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Research report

Depth perception from moving cast shadow in macaque monkey

Saneyuki Mizutani [a,b,c], Nobuo Usui [b,c], Takanori Yokota [a,c], Masato Taira [b,c], Narumi Katsuyama [b,c,*]

[a] Department of Neurology and Neurological Science, Graduate School of Medical and Dental Sciences, Tokyo Medical and Dental University, Tokyo, Japan
[b] Department of Cognitive Neurobiology, Graduate School of Medical and Dental Sciences, Tokyo Medical and Dental University, Tokyo, Japan
[c] Center for Brain Integration Research, Tokyo Medical and Dental University, Tokyo, Japan

HIGHLIGHTS

- We examined whether monkey can perceive motion in depth induced by cast shadow.
- A motion illusion induced by moving cast shadow was used.
- Monkey could discriminate motion in depth induced by binocular disparity.
- The illusion was intervened as a catch trial during the discrimination by disparity.
- Monkey could discriminate the illusionary motion in depth induced by cast shadow.

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ABSTRACT

In the present study, we investigate whether the macaque monkey can perceive motion in depth using a moving cast shadow. To accomplish this, we conducted two experiments. In the first experiment, an adult Japanese monkey was trained in a motion discrimination task in depth by binocular disparity. A square was presented on the display so that it appeared with a binocular disparity of 0.12 degrees (initial position), and moved toward (approaching) or away from (receding) the monkey for 1 s. The monkey was trained to discriminate the approaching and receding motion of the square by GO/delayed GO-type responses. The monkey showed a significantly high accuracy rate in the task, and the performance was maintained when the position, color, and shape of the moving object were changed. In the next experiment, the change in the disparity was gradually decreased in the motion discrimination task. The results showed that the performance of the monkey declined as the distance of the approaching and receding motion of the square decreased from the initial position. However, when a moving cast shadow was added to the stimulus, the monkey responded to the motion in depth induced by the cast shadow in the same way as by binocular disparity; the reward was delivered randomly or given in all trials to prevent the learning of the 2D motion of the shadow in the frontal plane. These results suggest that the macaque monkey can perceive motion in depth using a moving cast shadow as well as using binocular disparity.

1. Introduction

A shadow cast on a background surface by an object is called a cast shadow. Although the shape, transparency, and blur of cast shadows in our daily scenes vary based on the relative position between the light source and the objects casting them, they serve as a powerful monocular depth cue in spatial vision. This is well demonstrated by a motion illusion named 'square-over-checkerboard' (SOC) provided by Kersten et al. [1]. Fig. 1A illustrates shots from the movie. There is a square at the center with its shadow cast on the background at the right-bottom corner. When the cast shadow moves away from and toward the square in the frontal plane, observers experience a strong percept that the square approaches and recedes from them, respectively, whereas the size and position of the square are actually constant during the movie. Thus, cast shadows can provide salient depth cues for the perception of object position in three-dimensional (3D) space [1–3]. The effect of cast shadows as monocular depth cues is more prominent

* Corresponding author at: Department of Cognitive Neurobiology, Tokyo Medical and Dental University, 1-5-45, Yushima, Bunkyo-ku, Tokyo 113-8549, Japan. Tel.: +81 3 5803 5445; fax: +81 3 5803 0165.
E-mail address: katz.cnb@tmd.ac.jp (N. Katsuyama).

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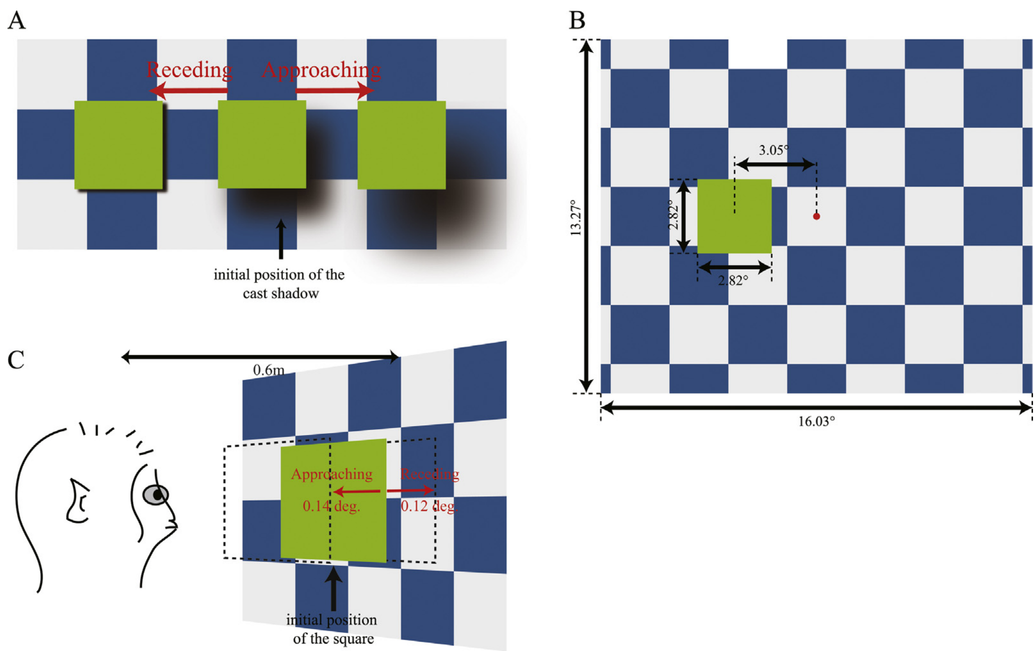

