Shape constancy measured by a canonical-shape method

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ABSTRACT
Shape constancy is the ability to perceive that a shape remains the same when seen in different orientations. It has usually been measured by asking subjects to match a shape in the frontal plane with an inclined shape. But this method is subject to ambiguity. In Experiment 1 we used a canonical-shape method, which is not subject to ambiguity. Observers selected from a set of inclined trapezoids the one that most resembled a rectangle (the canonical shape). This task requires subjects to register the linear perspective of the image, and the distance and inclination of the stimulus. For inclinations of 30° and 60° and distances up to 1 m subjects were able to distinguish between a rectangle and a trapezoid tapered 0.4°. As the distance of the stimulus increased to 3 m, linear perspective became increasingly perceived as taper. In Experiment 2 subjects matched the perceived inclination of an inclined rectangle, in which the only cue to inclination was disparity, to the perceived inclination of a rectangle with all depth cues present. As the distance of the stimulus increased, subjects increasingly underestimated the inclination of the rectangle. We show that this pattern of inclination underestimation explains the distance-dependent bias in taper judgments found in Experiment 1.

Keywords: Shape constancy, perspective, binocular disparity

1. Introduction

When a flat object is rotated out of the frontal plane the shape of its retinal image changes. Simple shape constancy refers to the ability to perceive that a flat object remains the same shape when seen in different orientations relative to the frontal plane. Shape constancy depends on the accurate registration of the shape of the retinal image and of the orientation of the object with respect to the frontal plane (Fig. 1). The orientation, in turn, can be estimated from depth cues such as perspective and stereopsis.

For a shape defined only by its outline, perspective can be divided into linear perspective (where parallel edges or lines extending in depth project to converging lines in a perspective projection) and foreshortening (aspect ratio). Fig. 2a shows the perspective produced by inclining a rectangle about a horizontal axis. In the absence of other depth cues, perspective provides

information about inclination[1] only for certain shapes. Linear perspective, but not foreshortening, provides information about inclination for shapes with parallel sides but no specified ratio of width to height, such as a rectangle. In our experiments we were concerned only with linear perspective produced by an outline rectangle.
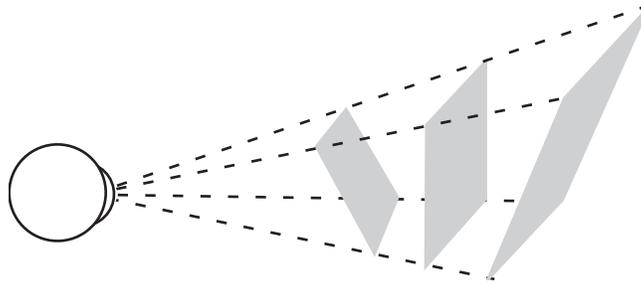

Fig. 1. A frontal rectangle produces the same retinal image as any inclined trapezoid that fills the same visual pyramid. The greater the inclination of the object, the more tapered it must be to produce the same image as the rectangle.
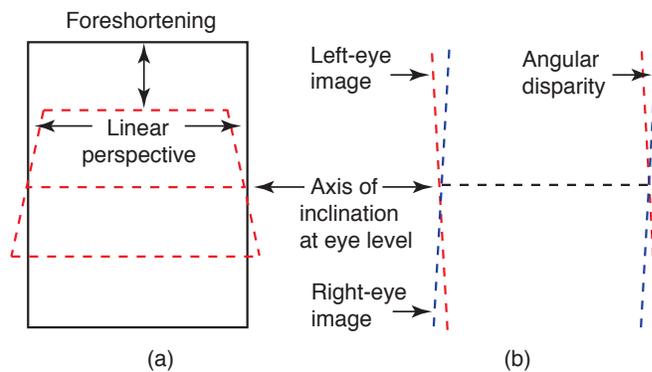

(a)   (b)

Fig. 2. (a) The linear perspective and foreshortening produced by an inclined rectangle. The dashed shape is the projection of the inclined rectangle onto the frontal plane. The projections of the parallel sides of an inclined rectangle are tapered due to linear perspective and the extensions of these projections intersect at an angle, p, which describes the taper due to perspective. (b) The angular disparity produced by the left and right edges of an inclined rectangle.

Binocular disparity (differential perspective) provides information about inclination for all shapes. However, the disparity signal is strong for shapes such as rectangles, and weak for circles due the large amount of vertically-oriented contour in the former from which angular disparity can be reliably extracted. An inclined rectangle produces an angular disparity between the left and right sides, as shown in Fig. 2b. However, angular disparity is inversely proportional to viewing distance and must therefore be scaled by distance. The angle of convergence of the eyes

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[1] The term *inclination* here refers to rotation of a surface in depth about a horizontal axis (slant with a surface-tilt angle of 90° in Steven's (1983) parameterization).

