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Analyses of Internal Depth Information of 3-D Objects in Apparent Motion Path

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In order to perceive apparent motion, it is necessary to determine the correspondence between the objects presented across time and space (the correspondence problem; Ullman, 1979). In addition, the internal representations of apparently moving objects are formed in the apparent motion path, which lacks any physical inputs. This research investigated the depth information of moving 3-D objects represented in apparent motion path in the case that visual systems solve the correspondence problem. The experiment examined how probe objects briefly presented in the motion path affected the perceived motion direction in an ambiguous apparent motion display. These objects comprised 3-D shaded (convex/concave) hemispheres or 2-D (flat) circles while the moving objects were convex hemispheres. The results of experiments showed that the probe depth information did not affect motion direction perception. Therefore, it can be concluded that are utilized in correspondence solving process, the internal representations only containing the 2-D information in apparent motion path.

Key words: apparent motion, internal representation, the correspondence problem, shape from shading

Introduction

When two lights that are spatially apart from each other are alternately turned on and off at an optimal interval, observers often perceive motion between these two lights. This phenomenon is called apparent motion (Wertheimer, 1912). In order to perceive apparent motion, it is necessary to determine correspondence between the objects that are presented across time and space. This problem is referred to as the correspondence problem (Ullman, 1979). It was pointed out that the correspondence problem was mainly solved with proximity or distance between moving objects (Kolers, 1972; Burt & Sperling, 1981; Ullman, 1978; Scholl, 2001). In particular, Ullman (1978) investigated the manner in which objects were corresponded using an ambiguous apparent motion display. In this display, the visual systems must solve the correspondence problem in order to decide perceived motion directions. He found that observers perceived apparent motion based not on the perceived three-dimensional (3-D) distance but the on retinal or physical two-dimensional (2-D) distance information (see also Mutch, Smith, & Yonas, 1983). Marr (1982) also indicated that low-level representations provided by local features (bar, edge, blob, etc.) are utilized in the correspondence solving process. Similarly, Dawson (1991) suggested that the correspondence problem is solved with 2-D coordinate system, whereas the motion quality or the appearance of trajectories is related to higher-order processing including 3-D properties.

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It has been known, moreover, that internal representations of moving objects are completed in the motion path in which any physical inputs is absent, and these representations mediate the apparent motion perception (Kolers, 1972; Kolers & von Grünau, 1976; Shepard & Judd, 1976; Robins & Shepard, 1977). Shepard & Zare (1983) demonstrated that the trajectory of an apparent motion was changed with interpolating a motion path, known as "path-guided motion. Yantis & Nakama (1998) also found that the letter discrimination performance was interrupted when a letter was presented in the apparent motion path. Another researches confirmed the existence of the internal representation through the object recognition task (Kourtzi & Shiffrar, 1997, 1999) or the attentive tracking task (Shioiri, Cavanagh, Miyamoto, & Yaguchi, 2000). The neurophysiological finding also revealed that there were overlapping cortical activation of the human motion processing complex (MT+) and Lateral occipital complex (LOC), which is considered to mediate the object recognition, when participants observed the apparent motion path (Liu, Slotnick, &Yantis, 2004).

Almost all the researches concerning the correspondence problem have mainly investigated spatial components regarding the depth information. However, depth information contained in the representation of moving objects has not been explored thus far. In the traditional research about apparent motion, it has been suggested that the form processing play a secondary role in the correspondence solving process (Kolers, 1972). Moreover, it was also indicated that the correspondence problem was solved with a 2-D image (Ullman, 1978; Mutch et al, 1983). If we assume that internal representation mediates the apparent motion perception by completing the lack of physical inputs in motion path, it would be possible that the perceptual representation of moving objects is also a 2-D image in the apparent motion path in correspondence solving process. In order to confirm the validity of this possibility, the current research investigates the manner in which visual systems represent 3-D moving objects in the apparent motion path in correspondence solving process.

General method

With regard to the stimuli, we used shaded hemispheres (Ramachandran, 1988: Kleffner & Ramachandran, 1992: see Figure 1) in order to define the dimensionality and therefore the 3-D and 2-D objects were denoted by the shaded and unshaded regions respectively. It was confirmed that observers perceived the shaded figures as convex or concave 3-D objects depending on the location of the shaded region, while the figures without the shaded region always appeared to be flat. Hence, we were able to easily manipulate the shape of objects — 2-D or 3-D (convex or concave) — by changing the shaded regions. This also enabled us to effectively exclude other 3-D cues, such as occlusion or disparity, from the stimuli.

