Extracting the orientation of rotating objects without object identification: Object orientation induction

Satoshi Shioiri

Research Institute of Electrical Communication and
Graduate School of Information Sciences,
Tohoku University, Sendai, Japan

✉

Kotaro Hashimoto

Graduate School of Information Sciences,
Tohoku University, Sendai, Japan

Kazumichi Matsumiya

Research Institute of Electrical Communication and
Graduate School of Information Sciences,
Tohoku University, Sendai, Japan

Ichiro Kuriki

Research Institute of Electrical Communication and
Graduate School of Information Sciences,
Tohoku University, Sendai, Japan

Sheng He

Department of Psychology, University of Minnesota,
Minneapolis, MN, USA

When a rotating object (inducer) is briefly replaced by a static face image (test stimulus), the orientation of the face appears to shift in the rotation direction of the inducer (object orientation induction, OOI). The OOI effect suggests that there is a process to continuously analyze and update the orientation of an object in motion. We investigated the perception of object orientation in motion, examining potential factors that contribute to OOI. Experiment 1 showed that the phenomenon is general to objects rather than specific to faces; OOI could be observed with non-face objects. Experiment 2 showed that OOI is a 3D effect, as the orientation shift for a bent-wire object depended on its configuration in the depth dimension. Experiment 3 showed that salient features are necessary to indicate the intrinsic orientation of the inducing object for producing OOI. Experiment 4 showed that change in the facing direction of the inducer object is a crucial factor for OOI, but neither the object shape nor its identity is important. A strong OOI effect was observed even when the inducer kept changing its shape and identity, as long as its direction change generated continuous rotation. Finally, Experiment 5 showed that OOI is a phenomenon in the pathway for fast visual processing. A single inducer presented shorter than 100ms before influenced the perceived orientation of the test stimulus. Together these results suggest that there is a predictive process that continuously analyzes and updates the orientation of rotating objects, independently of their identification.

Introduction

While changing viewpoint produces large changes in retinal image, our neural process for object recognition has to identify objects based on these differing retinal images projected from various viewpoints. The representations used for objects are thought to be either viewpoint independent object-center representations (Marr, 1982) or a set of images projected from different viewpoints (Poggio & Edelman, 1990). There are studies to support both viewpoint independent (Biederman, 1987, 2001; Biederman & Gerhardstein, 1993; Booth & Rolls, 1998; Grill-Spector et al., 1999; Tsuchiai, Matsumiya, Kuriki, & Shioiri, 2012) and viewpoint dependent processes (Bartram, 1974; Bulthoff & Edelman, 1992; Edelman & Bulthoff, 1992). It is possible that both types of representations exist at different stages of visual processing (Bar, 2001).

Knowledge of viewpoint or object orientation is another aspect of object recognition. The importance of object orientation processes for recognizing static
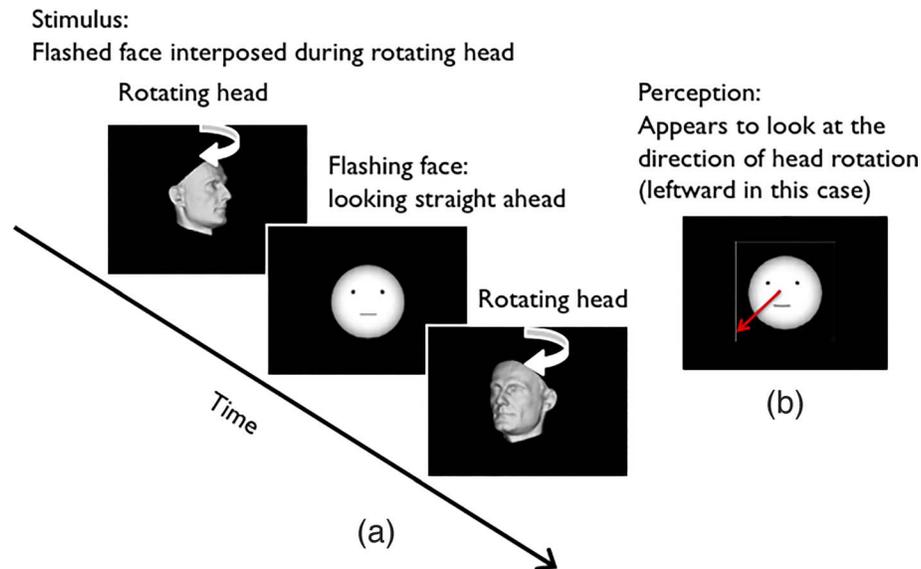
Figure 1. (a) The object orientation induction (OOI) effect: an illusory shift in the facing direction of flashed face induced by a rotating object, such as a head. A face oriented straight ahead appears to be rotated in the direction of the rotation of the head presented before and after the flashed face. (b) A demonstration of object orientation induction. The briefly presented face (test) appears to orient to the direction of the head rotation (inducer) even though the face is facing straight ahead.

objects has been investigated psychophysically (Fang & He, 2005) and physiologically (Logothetis, Pauls, Bulthoff, & Poggio, 1994). Fang et al., for example, revealed that there is a viewpoint dependent process for face orientation, showing an adaptation effect for face orientation (the viewpoint aftereffect (VAE)). The visual stimuli of everyday life are usually in motion due to either the object's or the observer's movements. Our visual system must process dynamic properties of objects in motion, including object orientation, in order to e.g. grab moving objects or estimate the heading direction of approaching predators. The present study focuses on the perception of object orientation or facing direction in motion.

In order to investigate the perception of object orientation in motion, we conducted experiments using a phenomenon which we named object orientation induction (OOI). In OOI, the facing direction of a test stimulus appears to shift in the direction of rotation of an object (inducer) when a face image (test stimulus) replaces the inducer briefly. In the original OOI setup, we used a rotating head as an inducer and a cartoon face as a test stimulus (Figure 1), and initially called the shift "looking off effect", regarding it as a phenomenon related to face perception (Hashimoto, Matsumiya, Kuriki, & Shioiri, 2010). OOI can be attributed to a mechanism that integrates object orientation in time along a 3D motion pathway without detailed processing of object identity so that there is an influence of the orientation of a different object on the perception of the test object orientation. The purpose of the present study is to demonstrate that the OOI effect indeed

indicates that the visual system integrates object orientation in motion without considering object identity.

