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A depth illusion supports the model of General Object Constancy: Size and depth constancies related by a same distance-scaling factor

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ABSTRACT

Perceptual constancy refers to the ability to stabilize the representation of an object even though the retinal image of the object undergoes variations. In previous studies, we proposed a General Object Constancy (GOC) hypothesis to demonstrate a common stabilization mechanism for perception of an object's features, such as size, contrast and depth, as the perceived distance varies. In the present study, we report another depth illusion supporting the GOC model. The stimuli comprised pairs of disks moving in a pattern of radial optic flow. Each pair consisted of a white disk positioned upper left to a dark disk, creating a percept of the white disk casting a shadow. As the pairs contracted towards the center of the screen in accordance with motion away from the observer, the two disks in each pair appeared to increase in contrast and separate farther away from each other both in the fronto-parallel plane (angular separation illusion) and in depth (depth separation illusion). While the contrast illusion and the angular separation illusion, which is a variant of the size illusion, replicated our previous findings, the illusion of depth separation revealed a depth constancy phenomenon. We further confirmed that the size and depth perception were related, e.g., the depth separation and the angular separation illusions were highly correlated across observers. Whereas the illusory increase in the angular separation between a disk and its 'shadow' could not be canceled by modulation of depth, decreasing the angular separation could offset the illusory increase in depth separation. The results can be explained by the GOC hypothesis: the visual system uses the same scaling factor to account for contrast, size (angular separation), and depth variations with distance; additionally, the perceived size of the object is used to scale its depth and contrast signals in order to achieve constancy.

1. Introduction

Perceptual constancy is a vital visual ability. Humans need to construct a stable and meaningful representation of objects in order to identify and interact with them. However, the retinal image of an object is constantly changing due to the continuous environmental changes. Perceptual constancy allows us to perceive the features of an object to be constant, even though the retinal image of the object undergoes variations. For example, size constancy is one of the constancy phenomena associated with variations in viewing distance (Boring, 1964; Carlson, 1962; Gregory, 1963). To stabilize the size perception of an object as viewing distance changes, researchers proposed that an estimate of distance can be used to compensate for the associated change in retinal image size (Boring, 1940; Epstein, 1963; Epstein, Park, & Casey, 1961; Kaufman et al., 2006; Qian & Yazdanbakhsh, 2015; Qian, Liu, & Lei, 2016). If distance estimation goes wrong, a size illusion occurs. A number of related size illusions, e.g., the moon illusion and the Ponzo illusion, are presumably due to the misapplied scaling of the size – distance relationship (Dees, 1966; Gregory, 1963; Kaufman & Kaufman, 2000; Ross, 1967; Ross, 2000).

Similarly to the object's size, the depth profile of an object varies with the viewing distance as well. It is often encoded as different depth cues on the retina. For example, the perceived depth change may result from variations in binocular disparity, which is approximately the inverse of the square of viewing distance (Foley, 1980; Wallach & Zuckerman, 1963). Although there were controversies (Johnston, 1991; Norman, Todd, Perotti, & Tittle, 1996; Todd & Norman, 2003), previous research has found that an object's depth profile is perceived to be almost invariant (with a tendency of underestimation) across various viewing distances, as long as observers could get an accurate estimation of the distance (Allison, Gillam, & Vecellio, 2009; Collett, Schwarz, & Sobel, 1991; Glennerster, Rogers, & Bradshaw, 1998; Ritter, 1977; Ritter, 1979). These revealed a depth constancy phenomenon.

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Compared to size constancy, research findings on the magnitude of depth constancy were less consistent over far distances. For example, Palmisano et al. found that the average depth-interval estimates of two depth-separated LEDs were 59% of the actual interval at a viewing distance of 20 m and 52% at a distance of 40 m, suggesting an overall underestimation but considerable constancy of the perceived relative depth over these two large viewing distances (Palmisano, Gillam, Govan, Allison, & Harris, 2010). In an earlier study, Cormack showed that depth constancy was nearly perfect up to 27 m (Cormack, 1984). However, the study was criticized for the use of a depth probe, since the probe might serve as a reference for comparing various depth cues. Despite these inconsistencies, it is widely accepted that the phenomenon of depth constancy exists as we encounter it in everyday life.

Estimation of perceived distance is crucial to size and depth constancies. Binocular disparity and oculomotor depth cues are usually more effective at near distances, typically within two meters (Campbell, 1957; Hillis, Watt, Landy, & Banks, 2004; Ono & Comerford, 1977). For example, Bradshaw, Parton, and Glennerster (2000) asked observers to set the depth interval between two test LEDs at 1.5 m or 3 m to equal the depth interval between a pair of comparison LEDs, and found that observers performed equally well when depth information was supplied by disparity, by motion parallax, or by both cues. Monocular depth cues, such as occlusion, linear perspective, familiar size, and motion parallax, could contribute to depth perception at much greater distances. Studies showed that long-range linear perspective cues could even override the contradictory binocular disparity cues (O'leary & Wallach, 1980; Wallach & Zuckerman, 1963). In addition to these visual cues, optic flow may affect depth perception as well, which often conveys important depth information through interactions between the observer and the environment. A study showed that adding stereoscopic cues, or changing-size cues to an optic flow pattern significantly increased the forward linear vection in foveal vision, suggesting that both changing-size and stereoscopic depth cues could provide additional motion-in-depth information that improves distance perception (Palmisano, 1996).