Since the object in the apparent motion path is internally represented in the brain, it is necessary to employ some indirect methods in order to investigate the shape of the internal representation. Since completed filled-in objects can interfere with the perception of objects in the motion path (Yantis & Nakama, 1998), we can estimate the property of the object representation in the apparent motion path by analyzing the perceptual interference in terms of the objects inserted in the motion path. Therefore, in this research, we investigated the manner in which 2-D or 3-D probe objects presented in the apparent motion path modify motion perception (Foster, 1975).

The current research investigated whether the probe objects (the 2-D or 3-D images inserted) affected the perceived direction of apparent motion in ambiguous apparent motion display. As mentioned above, visual systems must solve the correspondence problem in this display. We used a reliable measurement that was well-established in the previous study on the process solving directional correspondence (Shimojo & Nakayama, 1990). They investigated the motion direction perception by using a bistable apparent motion display in which the relative distance between the vertical and horizontal paths decisively affected the perceived direction (Figure 2). This was

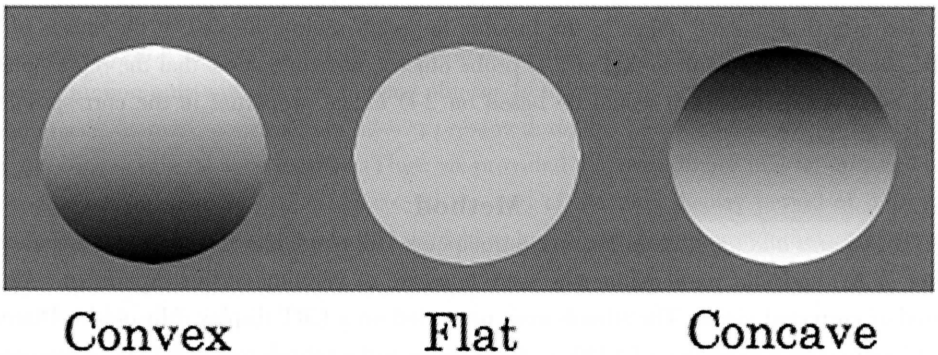

Figure 1. Examples of shape from shading. The left circle often appears to be a convex hemisphere, the center circle is perceived as flat, and the right circle appears to be a concave hemisphere.

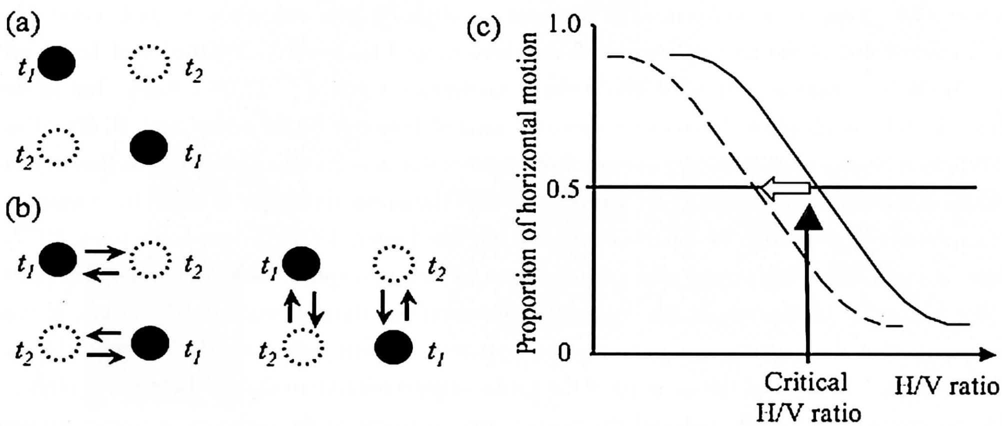

Figure 2. Bistable apparent motion display. (a) Targets appear alternately at time t1 and t2. (b) Perceptions of the bistable motion display. Observers often perceive either horizontal or vertical motion. (c) Predicted shift in the psychometric function. If the perception of vertical motion becomes dominant, the function plotted with the H/V ratio shifts as indicated by an empty arrow. A filled arrow indicates the critical H/V ratio where the proportions of horizontal and vertical motion are equal (see also the results of Experiment 1).

referred to as the H/V ratio. When the H/V ratios are large (close to 1), that is, the distance of the horizontal path is nearly the same as that of the vertical path, vertical motion is dominantly perceived. In contrast, the smaller H/V ratios, where the distance of the horizontal path is less than that of the vertical path, favor horizontal motion. A psychometric curve can be plotted as a function of the H/V ratios. This method is considered to be useful while researching similar topics because the perceptual change in the motion direction can be detected through shifts in the psychometric function.