There are three important issues to investigate regarding OOI as a phenomenon related to object motion: first, whether it is different from the VAE reported for static stimuli (Fang & He, 2005); second, whether it is a phenomenon related to 3D object motion, rather than a phenomenon of 2D motion such as the motion-induced position shift (Anstis, 1989; De Valois & De Valois, 1991; Ramachandran & Anstis, 1990) or the flash drag/grab effect (Cavanagh & Anstis, 2013; Whitney & Cavanagh, 2000); and third, whether it is a phenomenon related to object orientation, not 3D motion per se. In the motion-induced position shift effect, a stationary frame containing a moving texture appears to be shifted in the direction of the internal motion; in the flash drag effect, a flashed stimulus presented adjacent to a moving texture is perceived to be shifted in the direction of motion; and in the flash grab effect, a flashed stimulus presented on a moving object at the time the motion direction reversal is perceived to be shifted in the direction of the background motion following the direction reversal. The OOI could be considered the 3D version of the motion-induced position shift for motion of object orientation. Experiment 1 examined whether the OOI is a variation of the VAE or not, after confirming that the OOI is measurable psychophysically. Experiment 2 examined whether the OOI is a 2D phenomenon or a 3D phenomenon. Experiment 3 examined whether the
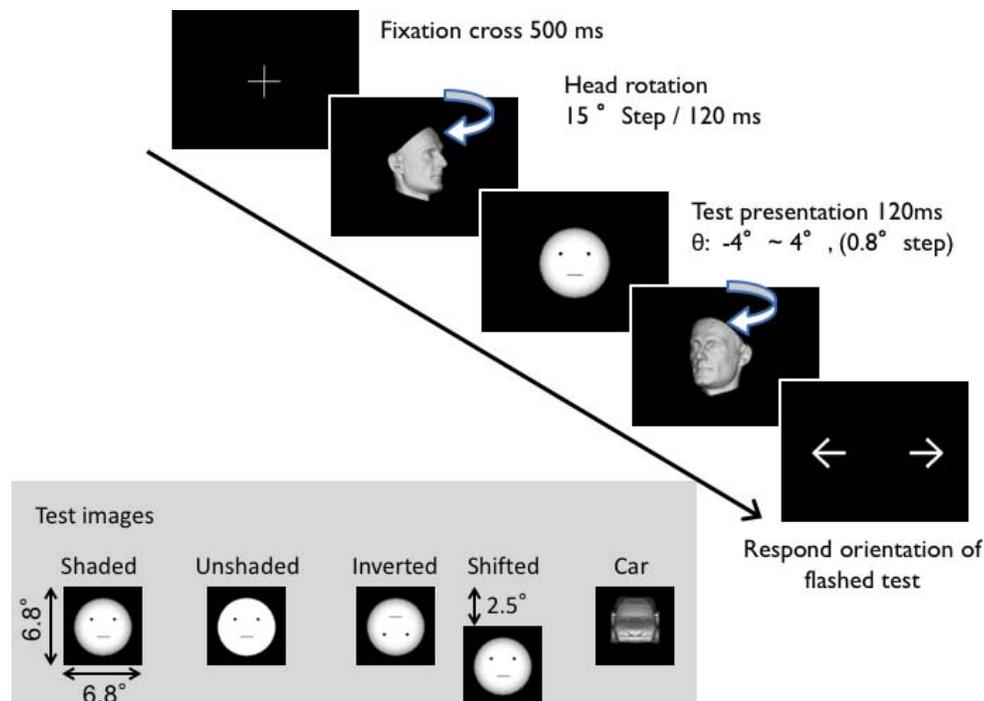
Figure 2. A trial sequence of experiments to measure the effect size of the object orientation induction (OOI) effect. After a 500 ms presentation of a fixation cross, a head started rotating from either side, i.e. from the left (-90°) or right (90°). At the time of the head orienting straight ahead, a test face was presented briefly. The facing angle of the test face was randomized in the range of -4 to 4° (at 0.8° steps). After the flash, the head continued rotating to the other side. Then, two arrows were presented to elicit a response evaluating the orientation of the test face, using either of two arrow keys. There were five types of test faces. "Shaded" was a cartoon face made from a shaded sphere with two dots representing the eyes and a line representing the mouth. "Unshaded" was the same without shading. "Inverted" was the inverted version of the shaded face. "Shifted" was a face positioned 2.5° below the center of the inducer. "Car" was a car image.

OOI is a mere motion phenomenon or whether object orientation is also involved. Experiment 4 investigated the effect of changes in the shape of the inducer object to examine whether a rotating object orientation in itself, independently of object identification, is critical for OOI. Experiment 5 investigated the effect of stimulus asynchrony between the inducer and the test stimulus using an inducer with only one frame, in order to examine the temporal properties of OOI.

Experiment 1: OOI for different test stimuli.

Method

Stimuli

The rotating inducer was a 3D human head (Max Planck Institute for Biological Cybernetics (http://www.kyb.mpg.de/)) and the test stimulus was either a shaded face, a 2D cartoon face without shading, an Inverted shaded face, a shaded face in a shifted position, or a car (Figure 2). Stimuli were observed through a mirror stereoscope, which provided binocular depth information. In each trial, the inducer rotated around its vertical axis from one side to the other (±90° rotation with 15° steps using 11 different angle images; 120 ms presentation time for each image). When the inducer reached its center position (0°, i.e. facing the observer), a test stimulus replaced it for 120 ms. All stimuli were presented within a 6.8° wide and high square frame on a cathode ray tube (CRT) display (75 Hz). The observer viewed the images through a mirror stereoscope at an optical distance of 57 cm. The stereoscope was used to provide binocular disparity only in Experiment 2, where whether the OOI is a 2D phenomenon or a 3D phenomenon was asked. Stimuli in all other experiments had zero disparity to simplify the condition (the same image was displayed to both eyes). The average luminance of the inducer head was 44 cd/m^2, that of the shaded face was 117 cd/m^2, that of unshaded face was 118 cd/m^2, and that of the car was 25 cd/m^2. The background was black at 0.04 cd/m^2.

Test stimulus conditions

The test stimulus is shown in Figure 2. A cartoon face with spherical shading (Shaded) was the test stimulus with which we first found the OOI. A face without shading (Unshaded) was used as a stimulus with fewer depth cues. An inverted face (Inverted) was used to investigate the effect of face perception. Performance in face recognition, including the identification of individuals and the interpretation of expressions, usually declines with face inversion (Thompson, 1980). If OOI were specific to faces, inverting the test face would be expected to reduce or eliminate the effect. The shifted face (Shifted) was used to examine how local the effect is. The car stimulus (Car) was used to examine the transfer of OOI to a different object category. The shifted face and the car were used to compare OOI with the VAE (Fang & He, 2005). The magnitude of the position shift relative to the inducer position was chosen to be equivalent to the shift used to demonstrate the spatial invariance of the VAE (Fang & He, 2005).