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and the associated accommodation provide the only cues to the distance of an outline shape viewed in dark surroundings. Several investigators have reported that people are reasonably accurate at judging the distance of an object within arm's reach when the only cue to distance is the angle of convergence. When subjects pointed with an unseen hand to a disc of light at vergence-specified distances of 25, 30, or 40 cm they were accurate to within 1 cm (Swenson, 1932). However, judgments of distance become more variable as distance increases. For example, the variability of setting an unseen rod to the same distance as a binocularly viewed vertical rod increased as vergence-specified distance increased from 30 to 100 cm (Tresilian, Mon-Williams, & Kelly, 1999).

In the absence of all depth information it is not possible to judge the true shape of any object because its image could arise from any combination of shape and orientation that projects that image, as illustrated in Fig. 1. This geometrical relationship between shape and orientation prompted Koffka (1935) to propose that an error in the perceived inclination of a flat object is accompanied by a corresponding error in the judged shape of the object. This is known as the shape-inclination invariance hypothesis.

Shape constancy has been the subject of much investigation and controversy but a comprehensive review is beyond the scope of this paper (for a recent review see Howard, 2012, pp 137-144). Shape constancy progressively fails as cues for 3-D orientation of the stimulus are weakened (Thouless, 1931; Joynson & Newson, 1962). However, experiments to prove the shape-inclination invariance hypothesis quantitatively have produced variable results because they suffered from procedural problems (Epstein & Park, 1963). One problem is that when asked to judge the shape of a frontal ellipse a person may state that it is a circle because most elliptical images arise from circles. But when asked to judge the orientation of the ellipse they may ignore its shape and concentrate on information that indicates that it is frontal[2]. A second problem is that simple shapes seen in dark surroundings appear to fluctuate over time so that a shape judgment made at one instant may have no relation to a judgment of inclination made at another instant. A third problem is that a person may correctly register the relation between two stimulus features but be unable to register the single features correctly.

Three methods have been used to measure shape constancy. Thouless (1931) described the

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[2] As a reviewer pointed out, it is conceivable that a subject could potentially show the opposite behavior, favoring a frontal interpretation for shape but not orientation judgment. We think this less likely as it deviates from norms (or priors) for both shape and orientation.

most frequently used method. Subjects select a shape in the frontal plane to match a shape inclined about a horizontal axis or slanted about a vertical axis. For example, subjects select an ellipse in the frontal plane that matches an inclined circle. Subjects typically select a frontal ellipse that is intermediate between a circle and the elliptical image of the inclined circle. Thouless referred to this as "regression to the real object".

There are two major problems with the Thouless method. Joynson (1958) pointed out that results depend on how subjects interpret the instructions. They could attempt to select a frontal shape that matches the image of the inclined shape. We will call this **image matching**. Otherwise, subjects could attempt to select a frontal shape that matches the actual inclined shape. We will call this **shape matching**. Even when subjects are instructed to respond in a certain way they may fail to follow the instructions (Kaess, 1978). The phrase "regression to the real object" presupposes that subjects are trying to match images. If they were trying to match actual shapes (shape constancy) one would have to say that they "regressed to the image"

The second problem with the Thouless method is that the frontal stimulus may be perceived inaccurately. For example, a frontal ellipse may be perceived as an inclined circle, which produces the impression that the minor axis of the elliptical image is elongated. This may occur even though other information indicates that the ellipse lies on a frontal plane. Thus one cannot know whether a failure of shape constancy arises from inaccurate perception of the inclined stimulus or of the frontal stimulus or of both. Epstein & Park (1963) reviewed these and other methodological problems with the Thouless method.

The second procedure for measuring shape constancy is to ask subjects to draw an inclined shape on a vertical surface. Thouless (1931), Clark, Smith, & Rabe (1956a), and Nelson & Bartley (1956) used this method. It is a very unsatisfactory procedure because subjects may attempt to draw in perspective rather than draw the actual shape of the inclined stimulus. In any case, most people draw an object in perspective very inaccurately even though they perceive the shape of the object accurately (Howard & Allison, 2011).

In a third procedure, which we will call the **canonical-shape method**, subjects select from a series of inclined stimuli the one that most resembles a defined shape such as a circle, cross, regular polygon, or rectangle. These are all uniquely defined (canonical) shapes. The method provides a direct measure of shape constancy and avoids ambiguities associated with comparing two shapes at different inclinations. It is highly unlikely that subjects would adopt an image matching approach in this task. While retinal shape could theoretically be judged (that is, is the

retinal image a rectangular image?), this is not natural and the subjects are explicitly instructed to report the true physical shape of the object. Furthermore, unlike the Thouless method, there is no comparison with shapes on a frontal surface; shapes that can be readily interpreted as both the physical shape or as a rendering/ projection of a shape on that frontal plane. Two investigators have used the canonical-shape method.

Stavrianos (1945) displayed a set of rectangles simultaneously on an inclined rectangular board viewed binocularly at a distance of 60 cm. The rectangles varied in height and subjects selected the one that most resembled a square. The results indicated a high level of shape constancy. As inclination was increased from 0° (vertical) to 55° the rectangle selected as square increased in height by 6% and the rectangle appeared less inclined. These results are what one would expect from shape-inclination invariance. However, the rectangular board upon which the stimuli were mounted was visible. Stavrianos admitted that this might have produced shape contrast between the board and the shapes on the board.