Our previous studies showed that a radial optic flow pattern consisting of disks moving towards/away from the center of the display could induce illusory variations in the perceived distance, which could further trigger visual illusions resulting from the constancy mechanisms (the StarTrek illusions, Qian & Petrov, 2012; Qian & Petrov, 2013). For example, both the size and the contrast of the moving disks appeared to increase with the apparent distance (Qian & Petrov, 2012). Based on the correlation found between the contrast illusion and the size illusion, we proposed the General Object Constancy (GOC) model. This model posits that in order to achieve the veridical perception of an object's feature, the same factor is used to scale various retinal metrics, such as contrast, size, and depth, as a function of perceived distance. Consistent with the model, several studies showed that perceived size and depth are related by a common distance scaling factor (Collett et al., 1991; Rogers & Bradshaw, 1993; van Damme & Brenner, 1997). In the current study, we investigated an illusion of depth separation by employing a new version of the StarTrek illusion paradigm. We found a strong correlation between the perceived angular separation and the perceived depth separation of the stimuli, supporting the GOC model.

2. Material and methods

2.1. Participants

Twenty-six observers with normal or corrected-to-normal vision were tested. Twenty-three of the observers were naive to the purpose of the study; only three were experienced psychophysical observers. Observers were trained for a short time (2–5 min) to get acquainted with the stimuli and the task. This research was approved by the Northeastern University Institutional Review Board (IRB), and was in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Written informed consent approved by the IRB was provided by each participant prior to the experiment.

2.2. Stimuli

We employed a pattern of radial optic flow to evoke perceived viewing distance changes. Similar to our previous experiments (Qian & Petrov, 2013), the optic flow stimuli were viewed through a Wheatstone stereoscope on a pair of linearized 21" ViewSonic G225f monitors. The frame rate was 75 Hz. The display resolution was set to 1600×1200 pixels; and for the typical viewing distance of 110 cm, a pixel subtended 1 arcmin.

The stimulus was a set of high-contrast disk pairs randomly located on a gray background. In the peripheral part of the display, disks formed a static stencil mask providing a depth reference plane. The mask had a 10° circular aperture positioned at the center of the display. Through the aperture, the observers saw pairs of disk moved in a pattern of radial optic flow (Fig. 1, the left panel). The optic flow could be perceived as the disks being positioned on a fronto-parallel plane moving back and forth with a constant speed. The magnitude of the motion corresponded to the disks moving farther away to 220 cm, i.e., twice the distance to the screen. At the beginning of each trial, 100 pairs of disks were displayed. As the disks moved towards the center of the screen, additional disks filled in along the boundary of the aperture from behind the occluding mask and continued to move in the pattern of optic flow. The observers perceived the disks to be moving farther away as they moved towards the center while the density of the disks increased. We referred to this motion phase as 'stimuli contraction'. The motion phase where disks moved away from the center and therefore appeared to move towards the observer was referred to as 'stimuli expansion' (Qian & Petrov, 2012, 2013). Each pair of disks comprised a white .05° disk positioned upper left to a dark disk of the same size but with a softer edge. This created a percept of a white disk casting a shadow. The angular separation between the white disk and the dark disk within a pair was .3°. An interpretation of 'disks casting shadows' was suggested to the observers, therefore the stimulus was referred to as "disks casting shadows".

At the beginning of each trial in Experiment 1, 2 and 4, a relative disparity of .02° was added between the disks and their shadows by using a Wheatstone stereoscope. This relative disparity corresponded to a depth interval of 0.65 cm at the viewing distance of 110 cm, creating a vivid three-dimensional percept of the "disks casting shadows". No relative disparity was applied in Experiment 3. The radial optic flow pattern was used to create a percept of viewing distance variation in Experiment 1–3. In Experiment 4, additional binocular disparity modulation, consistent with the viewing distance variation conveyed by the optic flow, was applied globally to all moving disks using the stereoscope. Therefore, the motion of the disks was defined by both the optic flow pattern and the binocular disparity modulation in this experiment. The observers carried out 300 trials for each condition. Each trial lasted for 2 s, including one contraction–expansion motion cycle of the optic flow.

2.3. Psychometric procedure

Before the experiment the observers viewed a short demonstration in which the relative disparity between the disks and their