Procedure

The observer fixated a central cross presented for 500 ms after pressing a button to initiate a trial (Figure 2). After the disappearance of the fixation cross, the inducer (head) was presented and started rotating. An illusion of continuous rotation was produced by presenting rotated views at discrete steps of 15° every 120 ms. The inducer was replaced by a test stimulus at the moment of facing straight ahead (0°), after which the inducer continued rotating until reaching the other side (90°). After rotation, two arrows (pointing left and right) were presented on the display as a cue for reporting the perceived orientation of the test stimulus by pressing either of two keys. The orientation of the test stimulus was randomized in the range of −4° to 4° with a 0.8° step size, and the observer reported whether it was either left or right relative to straight ahead. The unshaded 2D face was made from the 3D face by removing shading information after rotation of a given angle, which shifted the locations of the eyes (the two dots) and mouse (the line) in the facial contour (circle). Each test direction was presented ten times per session and each observer performed one session per rotation direction. We estimated the angle of the test object that appeared to be straight ahead, i.e. the subjective angle of facing front, for each observer with the method of constant stimuli using software to analyze the psychometric function (Wichmann & Hill, 2001). The subjective angle of facing front indicates the magnitude of OOI.

Observers

One author and fourteen observers with normal or corrected-to-normal visual acuity who were naive to the
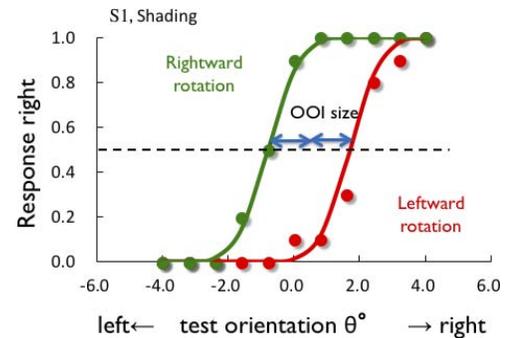

Figure 3. Typical psychometric functions for right responses in rightward and leftward rotation of the inducer using the shaded test face. The size effect of object orientation induction (OOI) is defined as half the difference between the points of subjective equality, the face direction that is appeared to be directing straight ahead, between the two rotation directions.

purpose of the experiments participated in one or several of the experiments in the present study. Observers S1, S2, S3, S4, S5, S6, and S7 participated in Experiment 1. This experiment was conducted according to the principles expressed in the Declaration of Helsinki in the treatment of the observers.

Results

Figure 3 shows typical psychometric functions obtained for leftward and rightward rotations. In the rightward rotation condition, a test face facing leftward by several degrees appeared to be facing the observer, whereas a test face facing rightward by several degrees appeared to be facing the observer in the leftward rotation condition. The difference between the points of subjective equality in the leftward and rightward rotation conditions was calculated and half of this value was defined as the effect size of the rotating inducer, which we call OOI.

Figure 4 shows OOI effect size for different test stimuli. A t-test demonstrated OOI effect size is significantly greater than zero for all test stimuli except one ($t(5) = 7.95$ and $p < 0.001$, $t(5) = 5.77$ and $p < 0.001$, $t(5) = 5.12$ and $p = 0.001$, $t(5) = 0.80$ and $p = 0.23$, $t(5) = 2.72$ and $p = 0.017$, for Shaded, Unshaded, Inverted, Shifted, Car, respectively). The depth cue from shading in the test stimuli is not critical for the effect because Unshaded also showed significant OOI, suggesting that OOI works on a face image with limited depth information. Since the flat face could be subjectively perceived as a 3D face, it would not be surprising that its facing direction is shifted by the inducer like for the shaded face. Instead, this may suggest that the OOI is a two dimensional effect. This question is examined in Experiment 2.
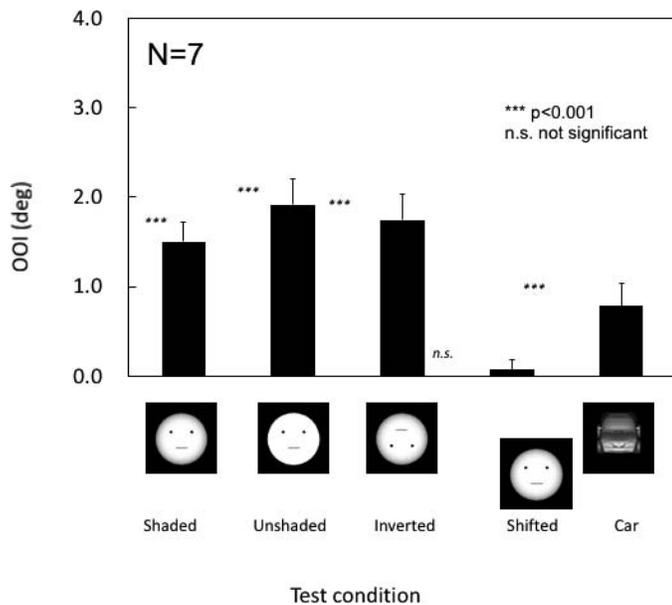
Figure 4. The object orientation induction (OOI) effect sizes for five types of test stimuli.

Face perception is not crucial for OOI because the perceived orientation of the inverted face was influenced by the rotating inducer just like that of the upright face, giving rise to a similar OOI effect size. Object identity is not crucial for OOI either, because a similar effect was found for the car stimulus. These results suggest that OOI is not specific to faces, and using the same type of object as inducer and test stimulus may not be required. The OOI may be an effect producing perceived change in object orientation in general. Experiment 4 investigates OOI across different objects.

In contrast to all other cases, the effect disappeared when the test stimulus was spatially shifted; estimates of the facing direction did not differ significantly between the leftward and rightward rotation conditions. Since the position shift between the inducer and test stimuli was chosen to be equivalent to the distance used to show the VAE, this disappearance of the OOI effect suggests that they are different effects.

