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Luminance-contrast properties of contour-shape processing revealed through the shape-frequency after-effect

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Abstract

We investigated the first-order inputs to contour-shape mechanisms using the shape-frequency after-effect (SFAE), in which adaptation to a sinusoidally modulated contour causes a shift in the apparent shape-frequency of a test contour in a direction away from that of the adapting stimulus [Kingdom F. A. A., & Prins N. (2005a). Different mechanisms encode the shapes of contours and contour-textures. *Journal of Vision* 5(8), 463, (Abstract)]. We measured SFAEs for adapting and test contours (and edges) that differed in the contrast-polarity, scale (or blur) and magnitude of luminance contrast. The rationale was that if the SFAE was found to be reduced when adaptor and test differed along a particular dimension of luminance contrast, contour-shape mechanisms must be tuned to that dimension. Our results reveal that SFAEs manifest (i) a degree of selectivity to luminance contrast polarity for both even-symmetric (contours only) and odd-symmetric (both contours and edges) luminance profiles; (ii) a degree of selectivity to luminance scale (or blur); (iii) higher selectivity to fine compared to coarse scale for broadband edges (iv) a small preference for equal-in-contrast adaptors and tests. These results suggest that contour shapes are not encoded in the form of a sparse, cartoon-like sketch, as might be presumed by local energy (i.e. non-phase-selective) or form-cue invariant models, but instead in a form that is relatively 'feature-rich.'

Keywords: Contour-shape; Adaptation; Shape-frequency after-effect; Contrast-polarity; Blur; Contrast

1. Introduction

Psychophysical and neurophysiological studies have suggested that shape processing involves a hierarchy of mechanisms located at different levels in the visual cortex, from low (DeValois & DeValois, 1988; Koenderink & Richards, 1988; Wilson, 1991; Wilson & Richards, 1989) to intermediate (Gallant, Braun, & van Essen, 1993; Gallant, Connor, Rakshit, Lewis, & van Essen, 1996; Habak, Wilkinson, Zahker, & Wilson, 2004; Keeble & Hess, 1999; Levi & Klein, 2000; Pasupathy & Connor, 2002; Regan & Hamstra, 1992) and high levels (Gross, 1992; Ito, Fujita, Tamura, & Tanaka, 1994; Tanaka, 1996).

Much of the psychophysical evidence regarding shape processing is based on the detection and discrimination of shapes such as sinusoidal-shaped contours (Tyler, 1973), curved contours (Kramer & Fahle, 1996; Watt & Andrews, 1982; Wilson & Richards, 1989, 1992), chevrons (Wilson, 1986), radial frequency patterns (Habak et al., 2004; Hess, Wang, & Dakin, 1999; Loffler, Wilson, & Wilkinson, 2003; Wilkinson, Wilson, & Habak, 1998) and dot-defined squares (Regan & Hamstra, 1992). Other psychophysical studies have investigated shape processing via shape after-effects (Anderson, Habak, Wilkinson, & Wilson, 2005; Anderson & Wilson, 2005; Kingdom & Prins, 2005a, 2005b; Regan & Hamstra, 1992; Suzuki, 2001, 2003; Suzuki & Cavanagh, 1998). A shape after-effect refers to the alteration in the perceived shape of a pattern following adaptation to a slightly different pattern, and is assumed to reflect changes in the activity of neurons that code for shape. Some shape after-effects are assumed to implicate global shape mechanisms because they transfer across size (Regan & Hamstra, 1992; Suzuki & Cavanagh, 1998) or are attention-dependent (Suzuki, 2001, 2003).

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In spite of the fact that the adaptation patterns in these studies were static, various control experiments make it unlikely that the after-effects were caused either by after-images or adaptation to local orientation, as was shown some time ago to be the case for curvature adaptation using static adaptors (Blakemore & Over, 1974; Stromeyer & Riggs, 1974).

Kingdom and Prins (2005a, 2005b) demonstrated a novel after-effect termed the *shape-frequency after-effect*, or SFAE, using a non-static adaptation stimulus. They showed that adaptation to a sinusoidal-shaped contour causes a shift in the perceived shape-frequency of a test contour in a direction away from that of the adapting stimulus. The SFAE is the shape analog of the well-known spatial-frequency after-effect found with luminance gratings (Blakemore & Sutton, 1969). The SFAE occurs even though the shape-phase of the adaptation stimulus is randomized every half second during the adaptation period. The reader can experience the SFAE in Fig. 1. If one moves ones' eyes back and forth along the marker between the pair of adapting contours on the left for about a minute, and then shifts gaze to the spot on the right, the two test contours, which have the same shape-frequency, should appear different in shape frequency. Thus adaptation to a contour of a given shape-frequency makes a lower-shape-frequency test contour appear lower in shape-frequency and a higher-shape-frequency test contour appear higher in shape-frequency. A movie demonstration of the SFAE can be found at http://www.mvr.mcgill.ca/Fred/research.htm#contourShapePerception.

