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Abstract

The visual capture of proprioception was examined in the visually left-right reversed condition. Under this condition, it had been thought impossible for visual capture to occur. The present research, however, demonstrated the capture using a sophisticated design.

In Experiment 1 the immediate effect was confirmed, and in Experiment 2 the persistence of the effect after eyes were closed was demonstrated. While subjects lightly touched a vibrating cylinder with their index finger(s), their hand(s) and arm(s) were moved passively in either a clockwise or counterclockwise direction. Looking through a left-right reversing prism, all 12 subjects perceived the direction of their hand movements based on visual information despite being aware of the visual transposition (Experiment 1). In Experiment 2 about half of the 15 subjects displayed characteristics of remaining greatly influence by vision when eyes were closed from the early stage of the experimental session.

1 Introduction

"Visual capture" is explained by Hay, Pick, and Ikeda (1965) as : "The immediate effects (rather than the after-effect) of viewing one's hand through a wedge prism. The feel of the hand is found to be pulled towards the displaced optical stimulus. The effect of capture lingers after the eyes are covered." This notion, it seems to me, presents some important and controversial aspects concerning the well-known capture phenomenon. First, visual capture concerns "immediate" effects, distinguishable by definition from effects obtained as a result of prism adaptation. Secondly, research into visual capture involves a non-change of polarity visual transposition, such as displacement, realized by means of a "wedge prism." This fact suggests that visual capture would not be an all-or-none phenomenon and should be

* *Studies and Essays, Behavioral Sciences and Philosophy, The Faculty of Letters, Kanazawa University, 15,* 1-12. (1995)

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estimated quantitatively by percentage bias values (e.g., Welch & Warren, 1980). Finally, vision during the discrepancy period would bias proprioception even after the goggles have been removed ("aftereffects"), especially when observers are not aware of receiving conflicting sensory information (Rock & Victor, 1964; Rock & Harris, 1967).

These in total indicate that the visual capture (of proprioception) would not arise when vision is transposed in a change of polarity manner, such as left-right reversal, because in such cases, subjects would necessarily be aware of the drastic visual transposition, and the capture of any modality would be realized in an all-or-none manner. Thus it is natural to think that it is nearly impossible for visual capture to occur under the visually left-right reversed situation. Certainly, subjects could represent their body in accordance with new visual information, but it would be recognized only after some amount of exposure to the visual transposition, that is, as a matter of perceptual adaptation. Yoshimura (1993, 1994, in Japanese) clarified that perceptual adaptation to change of polarity transpositions could be achieved on the basis of spatial representations of both the environment and the subject's own body which coincide with new visual information seen through the transposing goggles. In the present research, however, it will be called into question whether visual capture, the immediate effect, would occur during visual left-right reversal if one was able to provide the appropriate experimental conditions.

Using mirror devices, Warren and Cleaves (1971) set a wide range of visual-proprioceptive discrepancy situations: 10°, 20°, 40°, and 60°. Results showed that visual bias was weakened under conditions where the discrepancy between visual and proprioceptive information increased. It is reasonable to consider that left-right reversal is a more drastic discrepant situation than the 60° discrepancy condition adopted in their experiment. However, under extremely refined experimental conditions, it should be possible to realize visual capture under left-right reversal conditions. It has been found that when a limb was placed into position by the experimenter, visual bias was significantly greater than when the subject actively positioned the limb, suggesting that the greater salience of actively generated proprioceptive information allows proprioception to better withstand the influence of vision (Welch, Widawski, Harrington, & Warren, 1979).

Yoshimura (1983, in Japanese) showed that ten of sixteen subjects immediately misperceived the direction of their head movements when putting on left-right reversing goggles under the condition where they moved their eyes to synchronize with head turnings. This indicates that subjects perceived the direction of head movement not based on proprioceptive information from neck or vestibular systems, but on information from the field of vision contingent on head movement (both visual flow and information received from the occlusion-disocclusion relationship). It must be emphasized that the results occurred as an immediate effect when putting on the goggles.

As mentioned above, when subjects move their limbs actively, they feel a strong discrepancy between visual and proprioceptive information. Thus the situation will make it difficult to realize visual capture. On the other hand, passive movements will generate a haptic sense on the contact face with the stirring device, informing subjects of the veridical direction of their limb and thereby strengthening the proprioceptive information of the limbs. Therefore, we must devise a more skillful way to weaken the information.