Analysis of slopes of psychometric functions showed that there is no significant effect of inducer on the just noticeable difference (JND) for the facing direction judgments. We compared JNDs between Shaded and Shifted conditions because they used the same inducer and test. The average of the space constant, σ, of the cumulative gaussian function fitted to the data is 1.80 deg with standard deviation of 1.05 for Shaded and 1.05 deg with standard deviation of 0.57 for Shifted. The difference between the two values is not statistically significant ($t(6) = 1.58, p = 0.17$). This indicates that the OOI is not related to discrimination sensitivity, but to a bias on the point of subjective equality (PSE). Since the PSE shift depends on stimulus condition (no shift was found with the test
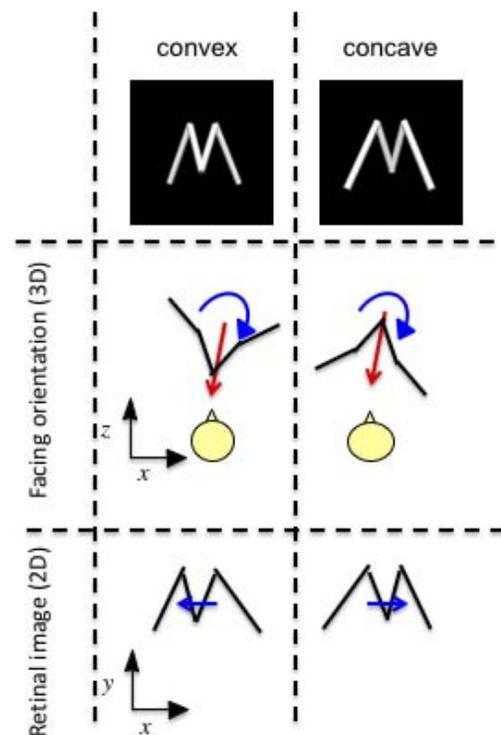

Figure 5. Test stimuli for Experiment 2. A wireframe object was used with the vertex at the center of the object pointing either forward (convex) or backward (concave). Their 3D shape was defined by binocular disparity as well as pictorial cues (shading, occlusion, and so on), and the images at the top depict the single view images of convex and concave stimuli for the purpose of description. The same direction of rotation results in opposite directions of lateral motion of the apex on the screen for the two cases.

shifted vertically), the bias is suggested to originate from processing at the perceptual level.

Experiment 2: Motion in 3D

The results of Experiment 1 show that OOI occurs also on a cartoon face without shading. This may suggest that the OOI is a two-dimensional (2D) effect and can be explained in terms of an illusory position shift due to lateral motion just like the motion capture, flash drag and flash grab effects. Although we used depth rotation around the vertical axis, still lateral (2D) shifts of parts of the stimulus such as the eyes could be thought to explain the apparent shift in its facing direction. Indeed, a shift of the eyes cannot be distinguished from a rotation of the facing direction for flat faces. We conducted Experiment 2 to examine whether lateral motion or depth rotation determines OOI, using bent-wire objects as test stimuli whose 3D shape was defined by binocular disparity as well as pictorial cues (shading, occlusion, and so on) as can be seen in Figure 5.
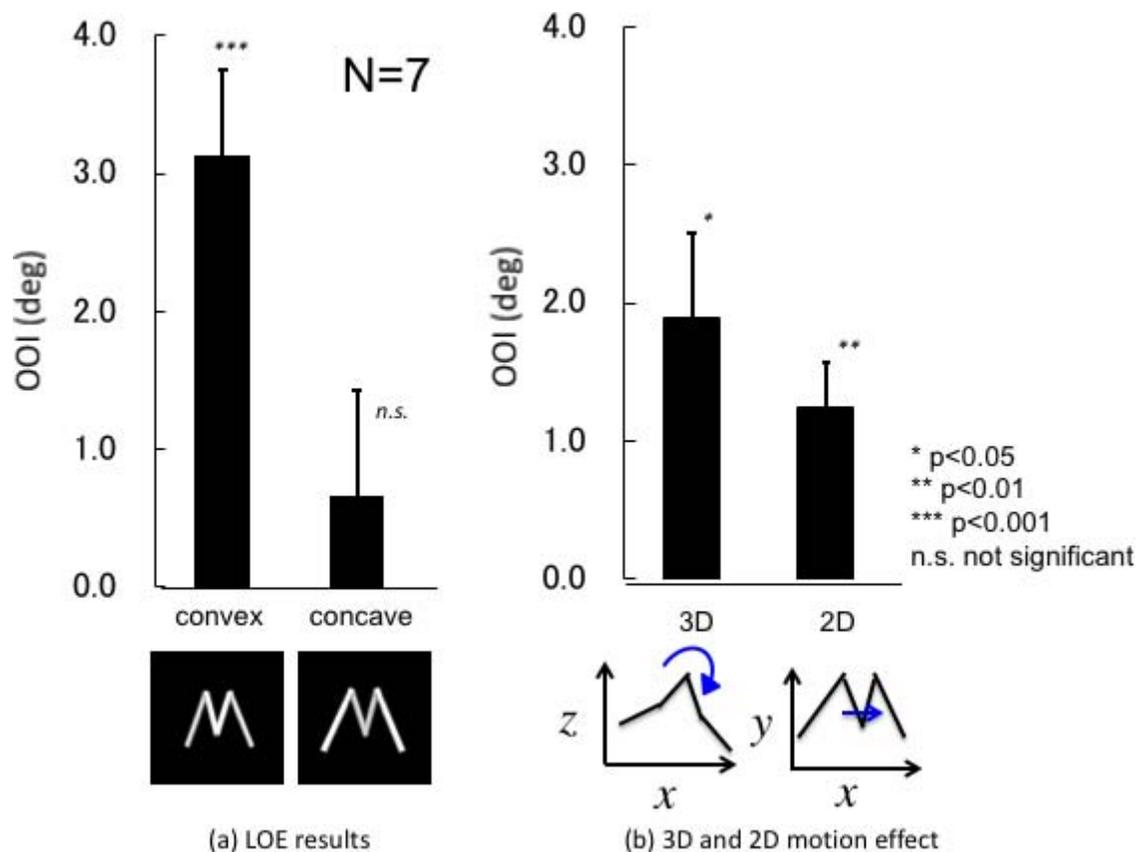
Figure 6. (a) The object orientation induction (OOI) effect for concave and convex test stimuli. (b) The OOI effect for 3D motion and 2D motion. The 3D OOI effect size is the average of the effect sizes for the concave and convex stimuli in panel (a). The average effect size of 2D motion is the average of the effect sizes for the concave and convex tests but after taking the negative of the value for concave test stimulus so that the effect corresponds to the average size of 2D shift.

Method

The experimental method was the same as in Experiment 1 except for the test stimuli. We used wireframe stimuli with binocular disparity as test stimuli to assess the effect of 3D motion effects using two test stimuli with different depth information. Two four-segment 3D wireframe shapes were used. One shape was convex and the other concave (Figure 5) so that the rotation of the two stimuli around the vertical axis provides similar lateral motion but in opposite directions. Clockwise rotation (from the top view) of the convex stimulus provides leftward lateral motion of the vertex while the same rotation of the concave stimulus provides rightward lateral motion of the vertex (Figure 5). If OOI were a 2D effect, it would be expected to manifest in opposite directions when expressed in terms of the rotation angle around the vertical axis for the convex and concave stimuli. Observers were the same as in Experiment 1.

