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Imagining circles – Empirical data and a perceptual model for the arc-size illusion

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ABSTRACT

An essential part of visual object recognition is the evaluation of the curvature of both an object's outline as well as the contours on its surface. We studied a striking illusion of visual curvature – the arc-size illusion (ASI) – to gain insight into the visual coding of curvature. In the ASI, short arcs are perceived as flatter (less curved) compared to longer arcs of the same radius. We investigated if and how the ASI depends on (i) the physical size of the stimulus and (ii) on the length of the arc. Our results show that perceived curvature monotonically increases with arc length up to an arc angle of about 60°, thereafter remaining constant and equal to the perceived curvature of a full circle. We investigated if the misjudgment of curvature in the ASI translates into predictable biases for three other perceptual tasks: (i) judging the position of the centre of circular arcs; (ii) judging if two circular arcs fall on the circumference of the same (invisible) circle and (iii) interpolating the position of a point on the circumference of a circle defined by two circular arcs. We found that the biases in all the above tasks were reliably predicted by the same bias mediating the ASI. We present a simple model, based on the central angle subtended by an arc, that captures the data for all tasks. Importantly, we argue that the ASI and related biases are a consequence of the fact that an object's curvature is perceived as constant with viewing distance, in other words is perceptually scale invariant.
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1. Introduction

Curvature is an important feature of objects that is ubiquitous in natural scenes. Evidence for the existence of specialized detectors for curvature in the visual system (Watt, 1984; Watt & Andrews, 1982; Wilson & Richards, 1989) is supported by the observation that curvature is an adaptable feature (Arguin & Saumier, 2000; Gheorghiu & Kingdom, 2007, 2008, 2009; Hancock & Peirce, 2008). Furthermore, curvature has been hypothesized to play an important role in building object representations (Loffler, 2008; Wilson & Wilkinson, 2015). Many studies investigating curvature perception have focused on circles or circular segments, which are a special class of curves. Circularity has been the subject of many studies (see Loffler, 2008 for review) and it has been suggested that it plays a special role in contour detection (Achtman, Hess, & Wang, 2003), texture detection (Motoyoshi & Kingdom, 2010) and Glass pattern detection (Wilkinson, Wilson, & Habak, 1998; Wilson, Wilkinson, & Asaad, 1997), *cf* (Dakin & Bex, 2002 and Schmidtmann, Jennings, Bell & Kingdom 2015).

Given the importance of curvature for object detection and recognition, it may be surprising that curvature is misperceived in certain circumstances. Some studies find evidence for an overestimation of curvature (Coren & Festinger, 1967; Piaget & Vurpillot, 1956) – in this case subjects tend to perceive circular arcs as more curved than circles. Other studies have found an underestimation of curvature, at least for short arcs (Virsu, 1971b,a; Virsu & Weintraub, 1971). Virsu (1971b) asked observers to compare the curvature of drawn arcs with a set of reference circles of varying radius, and found a consistent underestimation of curvature for arcs up to about 72°. For longer arcs, curvature estimation became veridical. This underestimation of curvature for short arcs is convincingly demonstrated in the "Arc-size Illusion" (ASI), shown in Fig. 1. In this simple geometric illusion, short arcs are perceived as flatter (less curved) compared to longer arcs of the same radius (Virsu, 1971b; Virsu & Weintraub, 1971).

According to Virsu (1971a) this underestimation of curvature is caused by the observers' tendency to produce straight eye movements (see Section 4 for details).

Here we employ a novel experimental method to measure and quantify the ASI. We then consider whether the misperception of curvature in the ASI underpins three other tasks that involve

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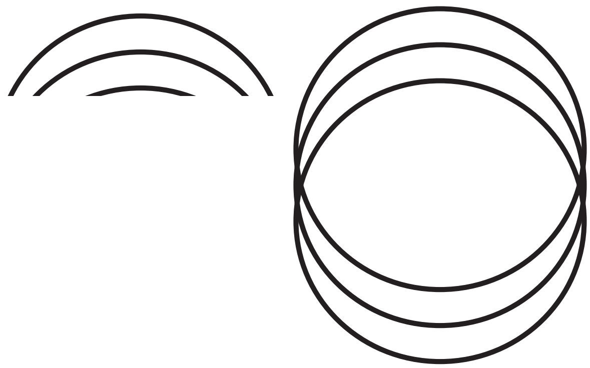

Fig. 1. The arc-size illusion. In this illusion, arcs of the same radius (i.e. curvature) are perceived as flatter the shorter the size of the arc. The arcs on the left all have the same radius and therefore the same curvature. They are segments of the circles on the right. Observers typically describe shorter (e.g. innermost) arcs as flatter than longer ones (e.g. outermost).

curvature judgments: judgments of the centre of a circular arcs, alignment judgments of two circular arcs, and interpolation judgements of curvature. Based on the results, we suggest a model for curvature perception and offer a functional explanation of the ASI in terms of perceptual scale invariance.

