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Solving the Aperture Problem: Perception of Coherent Motion

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SOLVING THE APERTURE PROBLEM:
PERCEPTION OF COHERENT MOTION

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By
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ABSTRACT

The aperture problem describes an effect by which a contoured stimulus, moving behind an aperture with both ends occluded, appears to move in a direction perpendicular to its own orientation. Mechanisms within the human visual system allow us to overcome this problem and integrate many of these locally ambiguous signals into the perception of globally coherent motion. In the current experiment, observers viewed displays composed of many straight contours, arranged in varying orientations and moving behind apertures. The total pattern of movement was consistent with a globally coherent trajectory. Observers were asked to estimate direction of global motion over a range of 0 to 360 degrees. Given a greater number of motion signals (i.e., 64 motions within apertures), younger adults can reliably and accurately judge coherent motion direction with an average error below 10 degrees. For fewer motion signals (i.e., 9 motions within apertures), younger adults exhibit greater error in their direction judgments.

Key words: aperture problem, motion perception, coherent motion

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Norman, J. F., Adkins, O. C., Dowell, C. J., Shain, L. M., Hoyng, S. C., & Kinnard, J. D. (2017). The visual perception of distance ratios outdoors. *Attention, Perception, & Psychophysics*. doi: 10.3758/513414-017-1294-9.

O’Connor, S. S., Shain, L. M., Whitehill, J. M., & Ebel, B. E. (2017). Measuring a conceptual model of the relationship between compulsive cell phone use, in-vehicle cell phone use, and motor vehicle crash. *Accident Analysis & Prevention, 99*, 372-378. doi: 10.1016/j.aap.2016.12.016.

PRESENTATIONS

Norman, J. F., Adkins, O. C., Dowell, C. J., Shain, L. M., Hoyng, S. C., & Kinnard, J. D. (2017, May). *The outdoor perception of distance ratios*. Poster presented at the Vision Sciences Society Annual Meeting. St. Pete Beach, FL.

Shain, L. M. & O’Connor, S. S. (2015, March). *Compulsive cell phone use and history of motor vehicle crash*. Poster presented at the WKU Student Research Conference. Bowling Green, KY.

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INTRODUCTION

Almost constantly, animals move relative to their surroundings or their environment moves relative to them. Therefore, the perception of motion is, an ability that is essential for avoiding danger, detecting food, and living an effective life. Through the use of photoreceptors in the retina, light signals from the environment are converted into neuronal sensory responses. Specific patterns of photoreceptor activity enable the detection of object motion. Current understandings of the mechanisms by which motion is detected are based on the Reichardt detector model (Barlow & Levick, 1965; Reichardt, 1961; van Santen & Sperling, 1985). This model (see Figure 1) incorporates a delay and compare mechanism in which light is detected by a photoreceptor (imagine a light object moving against a dark background), but its signal is delayed temporally. The light object moves (e.g., to the right) and is then detected by a second photoreceptor. Because the neural activity from the first photoreceptor was delayed, the two neural signals (from the photoreceptors) arrives simultaneously at a subsequent neural level. This simultaneous activity being detected enables the perception of motion. This model of a motion detector was first developed by Werner Reichardt (1961) based upon studies with beetles. The overall model was later explored by Barlow and Levick (1965), who studied neuronal responses in rabbit retinas. More recent psychophysical studies have further investigated the parameters of this model (e.g., Koenderink, van Doorn, & van de Grind, 1985; Todd & Norman, 1995; van de Grind, Koenderink, & van Doorn, 1986). The span between photoreceptors and the magnitude of the time delay determine the specific speed of motion that is detected by a particular Reichardt detector. If only one configuration of motion detector existed (i.e., a fixed span and magnitude of temporal delay), human observers, and other animals, would be able to detect only one specific speed. However, these psychophysical studies (Koenderink, et al., 1985; Todd & Norman, 1995;

van de Grind et al., 1986) have determined that there are multiple spans and temporal delays to enable the detection of a wide range of speeds, and that the delay parameter for a majority of motion detectors tuned for velocities above 10 degrees per second is approximately 50 milliseconds.

