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Discrimination of rotated-in-depth curves is facilitated by stereoscopic cues, but curvature is not tuned for stereoscopic rotation-in-depth

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ABSTRACT

Object recognition suffers when objects are rotated-in-depth, as for example with changes to viewing angle. However the loss of recognition can be mitigated by stereoscopic cues, suggesting that object coding is not strictly two-dimensional. Here we consider whether the encoding of rotation-in-depth (RID) of a simple curve is tuned for stereoscopic depth. Experiment 1 first determined that test subjects were sensitive to changes in stereoscopic RID, by showing that stereoscopic cues improved the discrimination of RID when other spatial cues to RID were ineffective. Experiment 2 tested directly whether curvature-sensitive mechanisms were selective for stereoscopic RID. Curvature after-effects were measured for unrotated test curves following adaptation to various RID adaptors. Although strong adaptation tuning for RID angle was found, tuning was identical for stereo and non-stereo adaptors. These findings show that while stereoscopic cues can facilitate three-dimensional curvature discrimination, curvature-sensitive mechanisms are not tuned for stereoscopic RID.

1. Introduction

In normal viewing our visual system must handle a range of image transformations to achieve object recognition. Typical transformations include changes to an object's size, brightness, colour, retinal position and viewpoint. Changes in viewpoint occur every time we, or the object, moves, and numerous studies have reported that the accuracy and speed of object recognition suffers as a result (Bennett & Vuong, 2006; Bulthoff, Edelman, & Tarr, 1995; Burke, 2005; Burke, Taubert, & Higman, 2007; Edelman & Bulthoff, 1992; Lim Lee & Saunders, 2011; Parr, Siebert, & Taubert, 2011). However, stereoscopic cues to the object's 3D (three-dimensional) structure can reduce the costs of viewpoint change (Bell, Dickinson, & Badcock, 2008; Bennett & Vuong, 2006; Bulthoff, Edelman, & Tarr, 1995; Burke, 2005; Burke, Taubert, & Higman, 2007; Lim Lee & Saunders, 2011), supporting the idea that object encoding is not strictly 2D (two-dimensional).

The current study extends that literature by considering the role of stereoscopic cues when encoding viewpoint-rotated shapes. The shape of an object is a powerful cue to its recognition (Attneave, 1954; Bertamini, 2008; Biederman, 1987; Hayworth & Biederman, 2006; Hoffman & Richards, 1984; Hoffman & Singh, 1997; Loffler et al., 2005; Pasupathy & Connor, 2002; Wilkinson, Wilson, & Habak, 1998). Moreover, the curves in an object's outline are more important for recognition than the straight lines. The importance of curves is made explicit in several recent models of shape and/or object perception (Connor, 2004; Pasupathy & Connor, 2002; Poirier & Wilson, 2006, 2010; Yamane et al., 2008).

Previous research, including our own, has examined the selectivity of curvature mechanisms for an orientation change in the 2D plane (Bell, Gheorghiu, & Kingdom, 2009; Timney & Macdonald, 1978). Tight selectivity is reported, with curvature after-effects abolished when a 45° orientation difference between adaptor and test is introduced. This is interpreted as evidence for independent processing of curves with distinct 2D orientations. For higher level objects such as faces, researchers have examined how strongly configural face after-effects (contraction and expansion of internal features) transfer across changes in viewpoint that are consistent with a rotation-in-depth (RID) (Jeffery, Rhodes, & Busey, 2006). Jeffery et al. report that such higher level after-effects persist and are in fact greater than half strength despite a 90° rotational difference between adaptor and test, in other words that they display broad viewpoint tuning. Here we measure the RID selectivity of curvature mechanisms. We aim to compare our findings with analogous studies involving higher level objects such as faces (Jeffery, Rhodes, & Busey, 2006), and to compare RID selectivity in the 3D plane with the reported selectivity for curvature orientation in the 2D plane (Bell, Gheorghiu, & Kingdom, 2009; Timney & Macdonald, 1978).

The primary aim of this communication is to determine whether contour curvature mechanisms are tuned for stereoscopic

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RID. In order to test for such tuning, we first establish that humans are *sensitive* to stereoscopic RID in our stimuli. To do this we use a same/different task to measure thresholds for detecting a difference in the RID angle of two curves, with and without stereoscopic cues. Having shown that human observers are able to use stereoscopic cues to discriminate between curves with different RIDs, we go on to ask whether curvature mechanisms are tuned to stereoscopic RID. To address this question we used an adaptation paradigm in which we measure the size of a curvature after-effect, or CAE (Bell, Gheorghiu, & Kingdom, 2009) as a function of the difference in the RID angle between adaptor and test curves. If the CAE is significantly reduced when adaptor and test have different RIDs we conclude that the human visual system is selective for stereoscopic RID.

2. General methods

2.1. Participants

Nine experienced psychophysical observers participated in the current study. Seven were naïve as to the experimental aims, whilst observers JB and JK were authors. All had normal or corrected-to-normal visual acuity. Each observer's stereo acuity was tested using the Stereo Fly and Stereo Butterfly Test made by Stereo Optical Co., Inc., Chicago. All observers had a stereo acuity better than 40 seconds of arc. Participation was voluntary and unpaid.

