The difference of mental processes between depth and plane rotation in natural objects

Nobuhiro KANAMORI National Institute of Advanced Industrial Science and Technology e-mail
Yuji TAKEDA National Institute of Advanced Industrial Science and Technology e-mail

The speed taken to rotate objects (reaction times, RTs) depends on the axes of rotation, whatever the object (e.g., Murray, 1997; Parsons, 1987; Parsons, 1995). Kanamori and Yagi (2002) demonstrated that no intermediate representation were necessary for flipping objects over in the horizontal axis but were utilized during plane rotation. The purpose of the present study was to examine the difference in the RT x angle function between depth and plane rotation. In this study, two line drawings of natural objects were presented successively. Participants were asked to perform the normal-mirror judgment task either on the horizontal depth rotation or the plane rotation. The results of this study show that the RT x angle function is steeper during plane rotation than depth rotation, and depth rotation depends on the visibility of specific parts of the objects. This indicates that identification of the position of specific parts of the object occurs during normal-mirror judgment in depth rotation whereas plane rotation involves analog rotation.

Keywords: mental rotation, depth and plane rotation, natural object.

Introduction

Early studies considered that the speed taken to mentally rotate objects was constant, whatever the direction of rotation, and that both mental and physical rotation were represented in the same way (Cooper & Shepard, 1973; Cooper & Shepard, 1978; Shepard & Metzler, 1971). That is to say, they were suggesting that both mental and physical rotation used an analogous process (Corballis, 1988). More recently, it has been reported that time taken (reaction time, RT) to mentally rotate an image, depends on the axes of rotation, whatever the object (e.g., Murray, 1997; Parsons, 1987; Parsons, 1995). For example, Parsons (1995) suggested that rotation around a viewer-centered axis can be performed faster and more accurately than around an object-centered axis. Furthermore, Murray (1997) demonstrated that when an inverted image of a natural object is mentally flipped to the upright position (rotating in depth around the horizontal axis), the RT for flipping is shorter than when spinning (rotating in the picture plane). However, it is still not clear why flipping is faster than spinning. If observers use the same strategy of mental rotation for both flipping and spinning, then they would expect to observe similar RTs .for both conditions. The fact that different RTs were found implies that there is different mental process occurring in each condition.

Kanamori and Yagi (2002) have provided some clues that help in understanding the mental process occurring in each rotation. They hypothesized that the shorter RTs in the flipping condition are due to an absence of intermediate representations. They used a priming paradigm, where a prime and probe task were presented successively during the trial. For the prime task, participants were asked to mentally rotate an inverted object into the upright position. Then, for the probe task, they were required to judge whether two objects appearing simultaneously were same or different. The results showed that the priming effects were observed in the spinning condition but not in the flipping condition. This indicates that intermediate representations are formed under the spinning conditions but are not necessary for rotating an inverted object back to the upright position. They suggested that the RTs are faster in the flipping task because they don't need to form intermediate representations.

However, it should be borne in mind that the findings from Murray (1997) and Kanamori and Yagi (2002) only apply to rotations of 180°, namely flipping inverted objects into the upright position, because other angles of rotation were not examined in those studies. More recently, Kanamori and Yagi (submitting) have speculated that flipping occurred through line symmetrical transformation. If so, one would only expect to observe that the RTs are faster for flipping than spinning when the rotation angle is 180° rotation but not for other angles.

The purpose of the present study is to examine the mental processes required for depth and plane rotation while manipulating the angles from 0° to 180° by increments of 30°. If the advantage of depth rotation is specific to a rotation of 180°, the advantage can then be attributed to line symmetrical transformation. For rotations of angles other than 180°, intermediate representations may be necessary. On the other hand, if the advantage of depth rotation can be observed through all angles, then one can probably exclude symmetrical transformation as the occurring process.

Experiment 1

The purpose of Experiment 1 was to examine the RT x angle function through increments of 30° in the depth and plane rotation.

Method

Participants. Eighteen undergraduate and graduate students (9 female, 9 male) participated in this experiment. They all had normal or corrected-to-normal vision, and none knew the purpose of Experiment 1.

Apparatus and Materials. This experiment was controlled by Matlab 6.5 using Psychophysics Toolbox extensions. Line drawings of natural objects on a black background were used as the stimuli (Figure 1). The stimuli were presented on a 17-inch CRT monitor and within a frame area of 5°× 5°of the visual angle in height and width on the screen. The viewing distance was about 120 cm.