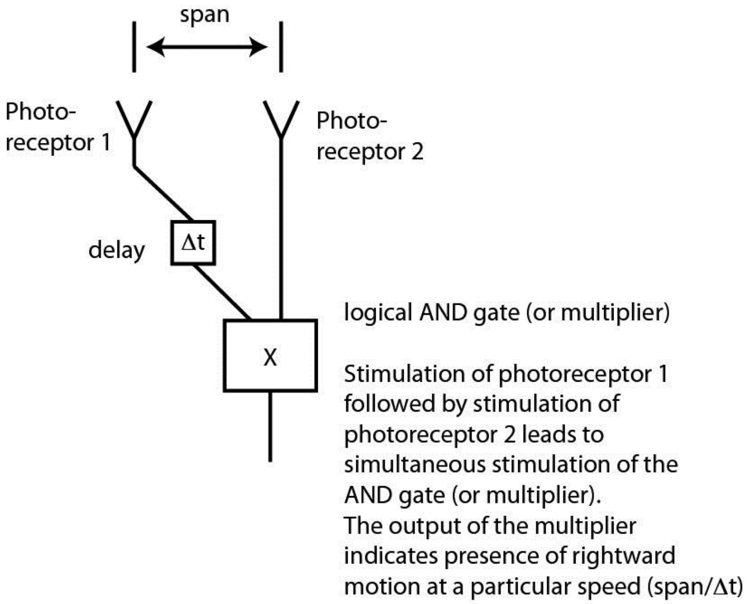

Figure 1. The Reichardt detector model

Any motion detector, since it samples motion over a limited part of the visual field, is subject to the "aperture problem." This is because the detector is "looking" out at the world through an aperture (the diameter of the aperture would equal the span indicated in Figure 1). Consider an extended object contour passing across a motion detector's receptive field, or span. Such a contour would appear to move only in a direction perpendicular to the contour orientation. Because the component of motion parallel to the contour cannot be perceived, the true direction of motion is indistinguishable. Figure 2 demonstrates this effect. It depicts a polygonal figure moving to the right behind an occluding surface; only parts of the object (3 outer boundary contours) are visible through apertures. Although the object moves directly rightward, the visible contours themselves only move perpendicular to their own orientations.

This “aperture problem” has been appreciated for decades (Marr & Ullman, 1981; Wallach, 1935). Due to their small receptive fields, individual motion-sensitive neurons within the visual system are subject to the aperture problem whenever they are activated by a contoured stimulus. Each of these cells can only measure the component of motion perpendicular to a presented edge.

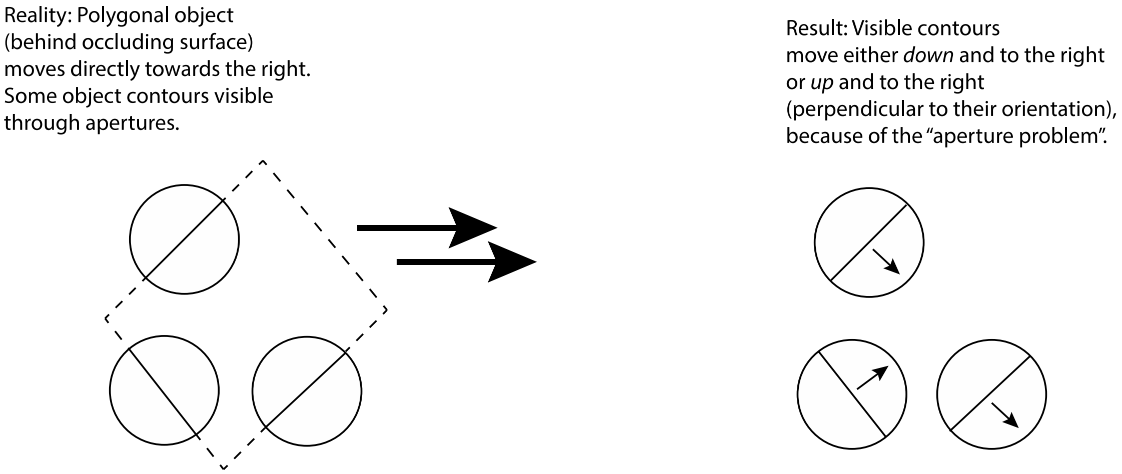

Figure 2. Despite the true rightward direction of motion of the polygonal object shown to the left, each of the three visible contours only moves perpendicular to its own orientation.