Using a sophisticated design, visual capture of proprioception will be examined under the visual reversal condition. In Experiment 1 the immediate effect will be examined, and in the second experiment, the possibility of the effect lasting after eyes are closed will be investigated.

2 Experiment 1: Visual capture when eyes are open

As a desirable setup which could eliminate the above mentioned difficulties, passive finger movements were used. While subjects lightly touched a vibrating cylinder with their index finger, their hand and arm were moved passively in either a clockwise (CW) or counterclockwise (CCW) direction. By vibrating the finger, tactile information concerning movement direction occurring at the contact face with the cylinder was expected to be weakened. It is certain that the situation is unnatural, suggesting that proprioception generated under such a contrived situation would be extraordinal. Recently, Benedetti (1988) demonstrated the existence of non-veridical proprioceptive spatial perception in two separate experiments: i) with subjects' tongues in 90° rotation (a peculiar body part); ii) with two adjacent fingers crossed (an unnatural posture). On the contrary, body parts focused on in the present experiment are typical for investigations into spatial representations of body scheme, and turning along the curvature of a round object is a natural movement of body repertoire.

2.1 Method

2.1.1 *Subjects.* Twelve undergraduate subjects participated in this experiment. All subjects were right handed, had normal vision, and volunteered to participate without payment or academic credit being provided. Before the experiment, none of them had experienced looking through a right-angle reversing prism.

2.1.2 *Apparatus.* An acrylic right-angle prism was used to make vision left-right reversed, measuring 60 x 42 x 42 mm, hypotenuse face x lateral face x length, respectively. The prism was inserted into a rectangular hole bored in a screen placed in front of the subjects (see Figure 1). Behind the screen a vibrator (Akashi MEE-025) was set on a table, the frequency and magnitude of which were controlled by a function generator and an audio amplifier. At the tip of the vibrator an aluminum cylinder with a diameter of 20 mm and length of 35 mm was fixed horizontally. During the experimental periods, the cylinder was vibrating continuously in the perpendicular dimension with an amplitude of more than 1 mm p-p and a frequency of 60 cps.

2.1.3 *Procedure.* Subjects sat in front of the screen board and lightly touched the vibrating cylinder behind the screen. Two conditions were introduced: Eyes-open

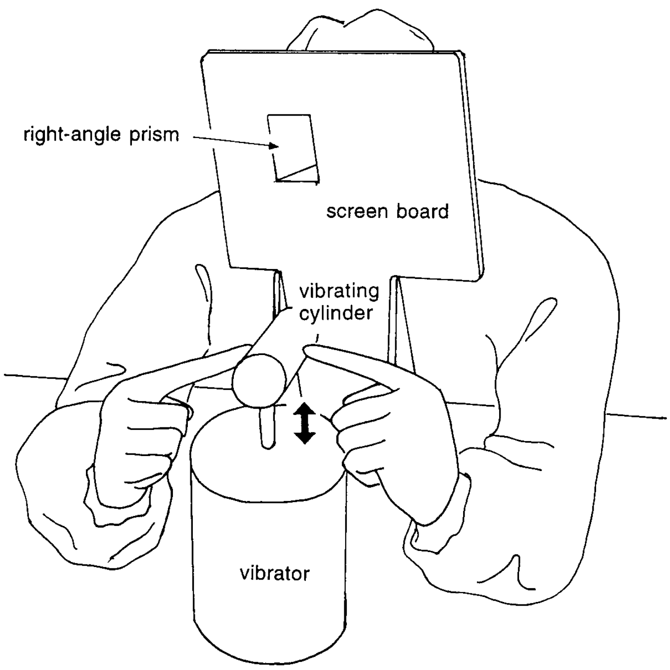

Figure 1. Schematic diagram of the experimental apparatus used in Experiment 1 and 2. Subjects, by touching the side(s) of the vibrating cylinder, answer the direction of their hand movements under eyes-open and eyes-closed conditions. Right-angle prism inserted in the screen board makes the vision left-right reversed.

condition was given first for all subjects and thereafter eyes-closed condition was imposed to confirm the veridical perception of his/her hand movement directions under the situation where only proprioceptive information was available. In the eyes-open condition, subjects saw the vibrating cylinder and his/her own hand (s) through the left-right reversing prism. Until the end of the eyes-open condition, subjects were not informed of the visual transposition, and after the completion they were questioned whether they had been aware of the visual transposition during the execution of the tasks.