Images of ten objects were used in Experiment 1; an airplane, car, chair, covered wagon, desk lamp, jag, kettle, pot, saucepan and space shuttle. For each object, the images of 12 orientations (from 0° to 330° by increments of 30°) x 2 rotation axes (depth and plane) x 2 directions (to the left and right) were created. Upright images were defined as having rotations of 0°. In the depth rotation condition, stimuli consisted of objects which were transformed around the horizontal axis. In the plane rotation condition, stimuli consisted of objects rotated clockwise on the picture-plane.

Procedure. Each trial began with the presentation of a fixation point for 500 ms, followed by Frame 1 for 200 ms, a mask (a random dot matrix) for 750 ms, Frame 2 for 200 ms, and then a blank display which remained in view until the subject responded. Frame 1 consisted of either an upright image (0°) or an inverted image (180°). Frame 2 consisted of a variable viewpoint of the image. RTs were recorded from the onset of Frame 2.

Participants were required to rotate the image shown in Frame 2 around the instructed axis and respond as to whether Frames 1 and 2 were oriented in the same direction or not (i.e., normal-mirror judgment) by pressing one of two corresponding keys as quickly and accurately as possible with their right or left index finger. Immediately after the response was made, a feedback was given by presenting “correct” or “incorrect” on the display.

The experiment was divided into a depth rotation block and a plane rotation block. The order of these blocks was counterbalanced across participants. Each block was made up of 12 practice trials and 480 experimental trials. Short breaks were given every 120 experimental trials in each block. The experiment took 1.5 hours.

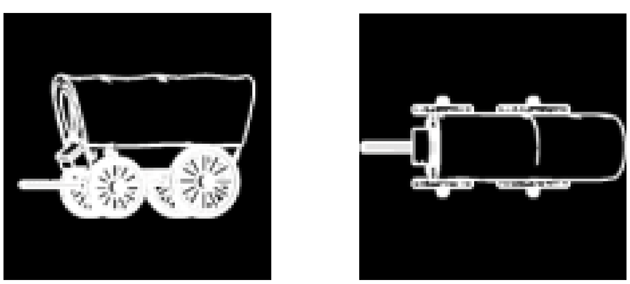

Figure 1. A typical object (covered wagon) as used in Experiment 1. The left panel shows the upright position (0°) and the right panel shows 90° of depth rotation..

Results and Discussion

The data of one participant was excluded from further analysis, because the mean error rate was too close to chance level (54%). All trials with incorrect responses, as well as trials with RTs greater than 2.5SD as outliers (1.1%), were excluded from the data analysis (the same procedure was used in Experiment 2). Correct responses were collapsed across objects and the angles of Frame 1 (i.e., upright vs. inverted). Mean RTs were calculated for seven angles of the difference between Frames 1 and 2 (i.e., 0°, 30°, 60°, 90°, 120°, 150°, and 180°). Figure 3 shows the RTs x angle functions in the positive trials (where the image directions of Frames 1 and 2 were the same). RTs were subjected to a two-way analysis of variance (ANOVA) with the direction of rotation (plane vs. depth) and angles (from 0° to 180°) as the main terms. The ANOVA indicated that the main effect of direction was significant, F (1, 16) = 20.31, p < .0001, suggesting that RTs for depth rotation were shorter than those for plane rotation. Moreover, there was a significant interaction between direction and angle, F (6, 96) = 12.14, p < .0001, suggesting that the slope of RT x angle function was steeper in the plane rotation condition than in the depth rotation condition.

The results in the plane rotation showed that RT increased in proportion to increasing angle, whereas this was not the case for depth rotation. The pattern of RT x angle function in the plane rotation condition was similar to the findings in the previous studies (Shepard, 1978; Shepard & Metzler, 1971), indicating that the process involved in plane rotation was analogous to that of physical rotation. On the other hand, depth rotation in this experiment seems to involve a different mental process from analog rotation.