What mechanisms mediate the SFAE? The SFAE occurs even though the shape-phase of the adaptation contour is randomly changed every half second during adaptation. This might be taken to imply that the effect could not be mediated by the tilt after-effect (TAE) because the orientation content of the adaptor at any one visual location is constantly changing. However, the geometrical relationships between adaptor and test are such that the TAE cannot on a priori grounds be ruled out. Recently however, in a preliminary report, Kingdom and Gheorghiu (2006) have shown that sine-wave-shaped adaptors induce equal-sized SFAEs in square-wave-shaped not just sine-wave-shaped tests. At any one visual location the set of possible orientations from a phase-randomized sine-wave adaptor will always be such as to produce equal and opposite TAEs in the oriented segments of a square-wave test, and so local TAEs would simply cancel. Hence, the TAE is unlikely to be the cause of the SFAE. Kingdom and Gheorghiu (2006) also found sizeable SFAEs from adaptor and test pairs that had the same global average curvature, thus ruling out global average curvature as the spatial feature underlying the SFAE. They also ruled out global spatial frequency and density (e.g. see Durgin, 1996, 2001; Durgin & Proffitt, 1996; Durgin & Huk, 1997) by showing that the perceived spacing/density of an array of identically oriented elements was unaffected by adaptation to the sine-wave-shaped contour. Finally, Kingdom and Gheorghiu (2006) showed that SFAEs reached asymptotic levels when the test contour was gated down to just half a cycle of shape modulation centered on the peak or trough. This suggests that the SFAE operates locally on contour segments that have constant sign of curvature. Thus the SFAE is likely mediated by intermediate-level curvature detectors that lie beyond those responsible for local orientation and positional adaptation, but prior to those involved in global shape analysis.

The cross-sectional luminance profiles of natural contours and edges can vary in luminance phase, scale (or blur) and contrast. Models of early human vision designed to detect contours and edges invariably use operators that are sensitive to these luminance attributes; for example bandpass filters tuned to spatial frequency. However, the extent to which information about the luminance profile is preserved for higher visual functions, such as shape processing, is not at all well understood. Some models, termed here 'feature-rich' explicitly represent the luminance scale and luminance phase of contour/edge segments for higher stages of processing (Hesse & Georgeson, 2005; Marr, 1982; Marr & Hildreth, 1980; Watt, 1988; Watt & Morgan, 1985). Other models, termed here 'feature-agnostic,' do not represent luminance phase for higher stages of processing, for example those based on local contrast energy (e.g. Moronne & Burr, 1988—see Section 7 for details).

The evidence for visual mechanisms that are selective for luminance phase comes mainly from studies that have measured phase discrimination at contrast threshold for line-like, edge-like and gabor stimuli (reviewed by Huang, Kingdom, & Hess, 2006). In general, studies of luminance phase discrimination have restricted themselves to phases represented by opposite contrast-polarities of edge-like and bar-like stimuli, and from now on our discussions of luminance phase will be couched in terms of contrast polarities. With regard to shape perception, contrast-polarity consistency has been shown to be an advantage for illusory contour perception (He & Ooi, 1998), and contrast-polarity specificity has been demonstrated for the luminance spatial frequency after-effect (Blake, Overton, & Lema-Stern, 1981; Blakemore & Sutton, 1969; Burton, Nagshineh, & Ruddock, 1977; DeValois, 1977a, 1977b; Fiorentini, Baumgartner, Magnusson, Schiller, & Thomas, 1990), but not for the tilt after-effect (Magnussen & Kurtenbach, 1979). However to our knowledge no study has investigated whether contour-shape mechanisms are contrast-polarity-tuned.

With regard to luminance scale, or blur, this is by definition important for edge blur perception (Hesse & Georgeson, 2005; Watt & Morgan, 1985), and generally assumed to be an important factor for both edge detection (Marr, 1982; Marr & Hildreth, 1980; Watt & Morgan, 1985) and the reconstruction of an image from an edge representation (Elder & Sachs, 2004). For shape, Wilson and Richards (1989) have shown that curvature discrimination thresholds for contours were unimpaired by high-pass but impaired by low-pass luminance filtering. On the other hand, Hayes, Kingdom, and Prins (2002) found that the