Results

Figure 6a shows the OOI effect size for the convex and concave test stimuli. Both produced an orientation shift in the direction of inducer rotation, although the concave test stimulus did not show a statistically significant effect size (t(5) = 4.63, $p = 0.002$ for convex and t(5) = 0.78, $p = 0.23$ for concave). If OOI were caused by lateral motion, the inducer effect should be in opposite directions for the convex and concave test stimuli in terms of rotation around the vertical axis. This is not the case in the present results, and thus a 2D motion analysis is not sufficient to explain the effect. It should be noted, however, that the effect was weaker (not statistically significant) for the concave than the convex test stimulus. This is consistent with weaker impression of depth in concave stimulus. There is a tendency that the vertex at the center appears to point to the viewer even in the convex stimulus (see Figure 5), and this, perhaps, reduces the perceived depth in the opposite direction indicated by binocular disparity even with stereoscope. Therefore, the difference in OOI effect size between convex and concave test stimuli shown in Fig. 6a can be attributed to the difference in depth perception and is consistent with the hypothesis that OOI is a three dimensional and object-based phenomenon.

It is possible that the observed effect has contribution from both 3D and 2D motion components. To examine the effects of rotation in depth (3D effect) and that of lateral motion (2D effect) separately, we averaged the effect sizes for the convex and concave test stimuli in terms of the 3D or 2D motion. The average effect size of 3D motion is the average of the effect sizes for the convex and concave test stimuli shown in Figure 6a. The average effect size of 2D motion is the average of the same two values but after taking the negative of the value for concave test stimulus so that the effect corresponds to the average size of 2D shift. Figure 6b shows a comparison of 3D and 2D effects. Both differ from zero with statistical significance, which suggests that both 3D and 2D motion components of the inducer motion contributed to the OOI effect ($t(5) = 2.83$, $p = 0.015$ for 3D and $t(5) = 3.45$, $p = 0.006$ for 2D).

There was an alternative interpretation of results of the concave test. The concave test may have been perceived as facing the opposite direction (the direction away from the observer). The difference in facing direction between inducer and test may be too large in such a case for them to interact. In this case, however, the difference between the convex and concave tests is attributed to 3D information, suggesting that OOI is 3D phenomenon. Future study is necessary to reveal how much of the effect shown in Figure 6b is the 2D effect and how much is the 3D effect from shape cue to depth perception.

Experiment 3: Object orientation

OOI was demonstrated for rotating objects so far and the effect suggests that the change of facing direction interacts across different objects. However, the previous experiments did not distinguish between the orientation change of the inducer object and its mere motion; rotation signals alone may cause OOI. To examine whether the rotation signal is sufficient to produce OOI or a perception of object orientation or facing direction is crucial, Experiment 3 used a rotating sphere with and without traceable features as the inducer.

Method

The experimental method is the same as in Experiment 1 except for the inducer stimuli and other details (presentation duration and viewing distance). The inducers used in Experiment 3 are shown in Figure 7. Three inducers had traceable features. One of the inducers had two red dots arranged horizontally over a yellow random dot pattern so that the red dots appear to be eyes (Eyes). Two of the inducers had two red dots
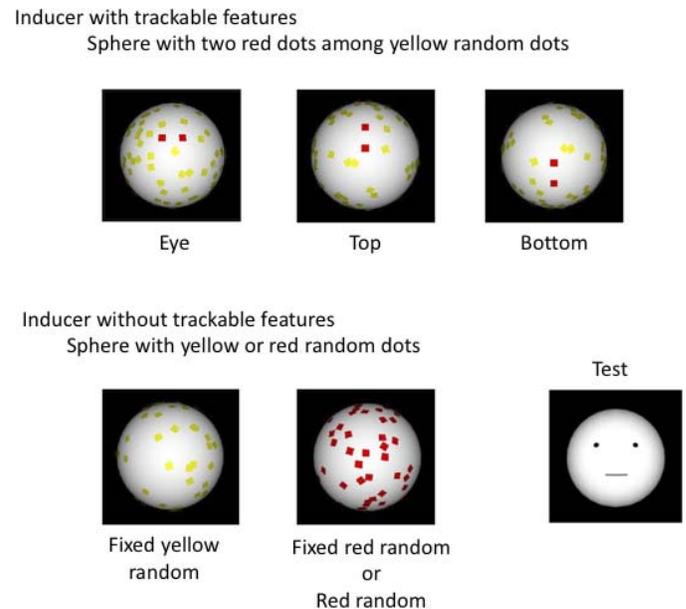

Figure 7. Inducer and test stimuli for Experiment 3. Five types of inducers were used with the shaded face as a test stimulus. Three of the inducers, Eye, Top, and Bottom, had features indicating the orientation of the sphere, while no distinguishable features were given to the other inducers.

arranged vertically: the dots were located either in the upper (Top) or lower (Bottom) half of the sphere. The three remaining inducers had only random dots on the surface and we assumed there was no traceable features; these were yellow in one inducer and red in the other two. The yellow inducer and one of the red inducers had a random dot pattern on the surface that was the same throughout the experiment (Fixed yellow random and Fixed red random, where 'fixed' indicates that the same dot pattern was used for all trials in the experiment). The observers potentially could have chosen a set of dots to form a feature to indicate the facing direction of the inducers and used that in later trials, since random arrangements of items can be memorized implicitly by repeated observations (Chun & Jiang, 1998) even in the 3D space (Shioiri, Kobayashi, Matsumiya, & Kuriki, 2018; Tsuchiai et al., 2012). Thus, we included another inducer for which a new random dot pattern was assigned in each trial (Red random) to remove or minimize the influence of memory effect of the random dot patterns. Random dot patters of all the inducers did not change on the surface within a trial but moved with the object rotation. The inducers had a 5.2° diameter and were viewed from a 50 cm optical distance. The test stimulus was Shaded for all inducers. Rotation was simulated in steps of 15° using 11 different angle images as in Experiment 1, but here the presentation duration of each image was 150 ms.
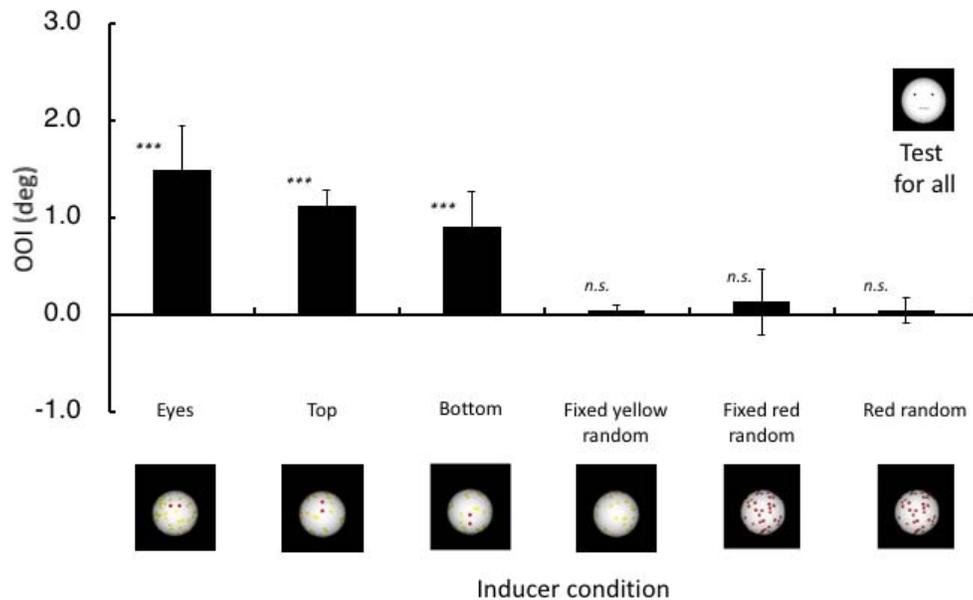
Figure 8. The object orientation induction (OOI) effect for inducers with and without features indicating the sphere's orientation (Eye, Top, Bottom vs. Random). In the delayed condition (extreme right), the test stimulus was presented after the inducer had passed its center-facing position.