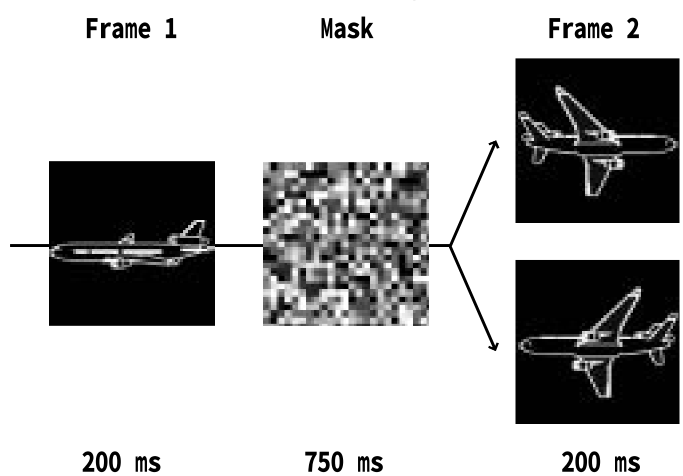

Figure 2. Schema for Experiment 1 and Experiment 2. For example, this figure shows the depth rotation condition used in Experiment 1. In Experiment 2, only the depth rotation condition was conducted.

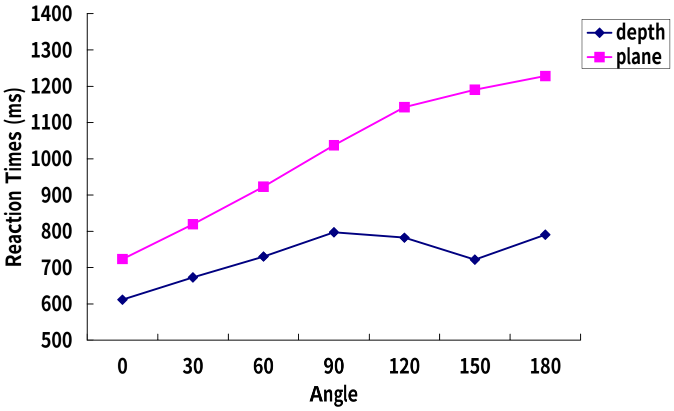

Figure 3. RTs for each condition in Experiment 1.

Experiment 2

The results in Experiment 1 illustrate the different mental processes used in depth and plane rotation. Observers might judge the orientation of objects by using positions of specific parts during depth rotation, whereas analog rotation would be performed for plane rotation. During depth rotation, the position of specific parts can be used as cues for orienting the objects whatever their angle. If so, then masking the specific parts of objects would influence the patterns of RT x angle function. In Experiment 2, we examined the RT x angle functions of depth rotation while comparing the effect of masking or not masking the stimuli.

Method

Participants. Fourteen undergraduate and graduate students (9 female, 5 male) participated in this experiment. They all had normal or corrected-to-normal vision, and none knew the purpose of this experiment.

Apparatus and Materials. Apparatus and materials were identical to those used in Experiment 1. Masked stimuli and unmasked stimuli (the same as in Experiment 1) were used. Twelve circles were superimposed onto each image in order to create the masked stimuli (Figure 4).

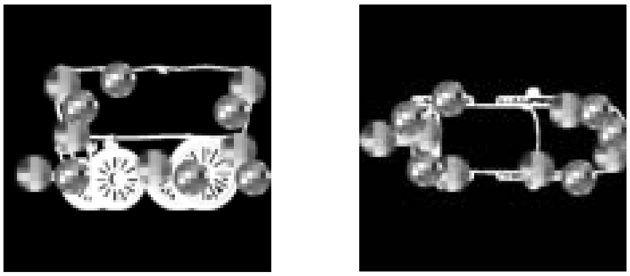

Figure 4. Stimuli as used in Experiment 2 showing the masked objects versions.

Procedure. The time course of the presentation of stimuli was identical to that in Experiment 1. In this experiment, the depth rotation task was carried out using both masked and unmasked stimuli. In the masked condition, both images of Frames 1 and 2 were masked. In the unmasked condition, the stimuli were identical to the depth rotation condition in Experiment 1. The experiment was divided into a masked condition block and an unmasked condition block. The order of these blocks was counterbalanced across participants.

Results and Discussion

The data from one participant was excluded from further analysis, because the mean error rate was too near chance level (45%). The data of outliers (1.3%) was excluded from the data analysis.

