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Perceived speed differences explain apparent compression in slit viewing

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A B S T R A C T

When a figure moves behind a stationary narrow slit, observers often report seeing the figure as an integrated whole, a phenomenon known as slit viewing or anorthoscopic perception. Interestingly, in slit viewing, the figure is perceived compressed along the axis of motion, e.g., a circle is perceived as an ellipse. Underestimation of the speed of the moving object was offered as an explanation for this apparent compression. We measured perceived speed and compression in anorthoscopic perception and found results that are inconsistent with this hypothesis. We found evidence for an alternative hypothesis according to which apparent compression results from perceived speed differences between different parts of the figure, viz., the trailing parts are perceived to move faster than the leading parts. These differences in the perceived speeds of the trailing and the leading edges may be due to differences in the visibilities of the leading and trailing parts. We discuss our findings within a non-retinotopic framework of form analysis for moving objects.

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1. General introduction

In human vision, the three-dimensional structure of an object is mapped through the optics of the eye onto a two-dimensional retina creating a *retinotopic image* of the object. The connections from the retina to the early visual areas of the brain are topographic in that, neighboring points on the retina project to neighboring points in the early visual areas, a property known as *retinotopy* (Sereno et al., 1995; Tootell, Silverman, Switkes, & De Valois, 1982). Neurons in these retinotopic areas analyze a visual scene locally through their retinotopically anchored receptive fields. Although this type of local processing may explain how form information is processed for static objects, it falls short when it comes to the analysis of form of moving objects. Moving objects activate retinotopically-localized neurons along the path of motion for a limited time which may not be sufficient for a complete analysis. The analysis of the form of moving objects becomes even harder in natural viewing conditions due to constant occlusions imposed by surrounding moving or stationary objects. These observations suggest that *non-retinotopic computational mechanisms* are needed to process the form of moving objects. In fact, psychophysical data show that a retinotopic image is neither necessary nor sufficient for the perception of form. One of the paradigms showing that the existence of a retinotopic image is not sufficient for the perception of form is visual masking (reviews: Bachmann, 1994; Breitmeyer & Öğmen, 2000, 2006). In this paradigm, a target can be rendered invisible by a retinotopically *non-overlapping* mask which is presented in the temporal vicinity of the target (*para-* or *metacontrast* masking). Slit viewing or anorthoscopic perception is an example showing that a retinotopic image is not necessary for the perception of form. When a figure moves behind a stationary narrow slit, observers often report seeing the figure as an integrated whole although each slice of the figure excites the same area on the retina (Parks, 1965; Zöllner, 1862), i.e., there is no spatially extended retinotopic image.

Helmholtz (1867/1962) argued that anorthoscopic percepts are merely the artifacts of ongoing eye movements, i.e., observers unconsciously track the figure when the figure moves behind the slit. Each successive slice of the figure is painted onto nearby positions on the retina. In support of this *retinal painting hypothesis*, Helmholtz (1867/1962) claimed that with proper fixation, a unified percept of the figure is not seen (see also Anstis & Atkinson, 1967; Haber & Nathanson, 1968).

A century after Helmholtz's studies, Parks (1965) re-visited this question by presenting observers a line drawing of a camel as it oscillated behind a vertical slit (Fig. 1). He reported that given proper stimulus conditions, the camel figure would appear as a whole in the vicinity of the slit, even in the absence of any eye movements. As a mechanism, he suggested that each part of the figure must be temporarily stored in a *post-retinal storage* and the whole figure must be integrated spatially by reading from this storage according to a "time-of-arrival coding".

Later studies also cast substantial doubt on the adequacy of the retinal painting hypothesis as the *exclusive* mechanism for anorthoscopic perception (Fendrich & Mack, 1980, 1981; Fendrich,

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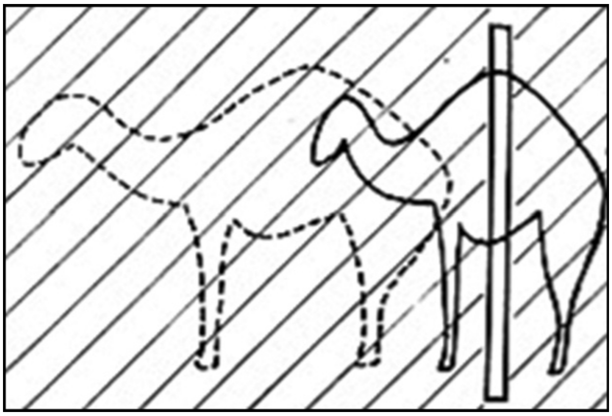

Fig. 1. Parks' camel. If a tall narrow slit (1 mm wide × 40 mm high) is cut in an opaque material, and then a black-on-white outline drawing of a camel (25 mm high × 40 mm long, dashed outline) is passed behind the stationary slit, "Observer will see the picture as a whole appearing briefly in the vicinity of the slit" (Parks, 1965, p. 145). Parks (1965) also reports that the camel appears foreshortened along the direction of movement (solid outline). Adapted from Parks (1965).

Rieger, & Heinze, 2005; Fujita, 1990; McCloskey & Watkins, 1978; Morgan, Findlay, & Watt, 1982; Nishida, 2004; Rieger, Grüschow, Heinze, & Fendrich, 2007; Rock, 1981; Sohmiya & Sohmiya, 1992, 1994). Under free-viewing conditions, anorthoscopic percepts cannot be accounted for by spontaneous pursuit eye movements (Fendrich et al., 2005; Rieger et al., 2007). On the other hand, these results also do not completely dismiss the possibility that anorthoscopic percepts can be generated or facilitated by a deliberate pursuit. In fact, Morgan et al. (1982) proposed a hybrid model in which an anorthoscopic percept can be the outcome of either a retinal painting or post-retinal process depending on the stimulus conditions, such as presence or absence of eye movements and slit width.