Fig. 1. A: Motion of the cast shadow. The shadow was presented at the initial position in all trials (center), and moved either away from (approaching, right) or toward (receding, left) the square in the AP and RC trials, respectively. In the DD + SCS conditions in session 4, the cast shadow did not move from the initial position. B: Basic configuration of visual stimulus. In session 1, the square was also presented to the right of, above and below the FP at the same distance from the FP. C: Motion of the square defined by binocular disparity. It was presented initially at 0.12 degrees of the uncrossed disparity. This corresponded to a location 25 mm in front of the background (initial position). The square moved either 0.14 degrees toward the monkey (approaching) or 0.12 degrees toward the background (receding) in the AP and RC trials, respectively. In the rDD condition, the motion of the square from the initial position was reduced to 0.021, 0.016, 0.010, and 0.0052 degrees (corresponding to an estimated distance of 4, 3, 2, and 1 mm). In the SD condition, the square did not move from the initial position. deg.: degrees.

in the movie, because it becomes easier to link objects to their cast shadows in a dynamic scene than in a static image [3].

As a cast shadow moves away from the object casting it, it can provide ambiguous information about the spatial layout of the object. Nevertheless, we can precisely infer the spatial position of the object by using the cast shadow. Previous studies hypothesized that to infer the spatial positions of an object in 3D space from its cast shadow, the visual system uses the *a priori* constraint that the light source is above the observers and is stable [2,3]. If this hypothesis is correct, it is expected that non-human primates who have an anatomically and functionally similar visual system to humans may also take advantage of cast shadows for spatial vision. However, only a few studies have investigated this topic so far [4–6].

In the present study, we investigated whether adult macaque monkeys can perceive motion in depth induced by cast shadows. For this purpose, we conducted two experiments. In the first experiment, we trained an adult macaque in a motion discrimination task in depth by binocular disparity. In the next experiment, we presented a moving cast shadow as part of the visual stimulus and examined the responses of the monkey to the apparent motion in depth induced by the shadow. Our results suggest that the adult macaque monkey can indeed perceive the motion in depth induced by cast shadows as well as by binocular disparity.

2. Methods and materials

2.1. Materials

We used a female Japanese monkey (*Macaca fuscata*). This monkey was 4 years and 5 months old when it was first presented with visual stimuli containing cast shadows. Throughout the experiments, the monkey was treated in accordance with the NIH Guide for Care and Use of Laboratory Animals. All animal experiments were approved by the Institutional Animal Care and Use Committee of Tokyo Medical and Dental University (approval number: 0150187A).

2.2. Experimental setup

All stimuli in the study were shown using software for 3D presentation (Omega Space ver. 3.1, Solidray Institute, Yokohama, Kanagawa, Japan). A liquid crystal display (LCD-3D231XBR, I-O DATA, Kanazawa, Ishikawa, Japan) was placed at 0.6 m in front of the monkey at eye level, and modified versions of the SOC movie were presented in a 265 × 155 mm (width × height) window attached to the front of the display. The monkey was trained to sit in a primate chair with its head fixed. It wore liquid crystal shutters (NVIDIA 3D Vision®, NVIDIA, Santa Clara, CA, USA) for stereo vision, operating at 120 Hz, so 60 frames/s of stimulus were presented to each eye. We implanted scleral search coils (DNI instrument, Newark, DE, USA) for monitoring eye position and vergence. A trial was aborted immediately when the eye position exceeded the limit of 1° from the fixation point (in this article, we describe the visual angle and binocular disparity with° and degrees, respectively, for clarity). The original images for the movie frames used in this study were created using drawing software (Illustrator CS5, Adobe systems incorporated, San Jose, CA, USA) and converted into movies by hand-made programs written in Matlab (MathWorks, Natick, MA, USA). The original spatial resolution of each movie was 72 pixels/inch and the frame rate of the movies was 27 frames/second. Binocular disparity was calculated on the basis of an interocular distance of 0.03 m for the monkey in the present study.

2.3. Experiments

2.3.1. Experiment 1: motion discrimination in depth by disparity

We first trained the monkey in a GO/delayed GO (dGO)-type discrimination task of the motion in depth defined by disparity. A trial began with presentation of a checkerboard (13.27 × 16.03° in