On touching the vibrating cylinder, the subject's finger was turned passively along the cylinder curvature in either a clockwise or counterclockwise direction depending on the point of contact. If subjects happened to touch the place of any upper position on the cylinder curvature, their finger was passively turned upwards, and vice versa. Their task was to make oral responses to the direction of finger and hand movements, performing trials with both hands, followed by the right and left hand in this order, two trials for each and six in total. Under single hand conditions the other hand was set outside the field of vision.

Following the eyes-open condition, subjects performed the same task with their eyes closed, thereby perceiving the direction of their finger and hand movements without vision.

2.2 Results and discussion

In the eyes-open condition, subjects perceived the direction of their hand movements based on visual information through the reversing prism. Ten of twelve subjects showed visual capture for all six trials, while the other two subjects responded to initial trials based on proprioceptive information, thereafter showing the property of visual capture for four or five of the remaining trials. Concerning the awareness of visual transposition during the eyes-open condition, all subjects had noticed it to some extent: Some reported a clear left-right reversed impression of vision and others remarked on the discrepancy between the seen and felt hands. Despite their recognition of this discrepancy, these subjects revealed visual capture under this experimental situation.

In the following eyes-closed condition, all subjects answered the direction of their hand movements veridically based on proprioceptive information for all six trials. In this case veridical refers to the correspondence of the physical direction of hand movement and the orally reported direction of this movement. If subjects answered "CW" for the physical clockwise movement, the response was counted as veridical. This means that the veridical direction would appear in opposition to the visual direction of hand(s) movement seen through the left-right reversing prism. In the eyes-closed condition all subjects performed the task veridically, suggesting that if vision is eliminated, we can perceive the direction of hand movements veridically, even if moved passively by vibration.

In short, these results indicate that visual capture should be possible even when vision is reversed in the left-right dimension and subjects are aware of the fact. If we can setup an elaborate experimental situation, the predominance of seen over felt body will be almost immediate.

Two constraints concerning visual capture were thereby eliminated in this experiment, the first of which was that the discrepancy between visual and proprioceptive information was not drastic, and the second of which was that subjects were not aware of it. Although one should avoid generalizing about the properties of visual capture, it is worth emphasizing that the present experiment confirmed that visual capture can be generated under sophisticated experimental conditions.

This fact provides another theoretical problem concerning the perceptual adaptation to visual transpositions. It is certain that visual capture and perceptual adaptation are distinct and that a better understanding of each will be enhanced from insight into their relationship. In the course of perceptual adaptation to the visual left-right reversal, we found that when eyes were closed subjects represented their own body as if they were existing in the place where they had been as seen through the reversing goggles (Yoshimura, 1993, 1994). Is a long period required for subjects to have such spatial representation? Or has the nature already started soon after putting on the goggles? It may be natural to think that a such visual image in darkness would be acquired after a prolonged exposure to reversed vision.

However, C.S. Harris in collaboration with J. R. Harris (Harris & Harris, 1965; Harris, 1980) demonstrated a rapid adaptive change of position sense of the writing hand in the following experiment. In their experiment, subjects sat and doodled for 15 minutes a day on four different days, while watching the moving hand through a right-angle prism attached to a rigid support. After each 15-minute adaptation period the prism was covered thereby blocking the subjects' vision, following which the subjects were asked to write several numbers and letters as the experimenter called them out. Results showed that when subjects tried to write normally without visual feedback, what they actually wrote was often backwards. The next experiment will deal with this problem.

3 Experiment 2: Body image when eyes are closed

Harris gave a special prominence to the rapidness of adaptive change which, nevertheless, required several 15-minute sessions of left-right reversed visual feedback. While we now have an adequate experimental situation to facilitate the visual capture, it is worth examining the possibility of new spatial representations immediately after putting on the left-right reversing goggles when eyes are closed. How soon will subjects perceive their fingers and hands based on new visual information which has been seen before eye closure?

3.1 Method

3.1.1 *Subjects*. The subjects were fifteen undergraduate and graduate school students with normal or corrected vision. None of them had participated in Experiment 1.

3.1.2 *Apparatus*. The apparatus were identical to that of Experiment 1. In addition, by means of a video-camera, subjects' hand movements and oral responses were recorded during the experimental sessions.