Experiment 1

In Experiment 1, we investigated whether 2-D or 3-D probe objects modify the perceived direction of a 3-D moving object in the bistable apparent motion display. If the effects of 3-D probe objects are equivalent to that of 2-D probe objects, we can assume that the representation in the apparent motion path would be based on 2-D image properties in the correspondence solving process.

Method

Participants and apparatus. The five participants (Tohoku University students) included the author (Y.K.) and four participants who were unaware of the aims of this experiment. All had normal or corrected vision. The stimuli were presented on a CRT display (Mitsubishi, Diamond M^2, 17 inch) with a resolution of 1280 $\times$ 1024 pixels and a refresh rate of 85 Hz. A customized PC (Apple Macintosh Power Mac G4) was used in order to control this experiment.

Stimuli. We used convex hemispheres as moving objects and a convex, concave hemisphere and flat circle as probe objects (see Figure 1). The diameter of each stimulus was 0.48 deg at the observation distance of 95.5 cm. The luminance values of these stimuli were as follows: The luminance value of the moving convex hemisphere ranged between 37.9 cd/m^2 and 16.21 cd/m^2 (Michelson contrast was 0.40; the average luminance value was 27.06 cd/m^2), that of the shaded probe hemisphere (convex or concave) ranged between 33.92 cd/m^2 and 18.89 cd/m^2 (Michelson contrast was 0.28; the average luminance value was 26.68 cd/m^2), and the luminance values of the flat stimulus was 27.07 cd/m^2. Although the probe technique is useful for estimating the internal representation of apparently motion objects (Foster, 1975; Robins & Shepard, 1977), there is a possibility that probes affect the apparent motion perception itself (Mcbeath & Shepard, 1989). In order to investigate the interaction between the moving and probe objects, it was necessary that the participants perceive the apparent motion only with the moving objects. Therefore, we diminished the contrast of the probe objects relative to that of the moving objects. This operation successfully induced the participants to perceive the ordinary apparent motion between the two moving objects even with the probe objects. The gray background luminance was 21.08 cd/m^2. The vertical separation of moving objects was maintained at a constant (2.5 deg) and the horizontal separation was altered to one of the following values: 1, 1.26, 1.5, 1.74, 2.04, 2.28 or 2.4 deg. Thus, the H/V ratio was ranged between 0.4 and 0.95. We did not use the condition in which H/V ratio was 1 because it has been known that the vertical motion is dominantly perceived in case that the horizontal and vertical distance is equal (Ramachandran & Anstis, 1983).

Procedure. Figure 3 illustrates the experimental procedure. A trial was initiated when the participants hit the start button. The experiment began with a blank screen. After 1500 ms, a fixation point appeared for 500 ms at the center of the screen. An apparent motion display was then presented. Frame 1 consisted of two moving objects; one was located in the upper left area and the other in the lower right area of the screen. The positions of the two moving objects were reversed in Frame 2. The first frame of the moving objects was randomly chosen from these two frames at the initiate of each trial. These two frames were alternately presented three times. The stimulus onset asynchrony (SOA) was 300 ms. An inter-frame was inserted between Frames 1 and 2, and it appeared for 11.76 ms (= one vertical sweep interval). The inter-frame comprised four probe objects that were constantly located at the center of the motion path. We presented the low-contrast probe objects as briefly as possible so that the participants could perceive the apparent motion only with the two moving objects. In the vertical path, one of the three kinds of probe objects (convex, concave, or flat) was presented; on the other hand, in the horizontal path, only the convex objects were inserted. Thus, we provided three conditions in a randomized order depending on the kind of probe objects. At the end of the total display period of 3.86 s, the participants were asked to judge whether vertical or horizontal motion was dominantly perceived by pressing one of the two buttons.