Saunders and Backus (2006) projected trapezoids one at a time on a frontal screen at a distance of 2 m. They were viewed monocularly. The trapezoids produced the same images as squares inclined to the frontal plane by various degrees about a horizontal axis. The trapezoid judged to be square was considerably greater in height than the image of a square. This indicates that the simulated inclination of the trapezoids was underestimated. This is not surprising because binocular cues to inclination were absent, the boundaries of the screen were visible, and subjects would have been aware that the images were projected on a frontal screen. Monocular images on a frontal screen are unsatisfactory for measuring shape constancy.

In the above two experiments, viewing distance was not varied. Therefore, effects of changing vergence or of changing binocular disparity were not investigated.

In the experiments reported here we used the canonical-shape method to measure subjects' ability to detect whether an inclined shape is rectangular rather than tapered (trapezoidal), as a function of the angle of inclination and viewing distance. The experiments were also designed to investigate whether errors in shape constancy are related to errors in perceived inclination.

2. Experiment 1: Shape constancy for an inclined rectangle as a function of inclination and distance

2.1. Method

2.1.1. Subjects

The four female and four male subjects ranged in age from 20 to 83 years. They all had normal or corrected-to-normal vision and stereoscopic acuity of at least 40 arcsec as measured by the circles Stereotest of the Stereo Optical Co. The study was approved by York University Ethics committee in accordance with standards laid down in the 1964 Helsinki Declaration. All subjects gave their informed consent.

2.1.2. Stimuli

The stimuli were composed in LibreOffice Draw and Adobe Illustrator in a computer and printed on sheets of thick white paper. The basic stimulus was a white outline rectangle on a black background. The rectangle subtended 4.6° in height by 3.5° in width and each line was 7 arcmin in width. The other stimuli were 10 trapezoids formed by tapering the rectangle 0.2°, 0.4°, 0.6°, 0.8°, or 1° upward (+) or downward (-) as indicated in Fig. 3. The taper angle was defined as the angle formed at the intersection of the right and left sides of the trapezoid. The stimuli were placed one at a time on a white electro-luminescent panel (Innolite Inc.). The panel was mounted

Rectangle   Trapezoid tapered
             1.2° downward
             (each side tilts 0.6°)

Fig. 3. The rectangle and one of the tapered trapezoids used in the experiment. The shapes were either frontal or inclined top away by 30° or 60°. They were presented one at a time at distances of 0.5, 1, 2, or 3 m with the axis of inclination (dashed line) at eye level. The shapes were scaled in size so that the retinal image was the same size at all distances.

on a board in a chamber 3 m long lined with black velvet. Nothing was visible other than the white outline stimulus. The luminance of the white outline was 0.82 candelas/m^2 and that of the dark surround was 0.002 candelas/m^2. We used an electro-luminescent panel rather than a computer screen because it is not possible to produce straight lines tilted at small angles on a

computer screen without reducing sharpness by anti-aliasing and, at a near viewing distance, pixels provide information about inclination. Also, an electroluminescent panel is flat and lightweight.

Each stimulus was viewed binocularly with its centre at eye level in the median plane of the subject's head, which was stabilized on a chin and forehead rest.

The distal stimulus variables were the distance of the stimulus (50, 100, 200, and 300 cm), the inclination of the stimulus about a central horizontal axis (0˚, 30˚, and 60˚), and the taper of the lateral sides of the stimulus with respect to parallel (+1˚ to -1˚ in steps of 0.2˚). The stimulus was inclined by physically rotating the electroluminescent panel in depth about its central horizontal axis.

The following proximal stimulus variables were available to the subject:

Linear perspective in the image of the stimulus

Consider a perspective projection of the stimulus through a station point located midway between the two eyes of the subject. We define the image of a stimulus as the shape it projects onto a frontal plane passing through the mid-horizontal axis of the stimulus, as shown in Fig. 2a. The relative tilt between the left and right sides of each image had two components (1) The taper of the stimulus (+1˚ to -1°) and (2) the linear perspective produced by inclination. The linear perspective can be defined by the angle, p, formed at the intersection of the extended projections of the two sides of an inclined rectangle in the image (the vanishing point). If the rectangle is W cm wide at distance D and inclined i degrees about its mid-horizontal axis, then p is given by (Perrone & Wenderoth, 1991):

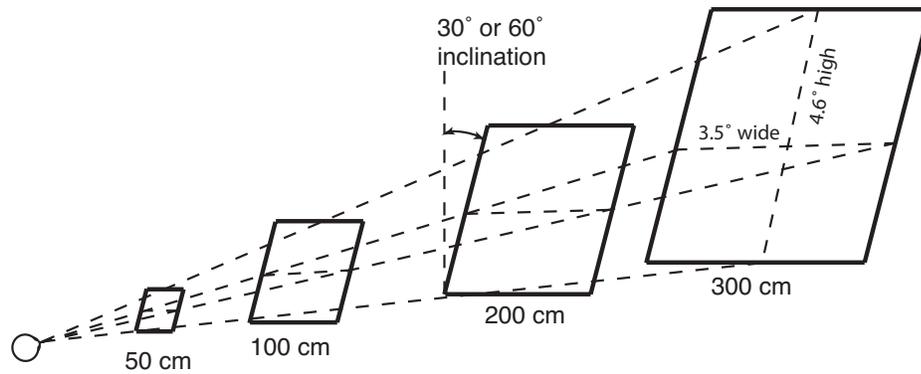$$p = 2 \cdot \arctan\left(\frac{W \cdot \tan i}{2D}\right) \qquad (1)$$

Fig. 4. All stimuli subtended 3.5° in width and 4.6° in height. They were inclined top away 0°, 30° or 60° and placed at distances of 50 cm, 100 cm, 200 cm, or 300 cm.