Despite the controversial debate about the underlying mechanisms of slit viewing, there is agreement that the target figure appears compressed along the axis of motion, e.g., as seen in Fig. 1, a camel is perceived foreshortened in the horizontal direction (Anstis & Atkinson, 1967; Haber & Nathanson, 1968; Helmholtz, 1867/1962; McCloskey & Watkins, 1978; Morgan et al., 1982; Parks, 1965; Rock, 1981; Rock & Sigman, 1973; Zöllner, 1862). Advocates of the retinal painting hypothesis have suggested that this distortion results from the failure of observers to move their eyes in perfect synchrony with the figure (Anstis & Atkinson, 1967; Haber & Nathanson, 1968; Helmholtz, 1867/1962). However, a recent study showed that under free-viewing conditions, the apparent figure compression is not related to either pursuit or saccadic eye movements and is unaffected by spontaneous tracking eye movements (Rieger et al., 2007). Another explanation for the apparent compression was proposed by Rock (1981). According to his argument, the speed and the direction of the figure are ambiguous (Shimojo & Richards, 1986). He argued that the perceived length of the figure depends entirely on its perceived speed and the apparent compression results from the *underestimation* of the actual physical speed.

Here, we directly tested Rock's hypothesis by measuring the perceived speed and the perceived width of an outlined ellipse moving behind a slit (Experiment 1). Contrary to Rock's hypothesis, the results of this experiment showed that the magnitude of the compression cannot be explained by the underestimation of the speed of the figure. In Experiment 2, we tested our alternative hypothesis which states that the apparent compression of a figure in slit viewing results from differential perceived speeds of its parts. In Experiment 3, we investigated the role of visibility in perceiving the different parts with different speeds. Finally, the results are discussed in a general theoretical framework for the analysis of form of moving objects.

2. General methods

Visual stimuli were generated via the visual stimulus generator card (VSG 2/3) manufactured by Cambridge Research Systems. The card was programmed by using its driver library and the stimuli were displayed on a 19-in. color monitor set at a resolution of 656 × 492 with a refresh rate of 100 Hz (Experiment 1 and 2) or at a resolution of 800 × 500 with a refresh rate of 160 Hz (Experiment 3). The distance between the monitor and the observer was 91 cm at which the screen covered a 25° by 19° visual area. The room in which the experiments were conducted was dimly illuminated by the light coming from the image on the screen. A chin rest was used to aid the observer to keep his/her head still while fixating his/her eyes on the fixation point displayed at the center of the monitor. The visual stimuli were presented on a uniform background. Practice sessions were run before the experimental sessions in order to familiarize the observer with the apparatus and the task. The results of the practice sessions were not included in the data analysis. Behavioral responses were recorded for offline analysis via a joystick connected to the computer which drives the VSG card. Details of the stimuli will be given in the methods of specific experiments.

Participants were two of the authors (M.A. and H.Ö.) and four volunteers who were naive to the purpose of the experiments. The age of the participants ranged from 17 to 49 years. All participants had normal or corrected-to-normal vision. The experiments were undertaken with the permission of The University of Houston Committee for the Protection of Human Subjects. Informed consent was obtained from the participants before the experiments were conducted.

3. Experiment 1: The perceived speed and width of an ellipse moving behind a slit

3.1. Introduction

As mentioned, there are several theories to explain the apparent compression of a figure moving behind a slit (Anstis & Atkinson, 1967; Rock, 1981; Zöllner, 1862). One such theory states that the perceived width of the figure depends entirely on its perceived speed and the apparent compression results from the underestimation of its actual physical speed (Rock, 1981). We tested this hypothesis by measuring the perceived speed and width of a figure moving behind a slit.

3.2. Methods

The perceived speed of an ellipse moving behind a slit was measured by using the method of constant stimuli (Fig. 2). The test ellipse, with a major axis of 7.1° and a minor axis of 5°, moved behind the slit with three different speeds: 3.6, 7.1, and 10.7°/s. The direction of motion of the test ellipse (rightward or leftward) was randomized from trial to trial. The center of the slit (21.3 arcmin wide and 6.4° tall) was presented 3.55° below the fixation point. To map the psychometric function, a comparison ellipse with the same dimensions as the test moved with five different speeds for each value of the test speed: (i) 1.8, 3.6, 5.3, 7.1, and 8.9°/s for the test speed of 3.6°/s, (ii) 5.3, 7.1, 8.9, 10.7, and 12.4°/s for the test speed of 7.1°/s, and (iii) 8.9, 10.7, 12.4, 14.2, and 16°/s for the test speed of 10.7°/s. The values of the comparison ellipse were chosen according to pilot experiments. The direction of motion of the comparison ellipse, which was presented simultaneously with the test ellipse, was always opposite to that of the test in order to eliminate possible position cues in speed judgments. The motion of the comparison ellipse, unlike the test, was fully visible from start to end and was centered 3.55° above the fixation point. The test and the comparison ellipses were black (4 cd/m^2) on a white background (40 cd/m^2). The luminance of the background on which the slit was cut was 20 cd/m^2. The task of the observer was to report whether the test or the comparison ellipse appeared to move faster. After mapping the psychometric functions, the speed of the comparison ellipse that yielded a 50% faster-or-slower response level was calculated and taken as a point