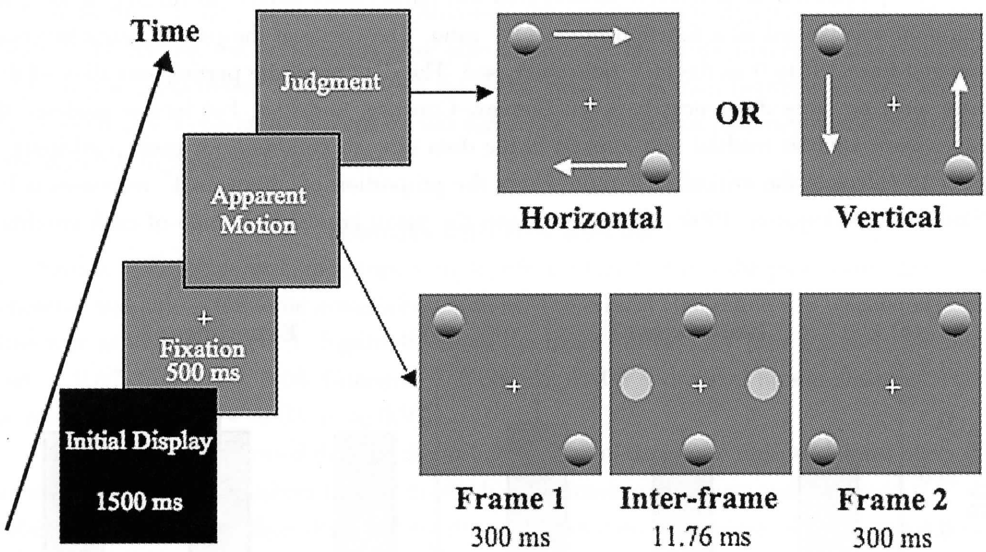

Figure 3. Experimental design for Experiment 1 and 2. Two moving objects were alternately presented in Frames 1 and 2, and four probe objects were located at the center of the motion path between these frames as the inter-frame. The convex hemispheres were constantly presented in both the horizontal motion paths. In contrast, one of the three kinds of probe objects (convex, concave, or flat) was presented in both the vertical motion paths.

The experiment was conducted in a dark room. At the beginning of the experiment, the participants were asked to confirm if they could perceive the depth in the case of the shaded stimuli and the absence of depth in the case of the flat stimulus. All participants reported that they perceived the depth or the lack of it. Then, the first practice session was conducted to ensure that the participants experienced spontaneous reversals of motion direction and completely understood the task. The participants observed the apparent motion display, which comprised only Frames 1 and 2, and reported their responses. The session consisted of four repetitions for each of the seven steps of horizontal separation in a randomized order. In addition, the second practice session was also conducted. In this session, Frames 1 and 2 and the inter-frame were presented. The session composed of 126 trials (six repetitions × seven separations × three conditions). Thus, we conducted a relatively long practice session in order to reduce the persistence of specific motion perception since it was known that hysteresis occurred in the bistable apparent motion display (Ramachandran & Anstis, 1983). Based on the data derived from the practice session, only those individuals did not appear to have a large hysteresis effect participated in the experiment that consisted of five sessions (420 trials) with each session comprising 84 trials (four repetitions × seven separations × three probe conditions). A short break of more than 5 min was given between the sessions. The experiment was completed in approximately 1.25 h.

Results and discussion

The proportion of perceived motion that the participants judged as horizontal for each condition was plotted as a function of the H/V ratio. The curve of the psychometric functions changed from 1.0 to 0 as the H/V ratio increased. The data of all the participants showed that there were no large differences between Convex, Concave, and Flat. For further analysis, the least-square analysis method was applied to the data of each condition for each participant in order to calculate the critical H/V ratio where the proportion of "horizontal" responses is 0.5 (Shimojo & Nakayama, 1990). Figure 4a shows the mean critical H/V ratio of each condition

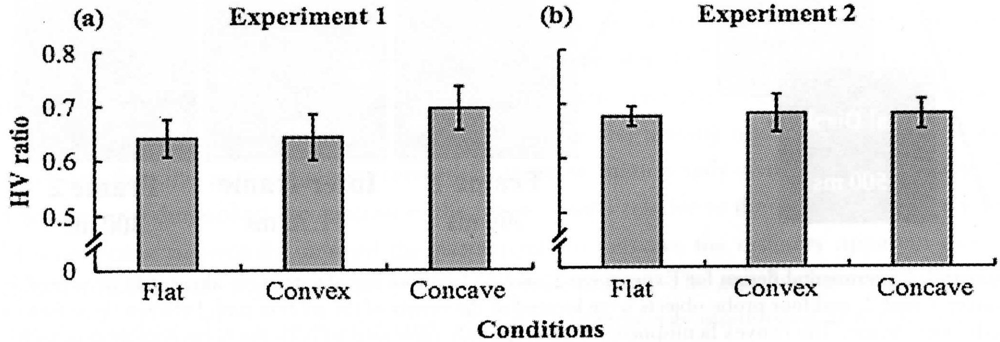

Figure 4. Results of experiments. The mean critical H/V ratios in each condition for Experiment 1 and Experiment 2 are shown in (a) and (b), respectively. Error bars denoted mean standard errors (N = 5).