3.1.3 *Procedure*. Subjects sat in front of the screen board and viewed their hands through the left-right reversing prism. Only two hand conditions were imposed for each subject, that is, right-hand and both-hand conditions, while the left hand condition which had been imposed in Experiment 1 was omitted because of redundancy. The order of the two hand conditions were counterbalanced between the subjects. For each hand condition, subjects performed one 5-minute session. During the session, eyes-open and eyes-closed conditions alternated for periods of 15 seconds, originating with the eyes-open phase. Subjects were instructed to try touch-and-rotation trials of their finger and hand as many times as possible within the period, and to orally respond to the direction for each trial. Further, for the eyes-open condition, subjects were instructed to answer the direction of movements based on visual information seen through the reversing prism, while for the eyes-closed condition they were instructed to respond based on the most reliable information they could discern themselves. Whenever ordered to open/close eyes they restarted the trial with their eyes open/closed. These procedures should make it possible to realize the smooth shift from eyes-open to eyes-closed conditions. After completing the two sessions, subjects were asked under which phase (eyes-open/eyes-closed) and for which hand condition (one-hand/both-hands) task performance more difficult.

3.2 Results and Discussion

For the closed-eyes trials, rates of veridical responses were calculated under each hand condition for each subject (see Table 1). Each 5-minute session had a two and a half minute closed-eyes period, during which time the subjects performed from 15 to 134 trials (mean = 49.0, SD = 28.57) in total.

A variety of responses were given which can be grouped into two types as shown in Table 1 according to the criterion subjects adopted as a strategy for judgment.

Table 1. Percentage of veridical responses under the eyes-closed condition in Experiment 2.

	single-hand session		both-hand session			
	15-second phase		15-second phase		first session	relative difficulty of tasks
subject	1-10	1 *	1-10	1 *	performed	reported by subjects
			proprioception-based type subjects			
1	100	2/2	100	3/3	both-hand	both-hand, eyes-open
2	100	4/4	100	5/5	single-hand	both-hand, eyes-closed
3	100	2/2	100	4/4	both-hand	single-hand, eyes-open
4	100	9/9	93	8/10	single-hand	both-hand, eyes-open
5	100	3/3	96	0/1	both-hand	eyes-open
6	100	8/8	91	3/3	single-hand	both-hand, eyes-open
7	93	4/4	95	5/5	single-hand	single-hand, eyes-open
			visually-influenced type subjects			
8	84	0/2	100	3/3	single-hand	single-hand, eyes-closed
9	76	3/4	77	3/3	both-hand	single-hand, eyes-closed
10	53	0/3	94	1/2	single-hand	both-hand, eyes-open
11	71	0/4	100	5/5	single-hand	single-hand, eyes-closed
12	5	4/4	75	4/4	both-hand	both-hand, eyes-closed
13	0	0/2	100	3/3	single-hand	single-hand, eyes-closed
14	3	2/5	63	5/5	both-hand	both-hand, eyes-closed
15	1	0/8	0	0/7	both-hand	both-hand

* Data in initial phase (1) are presented as fractions;
number of veridical responses / nunber of trials performed in that phase

About half of the subjects tried to perceive their hand movement direction on the basis of proprioception when their eyes were closed, thereby showing veridical responses for almost all the trials in this phase and thus not suffering from visual information seen through the reversing prism. This group can be named *proprioception-based type*. The remaining subjects received a strong influence of vision immediately after looking through the reversing prism and showed a number of responses in line with the visual information. Thus they frequently reported the direction of their hand movements in the same manner as when their eyes were open, as revealed in the low percentage of correct responses in Table 1. This latter group is named *visually-influenced type*. The proprioception-based type was distinguished from the visually-influenced type at the point of 90% correct response in the eyes-closed condition.

Let us consider the first period of the eyes-closed phase in the first session. Preceding this phase subjects had experienced left-right reversed vision for only 15 seconds. Nevertheless, not a few subjects answered the direction of their own hand (s) movements based not on the veridical proprioceptive information but on the incorrect visual information. Subjects 8, 10, 11, 13, and 15 responded perfectly in such a manner and even a subject belonging to the proprioception-based type (Subject 5) showed the manner for his first trial. These facts indicate that in an appropriate situation it would not require much time for subjects to represent their own body parts in accordance with the new visual information. Although subjects may not have performed the trials with complete certainty, it is clear that when representing their own body, the most reliable information for them was visual and freshly visualized images, not proprioceptive information.