Results

Figure 8 shows the OOI effect size for the Shaded test stimulus with different inducers. A t-test showed that significant OOI was obtained when inducers had traceable features on the surface ($t(5) = 3.26$ and $p = 0.011$, $t(5) = 6.64$ and $p < 0.001$, $t(5) = 2.48$ and $p = 0.028$ for Eyes, Top, and Bottom, respectively). Inducers with dots to index their orientation produced OOI just like those with features simulating faces. In contrast, OOI was not statistically significant when inducers had no traceable feature ($t(5) = 0.84$ and $p = 0.219$, $t(5) = 0.37$ and $p = 0.386$, $t(5) = 0.30$ and $p = 0.386$ for Fixed yellow random, Fixed red random, and Red random, respectively). These results clearly show that the mere motion signal of depth rotation is not sufficient to produce OOI. Instead, rotational change of object orientation is necessary.

Experiment 4: object changes in inducer

The previous experiments show that OOI is observed with stimuli that are not faces, and even with a head inducer and car test stimulus. Experiment 3 shows that a motion signal per se is not sufficient, but rather a changing object orientation is required to obtain OOI. These results suggest that the underlying mechanism of the OOI may pertain to object orientation regardless of object identity, and possibly not require object identi-

fication. Experiment 4 examines whether object identification is required for the effect.

Method

The experimental method was the same as in Experiment 1 except for the inducer and test stimuli, and other details (presentation duration and viewing distance). Nine objects were prepared as inducers (Max Planck Institute for Biological Cybernetics (http://www.kyb.mpg.de/)). One of the objects was randomly selected for each angle image, and the images were presented sequentially as before (Figure 9). The head image was used as a test stimulus with observers' task to estimate its facing direction. The inducer's orientation was controlled horizontally depending on the presentation angle, but the vertical orientation was kept as 30° below the horizon to avoid unintelligible viewing angles (such as facing a fish head-on). All objects were presented within an 8° square and the observers were instructed to fixate at the top of the stimulus field, although there was no fixation stimulus. This was to accord with the vertical orientation of the inducers, since images of objects oriented downward provide retinal images corresponding to a view from above. Like in Experiment 1, one rotation step was 15°, and 11 different angle images with a presentation duration of 150 ms each were used. The viewing distance was a 50 cm. Observers S1, S2, S3, S8, S12, and S13 participated in this experiment.
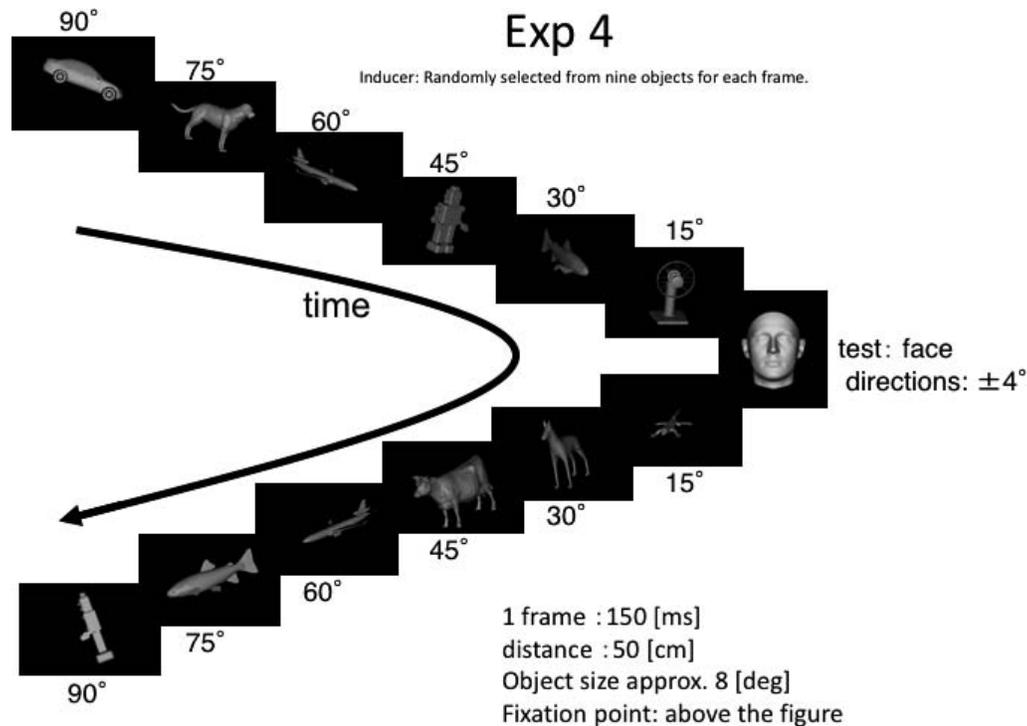
Figure 9. Inducer and test stimuli for Experiment 5. The inducer object identity changed at every frame while preserving a continuous rotational change of object orientation. The test stimulus was the head used as an inducer in Experiment 1.