(Flat = 0.64, Convex = 0.64, Concave = 0.69). An ANOVA revealed no significant effects of the conditions ($F(2,8) = 0.59$, $p = 0.48$).

These results clearly revealed that the depth information of the probe objects did not affect the perceived direction of the apparent motion. The lack of difference between the conditions, in particular, between Flat and Convex or Flat and Concave, suggested that the representation in the apparent motion path would comprise 2-D image properties without the use of 3-D information.

Experiment 2

With regard to the results of Experiment 1, a different interpretation could be considered. Since the probe objects had relatively low-contrast and were presented for a very brief period, these stimuli might not have substantial function as probes. Therefore, in order to exclude this possibility, we conducted another experiment. In this experiment, the contrast of the probe objects was the same as that of the moving objects.

Method

Participants and apparatus. The five participants (Tohoku University students) included the author (Y.K.) and four participants who were unaware of the aims of this experiment. Of these, three participants were new to the experiment. All had normal or corrected vision. The apparatus was identical to that of the previous experiment.

Stimuli and procedure. The shaded probe objects had the same luminance values and contrast as that of the moving objects. Although the probe objects appeared for a very brief duration (11.76 ms), the participants were able to perceive the probe objects in this condition. Note that the participants could perceive the usual apparent motion between the two moving objects even in this condition. Except for this difference, the stimulus parameters and procedures were identical to those in Experiment 1.

Results and discussion

Similar to Experiment 1, the proportion of perceived motion that the participants judged as horizontal was almost the same across all conditions. The critical H/V ration was calculated in the same way as in Experiment 1. Figure 4b shows the mean critical H/V ratio for each condition (Flat = 0.67, Convex = 0.68, Concave = 0.68). An ANOVA revealed no significant effects of the conditions ($F(2,8) = 0.03$, $p = 0.97$).

These results reconfirmed that the depth information of the probe objects did not affect the perceived direction of apparent motion even when the luminance values and the contrast of the probe objects was higher than those in Experiment 1. Based on the findings of Experiment 1 and 2, we can suggest that the representation in the apparent motion path would be composed mainly of 2-D properties.

General Discussion

The present study investigated the depth information contained in the internal representations of moving 3-D objects in the apparent motion path, which have no corresponding visual inputs, in the correspondence solving process. In Experiment 1, by using an ambiguous apparent motion display, we investigated the manner in which the shaded probe objects affected the motion direction perception. The results illustrated that the depth information of the probe objects did not have any effect on the perceived direction of the apparent motion. Experiment 2 confirmed that the results of Experiment 1 were invariance with the intensity or the saliency of the probe objects. These findings suggested that the representation of the moving objects would be like an image without depth information concerning the correspondence solving process.

In the current research, we very briefly presented the probe objects, whose contrast was the same with or lower than the moving objects. This procedure successfully induced the participants to perceive the apparent motion between the two moving objects. Consequently, the similar results were obtained regardless of the intensity of the probe objects. Therefore, it can be assumed that the probe objects did not deteriorate the normal apparent motion perception between the moving objects.

The previous researches about apparent motion perception have shown that the correspondence problem was mainly solved with the proximity of the distance between moving objects (Kolers, 1972; Burt & Sperling, 1981; Scholl, 2001). Especially, it was pointed out that 2-D depth information is utilized for the correspondence solving process regarding spatial depth information (Ullman, 1978, Mutch et al, 1983). The current research revealed that the representation of moving 3-D objects in motion path comprised only 2-D properties in ambiguous apparent motion display. Therefore, it can be assumed that the visual systems utilize the common depth information both the object representation and spatial components in the correspondence solving process.

Whereas our current results in line with the viewpoint that only 2-D information is used for the correspondence problem, it has been also known that apparent motion was perceived with 3-D information (Atteneave & Block, 1973; Foster, 1975, 1978; Shepard & Judd, 1976; Green & Odom, 1983; Koriat, 1994; Tse & Logothetis, 2002). Dawson (1991) pointed out that the motion quality or the appearance of trajectories is related to higher-order processing including 3-D properties. The future direction of this study will be one that investigates the information contained in the internal representation of apparently moving object in higher-order processing stage such as motion smoothness. We have conducted some experiments in this line (Hidaka, Kawachi & Gyoba, in submission)

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