The ratio of width to distance was the same for all stimuli. They all subtended 3.5° in width and 4.6° in height, as shown in Fig. 4. Therefore, the angle of perspective varied only with inclination. It was 2° at an inclination of 30° and 6° at 60°. To this was added a taper of between +1° and -1° in steps of 0.2°. The plus sign indicates that the stimulus tapered toward the top.

Foreshortening perspective, as indicated by the vertical height of the image of the stimulus relative to its width, is not relevant for judging the inclination of an unfamiliar rectangle (it does provide information if the aspect ratio of the rectangle is known or assumed).
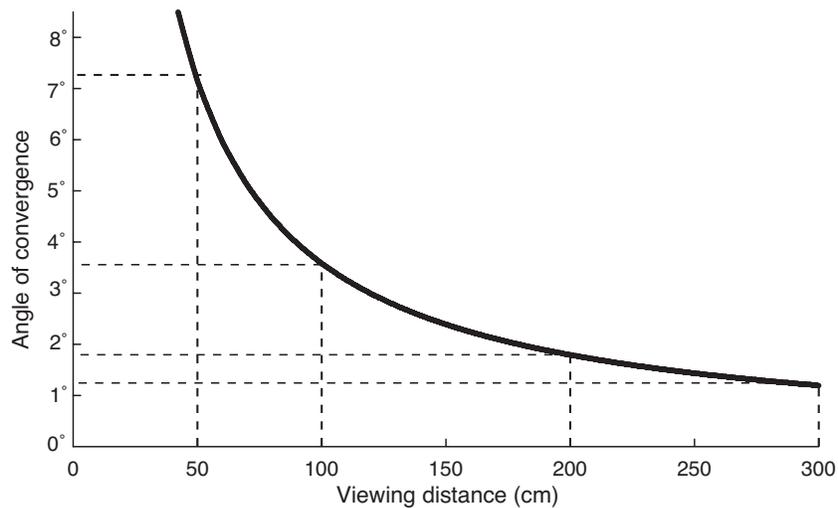
Fig. 5. The angle of the visual axes as a function of viewing distance. Note that convergence changes little beyond 2 metres.

Convergence of the eyes

The angle of convergence of the visual axes for an interocular distance of *a* and viewing distance *D* is given by:

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$$Convergence = 2 \cdot \arctan\left(\frac{a}{2D}\right) \quad (2)$$

For an interocular distance of 6.5 cm, the angle of convergence is 7.4° at a distance of 50 cm, 3.7° at 100 cm, 1.9° at 200 cm, and 1.2° at 300 cm, as shown in Fig. 5.

Binocular disparity

The angular disparity in degrees produced by a line at distance D and inclined i degrees from the frontal plane is given by:

$$Angular\ disparity = 2 \cdot \arctan\left(\frac{a \cdot \tan i}{2D}\right) \quad (3)$$

where a is the interocular distance (Ogle & Ellerbrock, 1946). Angular disparity is not much affected when a line is displaced from the midline by few degrees. Table 1 shows the angular disparities produced by the left and right edges of the rectangles used in the experiment. They are shown for each distance and each inclination for an interocular distance of 6.5 cm.

Table 1
Angular disparities produced by a rectangle inclined 30° or 60° at various viewing distances,
for an interocular distance of 6.5 cm.

Distance	30 ° inclination	60° inclination
50 cm	4.3°	12.9°
100 cm	2.15°	6.45°
200 cm	1.07°	3.22°
300 cm	0.72°	2.15°

To decide whether a quadrilateral with a certain width and inclination is a rectangle an observer must estimate the linear perspective that such a rectangle produces. If the quadrilateral conforms to that estimate it is perceived as a rectangle. Subjects could not use perspective to judge inclination because perspective was confounded with the taper of the stimulus. The stimuli were seen against a dark background so that cues arising from the background were not available.