We could not find any systematic difference between the single-hand and both-hands conditions. Contrary to this, the relative difficulty between eyes-open and eyes-closed conditions varied in accordance with the response types. While most of the proprioception-based type subjects estimated that the eyes-open condition was more difficult, most visually-influenced type subjects estimated it was more difficult to perform the task under the eyes-closed condition. For the former subjects, performance under the eyes-closed condition should be easy because switching to proprioception would be secured as soon as vision was eliminated. For them the performance in the eyes-open condition was rather difficult, because even if given visual information they could not disregard the proprioceptive body sense. Thus under the eyes-open condition "veridical" responses were included in some of the subjects' data (Subjects 3, 4, 5, 6, 7, and 8) though the rates were not high. On the other hand, the visually-influenced type subjects coped with the task easily under the eyes-open condition guided by visual information, while feeling difficulty under the eyes-closed condition in which they were uncertain about proprioceptive and visual frames of references.

4 General discussion

The present research confirmed that visual capture occurs in visual left-right reversal situations, and demonstrated that even when eyes are closed, the visual image in darkness takes the role of vision and may capture proprioception. Furthermore, evidence was provided which shows that the time necessary to reveal the capture is much shorter than noted by Harris and his colleagues. These findings facilitate our understanding that visual capture represents the initial stage of perceptual adaptation to the visually transposed world and suggests that perceptual adaptation begins immediately after putting on the visually transposing devices.

However, there is one aspect of visual capture which clearly contrasts with perceptual adaptation. While visual capture is strengthened when subject's body is moved passively as adopted in the present experiment, perceptual adaptation is facilitated more progressively by means of subject's active movements. This is pointed out by Welch, et al. (1979) in an experiment using visual displacement. He said, "it was speculated that the active/passive manipulation served to create differences in the degree of registered visual-proprioceptive discordance and that visual capture is facilitated by degraded proprioceptive input, whereas adaptation requires for its induction a relatively strong discordance". In other words, visual capture will occur when proprioceptive information is suppressed, and perceptual adaptation will be realized by the recalibration of proprioceptive spatial representation. In this important aspect, visual capture and perceptual adaptation have different properties.

In the present research, left-right reversal of vision was used as an example of change of polarity transpositions. Is it possible to generalize the findings of the present experiment to the other two visual transpositions, namely up-down reversal and inversion? Heller (1992) required subjects to identify letters such as p, q, b, d, W, and M, by touch and sight simultaneously. The visual information was given through a mirror placed perpendicular to a letter display which made the vision of the letter and subject's hand reversed in the up-down dimension. The majority of the subjects depended on touch and did not show visual capture. On the other hand, in Experiment 1 of the present research, all subjects showed visual capture for nearly all trials. It is true that there is an important difference between the two experiment: active touching for Heller's experiment and passive vibratory movement for the present experiment. Nevertheless, it is certain that there is a great difference in the nature of visual capture between the up-down reversed situation and the left-right reversed situation. In the latter, visual information has a strong correspondence to reality, easily misleading the subjects. On the other hand, the low degree that vision under the up-down reversed condition corresponds to reality makes task performance easier based on correct non-visual information, that is, proprioception. In conclusion, it is not appropriate to generalize the findings obtained in the present experiment to the other two visual transpositions. We can obtain the visual capture most prominently in the visual left-right reversal experiment.

Let us consider individual differences recognized in Experiment 2. About half of the subjects received a strong visual influence immediately after looking through the reversing prism and showed not a few responses in line with the visual information. However, the other half tried to perceive their hand movement direction on the basis of proprioception when their eyes were closed. This kind of individual difference has been noted in the research literature. McDonnell & Duffett (1972) found subjects who showed both "touch capture" and "visual capture" in a visual distortion experiment similar to Rock and Victor's (1964). In the present research I called the two types proprioception-based type and visually-influenced type, respectively. Questions such as which type is more common or which type is basic are not meaningful, because the situation will depend on differences involving experimental manipulations or instructions given to subjects. The important point in the present context is that there is an individual difference even in the eyes closed condition after a few seconds of exposure to left-right reversal vision, and that not a few subjects showed the tendency to represent their body and its movements in line with visual information which had been already shielded. Setting an appropriate experimental situation, we could observe the dominance of visual image over proprioceptive spatial representation.

Acknowledgment: This research was supported by the Japanese Ministry of Education, Science, and Culture Grant-in-Aid for General Scientific Research Grant No. 06610064 allocated to Hirokazu Yoshimura.

I wish to thank Mr. Dean Schimpf for his polite and careful proofing of my English manuscript.

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