Because single neurons cannot detect the true directions of motion of extended object contours, mechanisms must exist within the visual system that reduce the ambiguity so that we can perceive coherently moving environmental objects. Consider the right half of Figure 2: in this example, there are three local motion signals, but *none* of them correctly signify the direction of object motion. Two motion detectors indicate that the object is moving *down* and to the right, while one detector indicates that the object is moving *up* and to the right. However, by integrating locally ambiguous motion signals, it is possible to determine the actual direction of object motion. One combination rule involves an “intersection of constraints” (IOC, see Adelson & Movshon, 1982). Another possibility involves vector averaging (Mingolla et al., 1992; Wilson, Ferrera, & Yo, 1992). Notice, for example, that if one averages the two lower local motion signals shown in the figure, one can determine the true direction of object motion (pure rightward motion). Evidence currently exists to support both IOC and vector averaging combination rules. While it is clear that no single type of combination rule can account for all of the empirical data collected to date, it is nevertheless clear that spatial averaging of locally ambiguous motion signals allows human observers to visually perceive coherent object motion (Amano, Edwards, Badcock, & Nishida, 2009). The purpose of the current experiment is to determine exactly how well younger adults can perceive the direction of object motion from sets of locally ambiguous motion signals.

METHOD

Stimulus Displays

The study utilized a methodology resembling that used by Mingolla et al. (1992). The experimental stimuli consisted of numerous circular apertures displayed on a computer monitor. Two density conditions were used. In one condition, 64 total apertures (8 rows by 8 columns) were shown, while the other condition displayed a total of nine apertures (3 rows by 3 columns). Each aperture contained a linear contour in a random orientation. Because of the aperture problem, the contour within each aperture only moved perpendicular to its orientation. However, the aggregate stimulus motion was consistent with the motion of a single pattern that was moving coherently in a particular, or true, direction. The true direction was chosen on each trial from a set of 12 different directions (0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, & 330 degrees from vertical).

Apparatus

The moving patterns were created by an Apple PowerMacintosh G4 computer and were displayed on a 22-inch Mitsubishi Diamond Plus 200 color monitor (resolution: 1280 × 1024 pixels). The viewing distance was 100 cm.

Procedure

Each stimulus configuration was displayed to observers for 2.4 seconds. Each of the twelve direction conditions was displayed to observers five times under each of the two density conditions, such that there were 120 trials total (12 x 5 x 2). After viewing each stimulus, the observers were asked to judge the direction of coherent motion by adjusting an arrow’s orientation on the computer monitor such that it pointed along the perceived direction of motion. Observers were given the ability to fine-tune their judgments to a precision of 1 degree.