Some information about inclination could be provided by the relative focus of the images of the near and far edges of a shape. However, the evidence suggests that relative focus provides only a coarse signal for relative depth (Nguyen et al. 2005). Watt et al. (2005) specifically looked

at focal cues in the perception of surface orientation and found that, under monocular viewing, perceived slant from texture gradient was larger when the monitor was physically slanted than when it was frontal. They attributed this effect to the influence of relative focus cues; however this influence of monitor slant was not significant with binocular viewing of stereoscopic displays. In our stimuli, the angular binocular disparity between the images of the left side and of the right side of the stimulus provides the main information about inclination. However, angular disparity is an accelerating function of inclination. It can be seen from Table 1 that, at each viewing distance, disparity increases threefold as inclination increases from 30° to 60°. Table 1 also shows that angular disparity is inversely proportional to viewing distance. This means that angular disparity must be scaled by distance to estimate inclination. In our experiment, distance was indicated by only accommodation and the angle of convergence. For a given inclination, image size and the angle of perspective did not vary with distance. They therefore provided no distance information. Fig. 5 shows that vergence changes less rapidly as distance increases and changes very little beyond a distance of 2 m[3]. Therefore, registration of distance from vergence becomes more variable as distance increases, as Tresilian et al. (1999) showed. Consequently, registration of inclination from disparity should also become more variable.

These relationships led to two predictions. (1) As distance increases, judgments about whether the stimulus is rectangular or tapered (shape constancy) will become more variable. (2) As distance increases, judgments of distance will become unreliable and subject to bias. If distance is underestimated, binocular disparity will be too small for the judged distance. This will cause inclination to be underestimated, which in turn will cause linear perspective to be partially interpreted as taper toward the top. Downward taper will have to be added to make the stimulus appear rectangular. An overestimation of distance will have the opposite effect. Similar errors would arise if distance was registered correctly but binocular disparity was registered incorrectly. For example, if a rectangle inclined 30° were perceived as frontal, the 2° of perspective in the image would make it appear as a quadrilateral tapered 2° toward the top. Downward taper of 2° will have to be added to make the rectangle appear rectangular.

2.1.4. Procedure

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[3] The binocular disparity between points on an inclined surface also diminishes with distance; however, we are much more sensitive to relative disparity than vergence and observers can reliably judge surface inclination from stereopsis at distances much greater than those used here (Allison et al. 2009).

In a preliminary experiment the stimuli were presented in the frontal plane (0° inclination) at a distance of 1 m. Therefore, the only convergence of the lines in the images was due to the taper of the stimuli. The eleven stimuli were presented six times in different random orders. A shutter covered the electro-luminescent panel while the experimenter changed the stimulus. Subjects placed the head on a chin rest and pressed one of two buttons on a computer keyboard to indicate whether each stimulus was tapered upward or downward. They were allowed to move their gaze over the stimulus and take as long as they wished. This initial condition provided subjects with practice at judging taper and indicated their ability to discriminate tapers between +1° and −1°. All subjects correctly identified tapers of -1° and +1° on every trial.

In the main experiment the eleven stimuli were presented at a distance of 50 cm, 100 cm, 200 cm, or 300 cm. The stimuli were scaled in size so that they subtended the same visual angle at the three distances. At each distance the stimuli were inclined 30° or 60° top away about the mid-horizontal axis. This made a total of eight conditions: four distances and two inclinations. In each condition the eleven stimuli were presented in random order six times. The conditions were presented in a different order for each of the eight subjects.
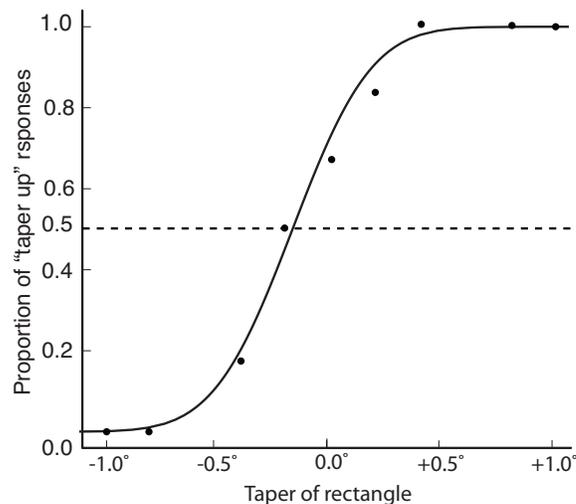

Fig. 6. A psychometric function of one subject. The stimulus was a
frontal quadrilateral at a distance of 100 cm, which tapered up or down.

2.2. Results

For each inclination-distance combination, the psychometric functions for each subject were fit to cumulative normal distributions, as shown in Figure 6. From these functions we estimated the points of subjective equality (PSE) and the just noticeable differences (JND) in units of degrees of taper. The PSE is defined as the taper level where the stimulus is equally likely to be judged as tapered upward as tapered downward (0.50 point on the psychometric function). The JND is defined as the difference in taper between the fitted 0.75/ 0.25 points on the psychometric function and the PSE. Although the JND measures cannot be used to directly assess the slant-inclination invariance hypothesis they do provide an indication of the precision of the canonical shape method.

Fig. 7 shows the mean JND of the eight observers (only 6 at 300 cm) as a function of inclination and viewing distance. A repeated-measures analysis of variance was run in R for the 30° and 60° inclinations. Only the main effect of inclination was significant ($F(1,49) = 5.7740, p = 0.020$) with the JND increasing with inclination angle. An alternative ANOVA model with angular disparity as the independent variable did not indicate any significant effect of angular disparity on the JND ($F(1,51) = 1.24, p = 0.271$).

