail, especially about the main effect of the adaptation location, we reanalyzed and re-plotted data (Figure 6). We re-constructed the conditions into 2×4 design. The first condition was identical to the original analysis and it was the adaptation gain (0.5, 1.0). The other condition was made with combining adaptation location and test location: Left - Left, Right - Right, Left - Right, and Right - Left (adaptation - test). We found the visual-motor adaptive change is most in the Left-Left condition. This is also statistically significant: the interaction of these two conditions was significant ($p<.045$). It is suggested that the right hemisphere of the brain, which is projected from the left visual field has a critical roll in the visual-motor adaptive change to stabilize the perceptual world. It is

known that the right hemisphere of human beings has an advantage in processing spatial information [16]. Thus, the processing of visuospatial information in the right hemisphere may be required to recalibrate the visual-motor coordination.

7. General Discussion

We found that the visual-motor adaptation occurred irrespective of the amount of visual information (Experiment 1), or active/passive self-movement (Experiment 2). Even though the eye for adapting and that for test were different, the adaptation was intact (Experiment 3). When the retinal location (left or right hemi-field) for test was different from that for adaptation, the adaptation still occurred, but it was less than in the case of same retinal location (Experiment 4).

The visual-motor system to make our perception of the world / environment stable or constant (position constancy) is very adaptive because the adaptation to a new combination of visual and motor information occurs with relatively poor visual or motor information for only a few minutes. It is generality of the visual-motor adaptive system. The adaptive process should use the visual information after left eye information and right eye information are combined, and be very affected by the processing in the right hemisphere of the brain, which is considered as dominant hemisphere for spatial perception. This makes the specificity of the visual-motor adaptive system to retinal location emerging in the virtual reality experiment.

The specificity to the retinal left-right location was, however, not perfect but partial. Even when the visual field for adaptation and that for the test were both right hemi-fields, we found still adaptive change of the visual-motor system, which was less than the case of left hemi-fields. This indicates that the retinal-location specificity is not caused by just retinotopy or retinotopic processing in early visual processing. Rather, integrated spatial processing in the right hemisphere of the cortex is critical. Since our subjects were not split-brain patients, some information in the right hemi-field must be processed in the right hemisphere as well as in the left hemisphere. It would be a cause of the partial specificity.

8. Conclusion

In conclusion, the visual-motor adaptation for visual stability or position constancy has a generality for the amount of visual information and type of self-motion. The adaptive visual-motor system 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. The right hemisphere of the brain has a critical roll in the processing.

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