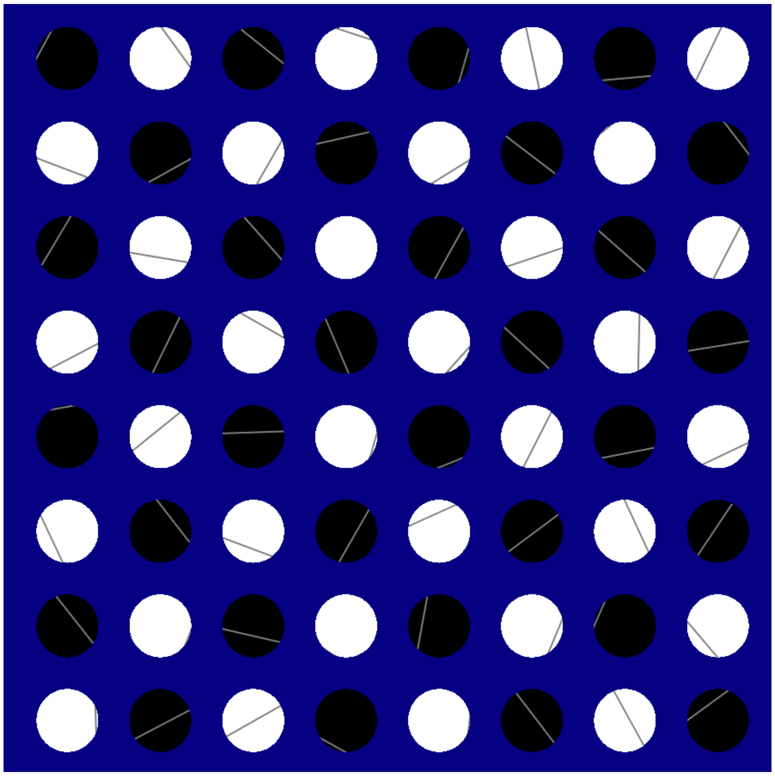

Figure 3. 64 aperture condition.

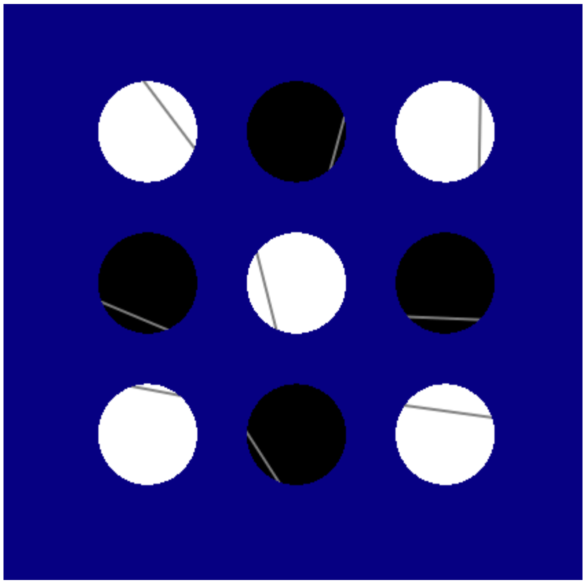

Figure 4. 9 aperture condition.

Observers

The stimulus displays were shown to five younger female adults (mean age = 21.6 years). The observers' visual acuities were all normal or corrected-to-normal. All observers gave written consent before participation in the experiment.

RESULTS

The results for a representative observer are shown in figures 3 and 4. All of the observers performed very similarly. As can be seen from the slopes of the best-fitting regression lines and the correlation coefficients provided in the figures, younger adults are very accurate when judging the global direction of motion, particularly when numerous motion signals (i.e., 64 motions) are displayed. For the five observers, Pearson r correlation coefficients reflecting the relationship between actual global motion direction and the judged motion directions when 64 motion signals were presented were: 0.992, 0.993, 0.997, 0.990, and 0.993. The analogous Pearson r correlation coefficients for the nine aperture condition were: 0.972, 0.985, 0.957, 0.947, and 0.973 (all correlations, $p < 0.000001$). From these results, it is clear that not only can young observers make very accurate judgments, but they can also (very) reliably judge the direction of global motion across repeated trials. A two-way Analysis of Variance (ANOVA; both factors, aperture density and direction of motion, were within-subjects) revealed a significant effect of aperture density on the observers' errors in direction estimation (i.e., error between actual and estimated direction of motion, $F(1,4) = 16.1$, $p < 0.02$; $\eta^2_p = 0.80$). However, no significant effect of stimulus direction upon the observers' errors was obtained ($F(11,44) = 1.1$, $p = 0.4$; $\eta^2_p = 0.21$). There was no significant interaction between density and stimulus motion direction (($F(11,44) = 0.8$, $p = 0.6$; $\eta^2_p = 0.17$). The average errors between the actual and estimated direction of motion for all five observers was 8.8 degrees and 20.8 degrees for the 64 and nine aperture conditions, respectively.