2.2. Apparatus and stimuli

Stimuli were created using Matlab version 7.6, and loaded into the frame-store of a Cambridge Research Systems (CRS) ViSaGe video-graphics system. Stimuli were presented on a Sony Trinitron G400 monitor with a screen resolution of 1024 × 768 pixels and a refresh rate of 100 Hz. The luminance of the monitor was calibrated using an Optical OP200-E (Head Model # 265). In all conditions, stimuli were viewed through an 8-mirror stereoscope. The mean luminance of the stimuli as measured through the stereoscope was 34 cd/m^2. The viewing distance through the stereoscope was 55 cm, resulting in each pixel subtending 2′ of visual angle. Prior to testing each observer performed a series of judgments in a control program, whereby they adjusted the horizontal distance between a pair of fixation crosses presented separately to the left and right eye until binocular fusion was achieved. This measurement was then used in the actual experiments.

Example test stimuli are shown in Fig. 1. Each curve represents a half cycle of a sinusoidal shape modulation along the horizontal, producing an inverse U-shaped curve. A contrast smoothing function was applied to each end of the contour to minimise orientation cues at the ends. Each curve was defined by its 'cord' and 'sag', corresponding to the shape-frequency and shape-amplitude of the sinusoidal shape from which the curve was derived. The cross-sectional luminance profile of each contour was a Gaussian with sigma equal to 0.12°.

2.3. Rotation-in-depth

Curves were rotated about their vertical axis, compressing the horizontal dimension of the contour in the fronto-parallel plane. The foreshortening was consistent with a change in horizontal viewing angle (Bell, Dickinson, & Badcock, 2008). In the stereo conditions the curves were rotated-in-depth stereoscopically by presenting a different rotation angle to each eye (+ and − the mean RID angle) (see free fusible examples in Fig. 1: bottom row). In our stereo conditions, all observers reported a vivid impression that the curves were physically rotated-in-depth. The stereoscope was also used in the non-stereo conditions; however in these cases the RID was the same in each eye.

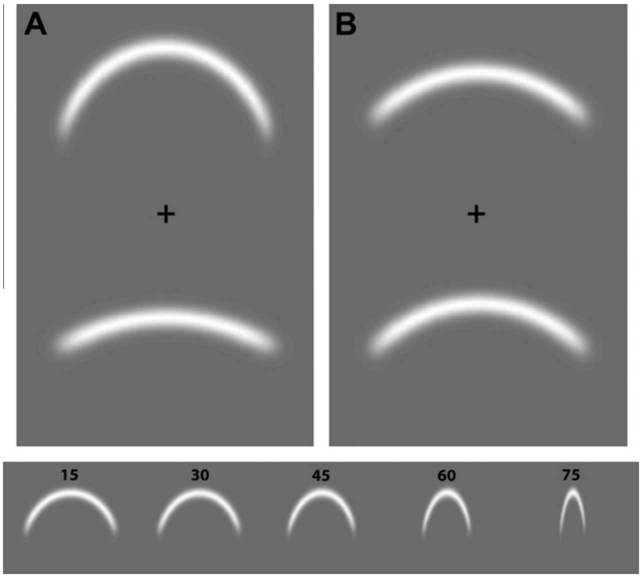

Fig. 1. Curvature after-effect (CAE) and example stimuli. The reader can experience the curvature after-effect by staring at the fixation cross on the left for at least 30 s and then switching their gaze to the fixation cross on the right, where they are likely to perceive the upper curve to be lower in amplitude (more flat) than the lower curve, and *vice versa*. The bottom row (left to right) shows examples of curves with different rotation-in-depth (RID) angles. If the reader free fuses adjacent patterns they may experience the RID stimuli in stereoscopic depth. The RID curves are all identical in their 'sag' i.e. amplitude (0.72°), which is equal to the high amplitude unrotated adaptor in the top left of figure.

3. Experiments

3.1. Experiment 1: Sensitivity to stereoscopic rotation-in-depth of a simple curve

In this experiment we employed a same/different task to measure thresholds for detecting a difference in RID angle, and compared thresholds with and without stereoscopic cues. We employed a 2IFC (two-interval forced-choice) same/different task (Kingdom & Prins, 2010) rather than conventional 2IFC task so that observers did not have to learn a reference RID angle, nor judge a particular direction of RID angle change. Each trial consisted of two intervals with two curves per interval, i.e. four stimuli per trial. In the reference interval the two curves had the same RID angle (45°) while in the test interval the two curves had different RID angles, and the observer had to choose the interval with the different RID angles. The two curves in each interval were presented 3° above and 3° below a central fixation dot. The method of constant stimuli was employed with 7 RID angle differences. The RID angle difference in the test interval was always symmetrical about 45°, which was also the RID angle of both curves in the reference interval. Each of the seven conditions was presented 20 times, in random order, giving a total of 140 trials per run. A minimum of 4 runs were completed for each observer in each condition, resulting in 560 responses from each observer per condition. The range of RID angle differences was adjusted for each observer in order to obtain a full psychometric function (∼ = 50–100% accuracy). A Logistic function was fit to the data to obtain an estimate of the threshold difference in RID angle corresponding to 75% correct. In Experiment 1a (fixed parameters) the unrotated shape frequency of the curves was set to 0.325c/° and the amplitude of modulation was fixed at 0.4°. In Experiment 1b, both parameters of the curve