Fig. 8 shows the mean PSE of the eight observers (only 6 at 300 cm) as a function of inclination and viewing distance. A repeated-measures analysis of variance was run in R for the 30° and 60° inclinations. There was a significant effect of distance ($F(1,49) = 92.16, p < 0.0001$) and an interaction between distance and inclination angle ($F(1,49) = 4.82, p = 0.033$). Post-hoc analysis indicated that the PSE was significantly more negatively tapered (tapered downward) at 300 cm than at 50, 100, or 200 cm ($p < 0.0001, p < 0.0001$, and $p = 0.013$ respectively, adjusted for multiple comparisons) and at 200 cm compared to 50 cm but this difference was only marginally significant ($p = 0.055$). An alternative 1-way ANOVA model revealed a significant effect of angular disparity ($F(1,51) = 30.89, p < 0.0001$). However, angular disparity and distance were correlated in our experiment.
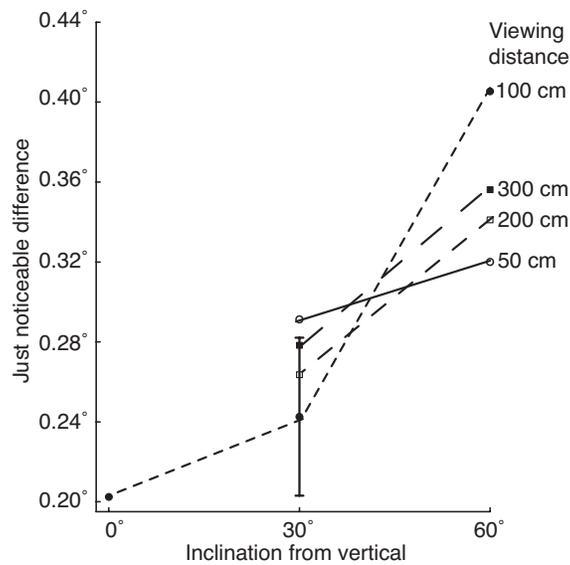
Fig. 7. The mean JND as a function of angle of inclination and viewing distance.
(n = 8, 6 at 300 cm).

2.3. Discussion

The main purpose of Experiment 1 was to demonstrate the canonical-shape method for measuring shape constancy. To succeed at the task of deciding whether an inclined trapezoid is a rectangle an observer must first estimate its inclination. In our stimuli, inclination was indicated by the angular disparity of the sides of the stimulus, scaled by its distance. So to register inclination an observer must register angular disparity and scale it by distance. An observer must then estimate the linear perspective that a rectangle with that inclination produces. Then an observer must register the relative tilt (convergence) of the lines in the image and decide whether it conforms to that estimate. If it does, the stimulus is a rectangle. If not it is a trapezoid.

Our results indicate that our subjects performed these tasks with great accuracy and precision. For example, a rectangle at a distance of 100 cm and inclined top-away 60° produced linear perspective of 6°. They detected a taper of the stimulus with a mean accuracy of about 0.1° and a JND of about 0.4°.
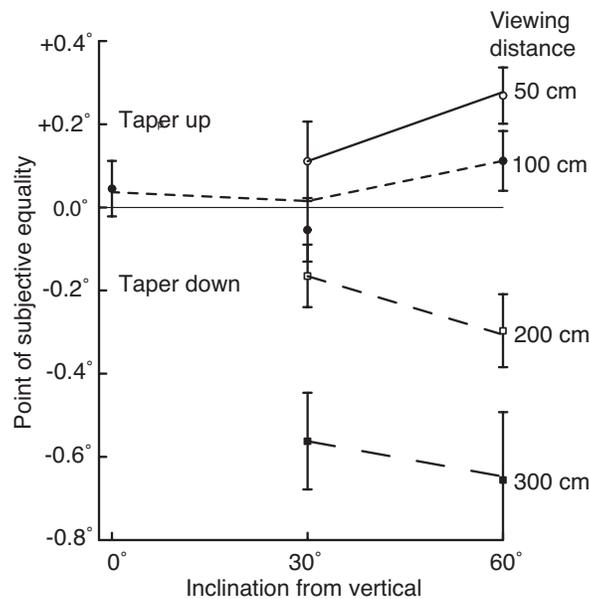
Figure 8. The mean taper of a quadrilateral that observers perceived as rectangular as a function of inclination and viewing distance. (n = 8, 6 at 300 cm)

It is important to note that accurate registration of linear perspective does not imply that we are aware of the perspective. For example, take a rectangular sheet of 8.5-inch by 11 -inch piece of card and incline it top away about 60°, as in Fig.2a. The retinal image of the top edge will be about two thirds as long as that of the bottom edge and the images of the left and right sides will converge several degrees. But the card appears rectangular and the linear perspective is not noticed. However, the perspective must have been registered in the visual system if the card appears rectangular. In a similar way, none of our subjects were aware of the 3° or 6° linear perspective produced by the inclined stimuli even though they must have registered the perspective with great accuracy.