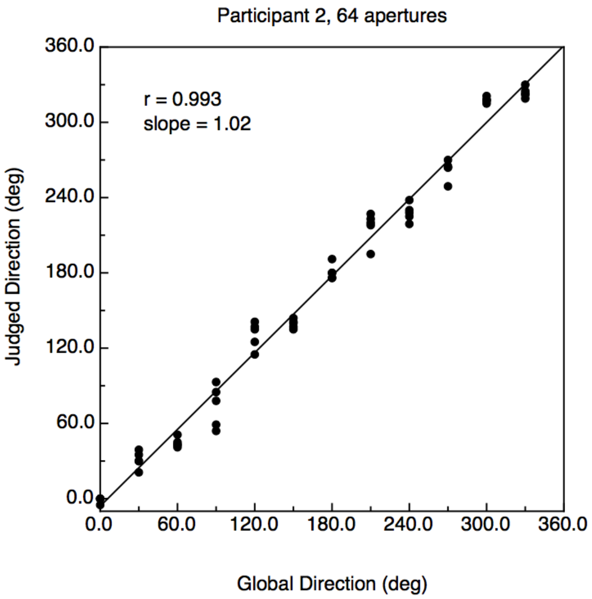

Figure 5. Correlation between actual global direction and judged direction of motion for the 64 aperture condition.

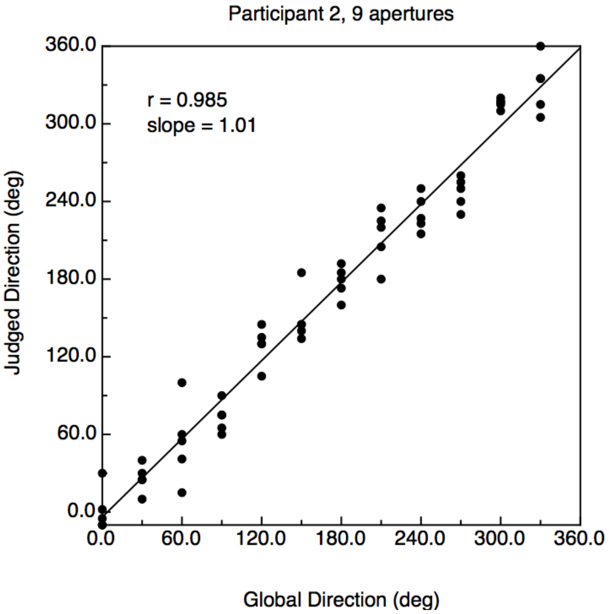

Figure 6. Correlation between actual global direction and judged direction of motion for the 9 aperture condition.

DISCUSSION

While the combination rules required to overcome the aperture problem and perceive coherent direction of stimulus motion have been studied for years (e.g. Adelson & Movshon, 1982; Mingolla et al., 1992), the ability of young observers to estimate specific directions of global motion from many locally ambiguous motion signals has been unstudied until now. The results of the present experiment provide insight into this ability, demonstrating that younger observers can both reliably and accurately judge coherent motion direction from locally ambiguous signals. Interestingly, the observers' errors in direction estimation do not vary across the stimulus range of zero to 330 degrees. Observers are equally capable of determining the true direction of motion whether that motion direction is oblique or aligned in a more cardinal direction. The observers' errors increased only when the number of ambiguous motion signals was reduced from 64 to nine. However, younger observers are still capable of making accurate judgements for both density conditions (i.e., slopes of best-fitting regression lines were always near 1.0).

Age-related deteriorations have been demonstrated for many aspects of motion perception, such as the perception of speed (Norman, Burton, & Best, 2010; Norman, Ross, Hawkes, & Long, 2003), the perception of 3-D shape from motion (Norman, Bartholomew, & Burton, 2008; Norman et al., 2013; Norman, Clayton, Shular, & Thompson, 2004), and the perception of biological motion (Norman, Payton, Long, & Hawkes, 2004). Therefore, it is possible that the ability to estimate coherent motion direction from locally ambiguous motion signals might also deteriorate with increases in age. In the present experiment, we only evaluated the performance of younger observers. Future research should examine motion direction estimation performance for older adults. Such a study would provide additional important information about the perceptual abilities of older adults.

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