Figure 5 shows the RTs for each condition in the positive trials. RTs were subjected to a two-way ANOVA with the type of mask (masked vs. unmasked) and angles (from 0° to 180°) as the main terms. The ANOVA indicated that the interaction between mask and angle was significant, $F(6, 72) = 10.38$, $p < .0001$, suggesting that the slope of RT x angle function was steeper in the masked condition than in the unmasked condition. A Tukey's HSD test indicated that there were significant differences between the masked and unmasked conditions using angles of 60°, 90°, 120°, and 150° ($ps < .05$).

The results in this experiment showed that the mask occupied on the specific parts of the object affected the performance of the normal-mirror judgment for the larger angles (i.e., 60° - 180°) but not for the smaller angles (i.e., 0° and 30°). The interaction between mask and angle indicates that the process for the specific parts of objects would play an important role in depth rotation. Furthermore, the RT x angle function was not linear even if masks were superimposed on the images. This indicates that depth rotation is different from the analog process which was demonstrated during plane rotation in Experiment 1.

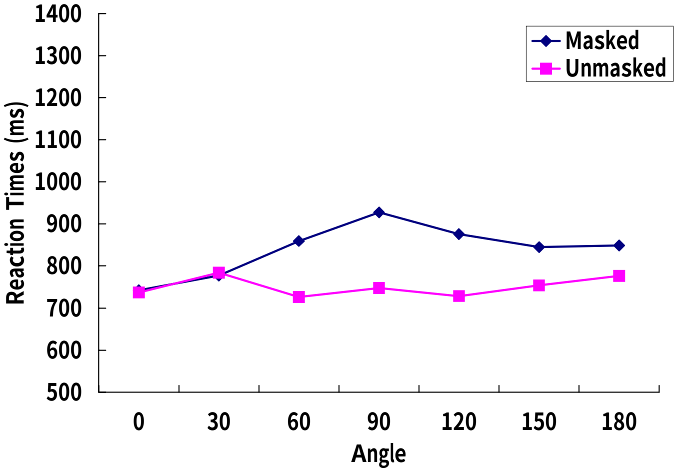

Figure 5. RTs for each condition in Experiment 2.

General Discussion

The results of the present study can be summarized by the following three points: 1) The difference in RT x angle functions between plane ration and depth rotation (Experiment 1) suggests that depth and plane rotation use different mental processes. 2) The increase of RTs for masked stimuli in the larger angle conditions (Experiment 2) suggests that depth rotation is influenced by the visibility of specific object parts. 3) The RT x angle function in Experiments 1 and 2 suggest that depth rotation does not utilize analog processes, whether the parts are visible or not. These results indicate that the transformation of image in the depth and plane rotation conditions operate through different processes. This is consistent with the findings from Kanamori and Yagi (2002) suggesting that intermediate representations are formed during the process of plane rotation but not during depth rotation.

How were objects transformed in depth rotation? Kanamori and Yagi (2002) speculated that a line symmetrical transformation might be a plausible process for depth rotation. It is considered that the line symmetrical transformation strategy is useful only for 180° rotation, namely from inverted image to upright image and vice versa. However, the results in the present study showed faster RTs in the depth rotation condition relative to the plane rotation condition. This cannot be explained solely by line symmetrical transformation.

The results in Experiment 2 indicate that the process for the parts of objects plays an important role during the depth rotation task. Furthermore, RTs for rotation angles of 90° were longer than any other angle in the depth rotation condition of Experiment 1 and in the masked condition of Experiment 2, although no angle effect was observed in the unmasked condition in Experiment 2. This implies that the normal-mirror judgment in the depth rotation condition could be occurring through the localization of specific parts of objects. In the images of 90° used in this study, several object parts were occluded by the body of the object. Therefore, it should be difficult to judge the normal or mirror of the images, if observers performed the task by locating the specific parts of the object.

It should be noted that the nature of depth rotation found in the present study could only apply to the normal-mirror judgment task. In the normal-mirror judgment task, the object parts in Frame 1 and 2 always appear at the same lateral position in the positive trials regardless of the angle in the depth rotation condition, whereas the lateral position of the parts varied with angles in the plane rotation condition. Therefore, further studies are needed to clarify the various aspects of depth rotation, and examine the RT x angle function during different tasks, for instance a naming task, a matching task, and so on, as well as the normal-mirror judgment task.

Conclusions

In conclusion, we propose two aspects of depth rotation. First, the process of depth rotation is different from that of plane rotation. Second, at least in the normal-mirror judgment task, lateral positions of specific parts are used as cues for the orientation of natural objects.

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