The analyses of the data show two main effects. First, as the inclination of the stimulus increased from 30° to 60° the variability of estimates of stimulus taper, as reflected by the JND, increased. Second, as distance increased above 100 cm there was an increasing tendency for stimuli that appeared rectangular to be tapered down. In other words, starting from a PSE that was on average tapered up (positive) at the nearest 50 cm distance, the PSE became increasingly tapered down (negative) as distance increased. We concluded that this was due to subjects increasingly underestimating the inclination of the stimuli as viewing distance increased. Experiment 2 was designed to confirm this underestimation of inclination. We will discuss the implications of the results of both experiments in the General Discussion.

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3. Experiment 2: Relating shape constancy to perceived inclination.

In experiment 1, we found that subjects systematically misjudged the taper of an inclined trapezoid, judging increasingly tapered-down trapezoids as rectangles as distance was increased beyond 100 cm. We reasoned that such a bias was consistent with a distance-dependent underestimation of inclination and consequent under-compensation for taper due to perspective. To explain the distance-dependent taper bias in Experiment 1, we predicted that the apparent inclination of the rectangle would become increasingly underestimated with increasing distance, especially at distances beyond 100 cm. Also, one would expect judgments of inclination from stereopsis to become more variable at the greater distances (Hillis et al. 2004).

3.1. Method
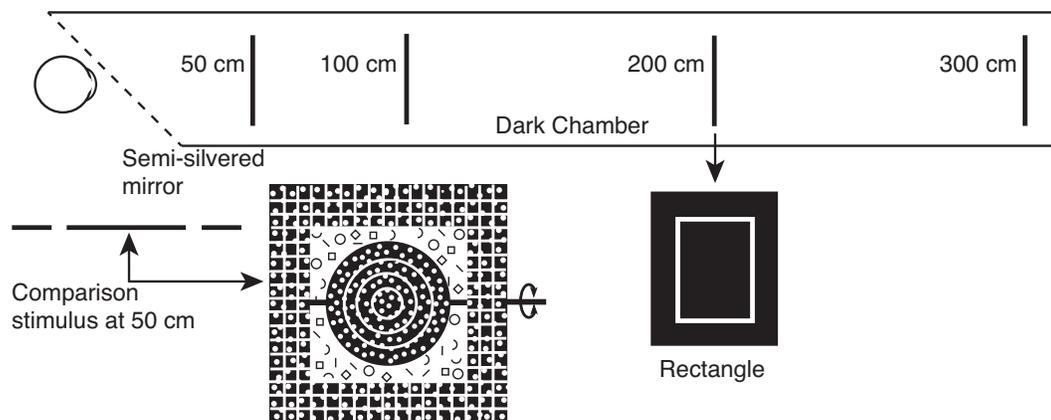
Fig. 9. Plan of the apparatus used in Experiment 2.

In this experiment we used an outline luminescent rectangle like the one used in Experiment 1. The rectangle was set in a dark chamber at each of four distances, 50, 100, 200, and 300 cm, and each of four inclinations, 20, 30, 40, and 60˚. A comparison stimulus was placed at a fixed distance of 50 cm and viewed through a semi-silvered mirror set at 45˚, as shown in Fig. 9. The comparison stimulus consisted of a central textured disc that the subject could rotate about a central horizontal axis. The disc was surrounded by a textured frame and set in front of a textured background. The comparison stimulus was illuminated by a 60-watt lamp. For each condition, subjects first looked at the luminescent rectangle set at one of the 16 distance/inclination conditions. They then flipped a switch that turned off the luminescent rectangle and illuminated the comparison stimulus. They set the inclination of the comparison stimulus to match that of the

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rectangle. They made several settings until satisfied. The order of conditions was randomized over subjects.

Although the comparison disc stimulus contained numerous inclination and distance cues it is still possible that its inclination was not judged perfectly accurately. Therefore, this procedure does not measure the absolute accuracy of the perceived inclination of the rectangles. However, it does measure the relative accuracy of the perceived inclination of the rectangles at different inclinations and distances.

3.2. *Results and Discussion*

For each condition, we subtracted the setting of the inclination of the comparison disc from the inclination of the rectangle. The results for the eight observers (only 6 at 300 cm) are shown in Fig. 10.

Repeated-measures ANOVA (with Huynh-Feldt correction when required) on the resulting data for the six observers who completed all conditions, showed a significant effect of viewing distance ($F(3,15) = 8.80$, $p = 0.01$, partial $\eta^2 = 0.64$) and of inclination ($F(2.09, 10.45) = 4.06$, $p = 0.048$, partial $\eta^2 = 0.45$). The interaction between distance and inclination was not significant ($F(4.58, 22.89) = 1.77$, $p = 0.164$, partial $\eta^2 = 0.26$).

Inclination tended to be underestimated and, as predicted, increased viewing distance produced increased underestimation of inclination. Planned comparisons showed that, compared to settings at 50 cm, the underestimation of inclination was significantly greater at 300 cm ($F(1,5)$ $=24.30$, $p = 0.004$) but only marginally at 200 cm ($F(1,5) =6.55$, $p = 0.05$) and not at 100 cm ($F(1,5) =0.64$, $p = 0.46$). Note that even at 50 cm, where the test and comparison stimuli were at the same distance, inclination was underestimated. This underestimation is probably because the cues to inclination were weaker in the test stimulus than in the comparison stimulus.