Results

The OOI effect size averaged over the six observers was 0.80 with a standard error of the mean of 0.27. This value is significantly different from zero ($t(5) = 2.96$, $p = 0.016$), although the size of the OOI effect is smaller than that for the Shaded test stimulus in Experiment 1 (1.52). The difference between the two conditions is statistically significant ($t(5) = 2.29$, $p = 0.048$). The change of inducer objects during inducer motion may reduce its influence on the perceived orientation of the test stimulus. It should be noted that there were differences between the two experiments other than inducers: presentation duration was longer in Experiment 4 (150 ms) than Experiment 1 (120 ms) and different observers were used between the two experiments. Direct comparison is required to examine the effect of the inducer differences.

Experiment 5: Single frame inducer

Preliminary observations showed that presentation of the inducer as short as one frame could provide OOI, suggesting that the underlying mechanism of OOI is a comparatively fast process. We conducted Experiment 5 to investigate the temporal characteristics of OOI.

Method

While the stimuli were the same as those used with the Shaded test stimulus in Experiment 1, the temporal conditions were different from the previous experiments. Only one image frame showing the inducer at either a +15° or a −15° angle was presented. When the observer pressed a key, a fixation point was displayed for 493 ms, after which the inducer was presented. The test stimulus was presented for 133 ms with variable stimulus onset asynchrony (SOA) after the one-frame presentation of the inducer. Observers were asked to report the facing direction of the test stimulus like in the previous experiments. The SOA between the inducer and test was either 26, 67, 133, 256, or 520 ms. The viewing distance was a 50 cm. Observers S1, S2, S3, S12, S13 and S14 participated in this experiment.

Results

Figure 10 shows the OOI effect size as a function of the SOA. One frame showing the inducer was sufficient for OOI when the SOA was appropriate. The largest effect was found with an SOA of 67 ms, with a reduction in effect size for both shorter and longer SOAs. The large effect size for SOAs of under 100 ms indicates that the underlying mechanism is sensitive to transient signals and/or motion. This is very different
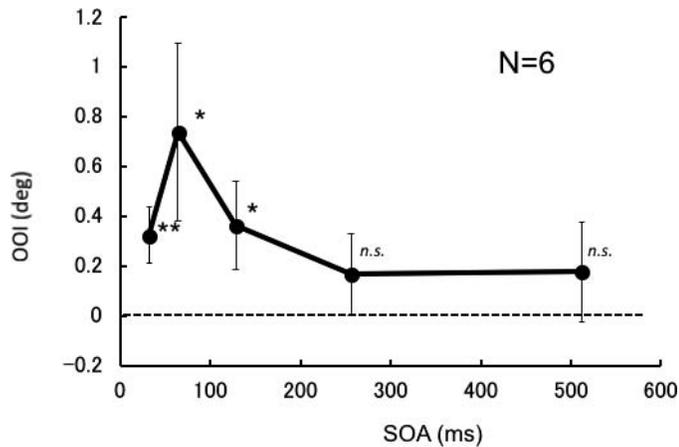
Figure 10. The object orientation induction (OOI) effect as a function of the stimulus onset delay (SOA) between inducer and test stimulus presentation. A single inducer and test stimulus was used with a presentation duration of 493 and 133 ms, respectively, with variable SOA in this experiment.

from the viewpoint aftereffect, which is found with adaptation periods as long as 5 s.

The visual system is often most sensitive to transient change at about 100 ms or 10 Hz (DeLange, 1958; Kelly, 1979a, 1979b), and the magno pathway, one of the two major neural pathway in the early vision, is thought to convey such high speed signals. The finding of the largest OOI effect with an SOA of 67 ms suggests that OOI is based on neural responses in the magno pathway instead of parvo pathway, which is thought to convey slower signals.

General discussion

The present experiments reveal a phenomenon we call object orientation induction (OOI). In the originally observed form OOI, the facing direction of a face (test stimulus) appears to shift in the direction of the rotation of a head (inducer) when the test stimulus briefly replaces the inducer. Further experiments showed that OOI is not specific to faces, and that identity between the inducer and test object is not necessary for it to occur. However, salient features to indicate the object orientation of the inducer stimulus are required and a motion signal by itself, whether lateral or in depth, is not sufficient. This also indicates that there will be little OOI effect if a facing direction of an inducer object is missing. The suitable temporal interval between the inducer and test stimulus presentation for OOI is between 50 and 100 ms, which is similar to the best temporal interval between the frames in two frame apparent motion (e.g., Shioiri & Cavanagh, 1990).

Considering all present results, we suggest that OOI is caused by the observer's continuous predictive estimation of a rotating object's orientation. When a moving object is being seen, the visual system needs to extract the moment to moment orientation of the object. This is essential for motor interaction with moving objects and to recognize the intentions of humans and animals. Because of the demand on analyzing dynamic change of object orientation quickly, it is more efficient to use fast coarse signals and not relying on detailed but slower analysis. The magnocellular-biased dorsal pathway seems to be appropriate for this purpose. As in other motion processes, the functional interpretation of OOI could be extrapolation or overshoot of the perceived direction. Since OOI requires more than just motion of the inducer, however, the extrapolation concerns more specifically the facing direction of a rotating object. We propose that for objects with an intrinsic facing direction (object orientation) there is a process to continuously estimate their facing direction during movement, which may be called a facing direction detector. We suggest this process is capable of extrapolating or predicting the future orientation of the moving object, or its intention regarding movement (for humans and animals).

In the above interpretation of OOI, we assume two factors, with which similar induction effects can be considered for object features in general. The first factor is the extraction of the facing direction of objects and integrating the extracted directions in time across different objects (inducer and test in our experiments). Integrating the facing directions of different objects can be considered as a false binding. This false binding may be expanded to any feature in general if the feature is extracted independently of other objects aspects. Indeed, a similar interpretation is possible for flash grab effect, assuming false binding of position information between motion and flash stimuli. The flashed stimulus presented closer to a feature of moving stimulus is critical for the flash grab effect (Cavanagh & Anstis, 2013).

The second factor is the perceived shift of facing direction. One interpretation of flash lag effect assumes the extrapolation of the position of moving object (Nijhawan, 1994). The position of the moving object is represented in the visual system to be ahead of the actual position so a flashed stimulus appears to be located behind the moving object in this interpretation. Although the flash lag effect cannot be explained solely by the extrapolation (Eagleman & Sejnowski, 2000; Murakami, 2001; Shioiri, Yamamoto, Oshida, Matsubara, & Yaguchi, 2010; Whitney & Murakami, 1998), there are physiological studies that suggest extrapolation process of moving objects (Berry, Brivanlou, Jordan, & Meister, 1999; Palmer, Marre, Berry, & Bialek, 2015). Such an extrapolation or prediction

process could explain the shift of facing direction of moving objects as well as position in the direction of motion. Perhaps, prediction processes at different stages are likely required for the perceived shift of different features.