2. Methods

2.1. Subjects

Four subjects participated in this study. Two of the observers (IE and MO) were naïve as to the purpose of the experiments. All observers had normal or corrected-to-normal visual acuity. Experiments were carried out under binocular viewing conditions. No feedback was provided during practice or during the experiments. Informed consent was obtained from each observer; and all experiments were conducted in accordance with the Declaration of Helsinki.

2.2. Apparatus

The stimuli were generated within the MatLab (MatLab R 2013a, MathWorks) environment and presented on a calibrated, gamma-corrected "Iiyama Vision Master Pro 513" CRT monitor with a resolution of 1024 × 768 pixels and a frame rate of 85 Hz (mean luminance 38 cd/m^2) under the control of an Apple Mac Pro (3.33 GHz). Observers viewed the stimuli at distance of 120 cm. At this distance one pixel subtends 0.018°. Experiments were carried out under dim room illumination. Routines from the Psychophysics Toolbox were employed to present the stimuli (Brainard, 1997; Pelli, 1997).

2.3. Stimuli

Stimuli were circles and circular arcs with radii of $r = 1°$, 2° and 3° of visual angle. Curvature was defined as $1/r$. Circular arcs were created by applying a pie-wedge shaped mask to the circles. In Experiment 1, where observers had to match the curvature of a test arc to that of a reference circle, the curvature of the circular arcs could be varied by altering their radii. In Experiments 2 to 4, observers had to judge the position of the centre of a circular arc (Exp 2), the position of a second arc so that it fell on the (invisible) circle given by a first arc (Exp 3), or the position of an interpolated point on the circumference of an (invisible) circle given two arcs (Exp 4). In these tasks, the circular arc remained fixed and the position of a reference dot (Exp 2 and 4) or the position of one of the arcs could be altered.

To create circular arcs of variable length, the contrast of the circle along its circumference was ramped down by half a Gaussian either side of the arc centre according to Schmidtmann, Kennedy, Orbach, and Loffler (2012).

The cross-sectional luminance profile of all stimuli was defined by a fourth derivative of a Gaussian with a peak spatial frequency of 8 c/° (Wilkinson et al., 1998) (Fig. 2).

2.4. Procedure

2.4.1. Experiment 1 – Arc-size illusion

Using the Method of Adjustment (MOA), observers were asked to adjust the curvature of a test arc of fixed arc length to the curvature of a complete reference circle of given radius. There were three different reference radii R_{ref} of 1°, 2° and 3° (visual angle), and these were interleaved in each experimental session.

The reference circle was presented in the top half of the display (Fig. 3A), the test arc in the bottom half. The horizontal position of both stimuli was varied randomly and independently on each trial within the range ±0.18° (100 pixels) from the centre of the screen. The arcs were presented vertically and to the left of their centres. The initial radius of the test arc was randomly determined within the range ±50% of the radius of the reference circle. Subjects adjusted the curvature of the test arcs by increasing or decreasing their radius until it matched that of the reference circle. They indicated their point of subjective equality (PSE) by pressing a key on a numeric keypad. Coarse (3 pixels steps = 0.0054°) or fine changes (1 pixel steps = 0.0018°) could be applied to adjust the radius, using different keys on a numeric keypad. Eleven different arc lengths, ranging between an angular extent of $\theta = 22.5°$ (16th of a circle) and 360° (full circle) were tested. Each of the 11 different arc lengths was tested 20 times in an experimental block. The stimulus design is illustrated in Fig. 3A. Observers completed three blocks for each experiment and the results from the blocks were averaged.

2.4.2. Experiment 2 – Estimation of the centre of an arc's circle

Using the MOA, the observers' task was to estimate the centre of the underlying circle of the arc, termed here the 'centre-point' (Fig. 3B). Each arc was positioned at the centre of the screen with a vertical and horizontal positional jitter of (±0.18°). The arcs were always presented on the left side (at 9 o-clock) of the centre of the screen. Observers positioned a white dot (2 × 2 pixels) where they estimated the centre-point. The white test dot was initially presented with a random horizontal offset within ±0.072° from the true centre-point. The dot was always positioned with zero vertical offset and observers only had to adjust the horizontal position of the dot (Fig. 3B). In all of the following experiments, coarse (0.0054°) or fine adjustments (0.0018°) of the centre-point could be applied by pressing different keys on a numeric keypad. As in Experiment 1, 11 different arc lengths ranging from $\theta = 22.5–360°$ were tested. Each arc length was tested 20 times.

2.4.3. Experiment 3 – Aligning two circular arcs

Observers were presented with two opposing arcs of the same arc lengths, placed at 3 and 9 o-clock (Fig. 3C). The arc pair was positioned at the centre of the screen with a random vertical and horizontal offset of ±0.18°. One arc (9 o-clock) remained fixed while observers adjusted the position of the other arc so that it appeared to fall on the circumference of the (invisible) circle given by the fixed arc. The second arc was initially positioned at a random location relative respect to its veridical position within ±0.072°. In order to avoid overlap of the two opposing arcs only seven different arc lengths, ranging from $\theta = 22.5–135°$ were tested

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