The ability to dynamically detect object orientation (facing direction detector) is important, considering the demand on processing facing direction in the general sense, including human and animal faces, the front of a car, the point of sword and so on. Determining the front face of objects is used, for example, for predicting their heading direction during motion. Given the generalized and common need for detecting of the front face of different dynamic objects, it would be efficient to represent the facing direction of the attended object regardless of its specific identity. This direction can be used to estimate future location as well as future direction of the object and to decide what will be the appropriate action to take.

Although OOI could be considered as a form of false binding of object information between the inducer and the test object, the effect is obtained only when the inducing object is replaced by the test object at the same location. In other words, the effect is location-specific. The object information bound by a facing direction detector is likely sequential information from the same object. If there is indeed such a facing direction extrapolation or prediction mechanism, its application would only make sense when the test object is presented in the same location and our results suggest actually it is the case.

Keywords: object orientation, induction effect, motion 3D, object identification

Acknowledgments

References

Anstis, S. (1989). Kinetic edges become displaced, segregated, and invisible. In D. M.-K. Lam (Ed.), *Neural mechanisms of visual perception, Proceedings of the Second Retina Research Foundation Conference* (pp. 247–260). Texas: Portfolio Press.

Bar, M. (2001). Viewpoint dependency in visual object recognition does not necessarily imply viewer-centered representation. *Journal of Cognitive Neuroscience*, *13*(6), 793–799.

Bartram, D. J. (1974). The role of visual and semantic codes in object naming. *Cognitive Psychology*, *6*(3), 325–356.

Berry, M. J., II, Brivanlou, I. H., Jordan, T. A., & Meister, M. (1999, March 25). Anticipation of moving stimuli by the retina. *Nature*, *398*(6725), 334–338.

Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, *94*(2), 115–147.

Biederman, I. (2001). Recognizing depth-rotated objects: a review of recent research and theory. *Spatial Vision*, *13*(2–3), 241–253.

Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth-rotated objects: Evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(6), 1162–1182.

Booth, M. C., & Rolls, E. T. (1998). View-invariant representations of familiar objects by neurons in the inferior temporal visual cortex. *Cerebral Cortex*, *8*(6), 510–523.

Bulthoff, H. H., & Edelman, S. (1992). Psychophysical support for a two-dimensional view interpolation theory of object recognition. *Proceedings of the National Academy of Sciences, USA*, *89*(1), 60–64.

Cavanagh, P., & Anstis, S. (2013). The flash grab effect. *Vision Research*, *91*, 8–20.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology*, *36*(1), 28–71.

De Valois, R. L., & De Valois, K. K. (1991). Vernier acuity with stationary moving Gabors. *Vision Research*, *31*(9), 1619–1626.

DeLange, H. (1958). Research into the dynamic nature of the human fovea—Cortex systems with intermittent and modulated light. I. Attenuation characteristics with white and colored light. *Journal of the Optical Society of America*, *48*(11), 777–783.

Eagleman, D. M., & Sejnowski, T. J. (2000, March 17). Motion integration and postdiction in visual awareness. *Science*, *287*(5460), 2036–2038.

Edelman, S., & Bulthoff, H. H. (1992). Orientation dependence in the recognition of familiar and novel

views of three-dimensional objects. *Vision Research*, *32*(12), 2385–2400.

Fang, F., & He, S. (2005). Viewer-centered object representation in the human visual system revealed by viewpoint aftereffects. *Neuron*, *45*(5), 793–800.

Grill-Spector, K., Kushnir, T., Edelman, S., Avidan, G., Itzchak, Y., & Malach, R. (1999). Differential processing of objects under various viewing conditions in the human lateral occipital complex. *Neuron*, *24*(1), 187–203.

Hashimoto, K., Matsumiya, K., Kuriki, K., & Shioiri, S. (2010). Looking off effect—Shift of face direction caused by a rotating object. *Journal of Vision*, *10*(7):802, https://doi.org/10.1167/10.7.802. [Abstract]

Kelly, D. H. (1979a). Motion and vision. I. Stabilized images of stationary gratings. *Journal of the Optical Society of America*, *69*(9), 1266–1274.

Kelly, D. H. (1979b). Motion and vision. II. Stabilized spatio-temporal threshold surface. *Journal of the Optical Society of America*, *69*(10), 1340–1349.

Logothetis, N. K., Pauls, J., Bulthoff, H. H., & Poggio, T. (1994). View-dependent object recognition by monkeys. *Current Biology*, *4*(5), 401–414.

Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. San Francisco: Freeman and Company.

Murakami, I. (2001). A flash-lag effect in random motion. *Vision Research*, *41*(24), 3101–3119.

Nijhawan, R. (1994, July 28). Motion extrapolation in catching. *Nature*, *370*(6487), 256–257.

Palmer, S. E., Marre, O., Berry, M. J., II, & Bialek, W. (2015). Predictive information in a sensory population. *Proceedings of the National Academy of Sciences, USA*, *112*(22), 6908–6913.

Poggio, T., & Edelman, S. (1990, January 18). A network that learns to recognize three-dimensional objects. *Nature*, *343*(6255), 263–266.

Ramachandran, V. S., & Anstis, S. M. (1990). Illusory displacement of equiluminous kinetic edges. *Perception*, *19*(5), 611–616.

Shioiri, S., & Cavanagh, P. (1990). ISI produces reverse apparent motion. *Vision Research*, *30*(5), 757–768.

Shioiri, S., Kobayashi, M., Matsumiya, K., & Kuriki, I. (2018). Spatial representations of the viewer's surroundings. *Scientific Reports*, *8*(1), 7171.

Shioiri, S., Yamamoto, K., Oshida, H., Matsubara, K., & Yaguchi, H. (2010). Measuring attention using flash-lag effect. *Journal of Vision*, *10*(10):10, 1–1, https://doi.org/10.1167/10.10.10. [PubMed] [Article]

Thompson, P. (1980). Margaret Thatcher: A new illusion. *Perception*, *9*(4), 483–484.

Tsuchiai, T., Matsumiya, K., Kuriki, I., & Shioiri, S. (2012). Implicit learning of viewpoint-independent spatial layouts. *Frontiers in Psychology*, *3*, 207.

Whitney, D., & Cavanagh, P. (2000). Motion distorts visual space: Shifting the perceived position of remote stationary objects. *Nature Neuroscience*, *3*(9), 954–959.

Whitney, D., & Murakami, I. (1998). Latency difference, not spatial extrapolation. *Nature Neuroscience*, *1*(8), 656–657.

Wichmann, F. A., & Hill, N. J. (2001). The psychometric function: II. Bootstrap-based confidence intervals and sampling. *Perception & Psychophysics*, *63*(8), 1314–1329.