We expected that precision of inclination matches would decline as the inclination of the rectangle increased but this was not convincingly demonstrated. As noted above, the main effect of inclination was significant.

Planned comparisons showed that, compared to settings at a true inclination of 20º, the underestimation of inclination was significantly greater at 30º ($F(1,5) =37.42$, $p = 0.020$) and 40º ($F(1,5) =12.40$, $p = 0.017$) but not at 60º ($F(1,5) =6.08$, $p = 0.060$).
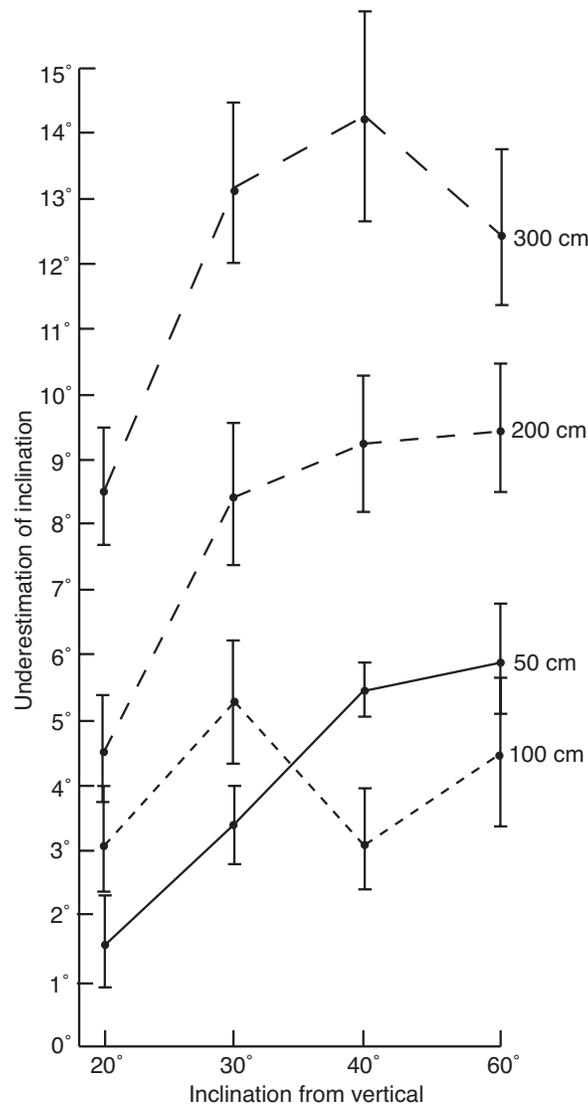
Fig. 10. Underestimation of the inclination of the rectangle relative to the inclination of the comparison stimulus as a function of the inclination and distance of the rectangle.

The linear perspective, p, for a rectangle was uniquely related to inclination in these experiments since W/D was constant (Equation 1). Therefore, we can convert the taper settings that corresponded to rectangularity in Experiment 1 into equivalent inclinations. As previously discussed, these conversions indicate effective overestimation of inclination at the farthest 100 and 200 cm distances and accurate or slight underestimation at the nearer distances. While this pattern of increasing underestimation with distance was also found in Experiment 2, there was underestimation at all distances. A rearrangement of Equation 2 can be used to obtain the distance where the angular disparity should geometrically produce the apparent inclinations. These distances are plotted in Fig. 11 as a function of true distance and inclination for both

experiments. The pattern of results, including the greater underestimation at 30° compared to 60° inclination, was similar for the two experiments. However, the effective distances were always smaller in Experiment 2 than 1, consistent with the greater inclination underestimation in the former experiment.

4. General Discussion

The main conclusion to be drawn from these experiments is that the canonical-shape method provides a good measure of shape constancy. We base this conclusion on the ease of explaining and performing the natural and unambiguous task, and the subjects' psychophysical performance. Our measurements show that people judge the taper of inclined trapezoids very accurately and precisely. The JND was only 0.35° and the constant error was only 0.65° at a distance of 3 m and an inclination of 60° that produced 6° of linear perspective. Our subjects were not aware of the linear perspective in the inclined stimuli. However, they must have registered the perspective because they were very good at detecting whether the stimulus was a rectangle or a tapered shape.

Experiment 1 showed that, as the inclination of the trapezoid increased from 30° to 60°, judgments of the taper of an inclined trapezoid became more variable. This is what one would expect. As inclination increases, the linear perspective increases. This should make it more difficult to distinguish the taper of stimulus from the perspective. According to Weber's law, one would expect the JND for detection of taper to be proportional to the perspective. Although the JND increased with inclination it was not proportional to inclination. This is not surprising as the discrimination of taper is a relative orientation discrimination task, which have been found to violate Weber's law. Orientation discrimination thresholds are lowest for vertical lines and increase with increasing tilt, at least for stimuli within 20° of vertical (Orban et al. 1984; Regan & Price, 1986). These findings are consistent with our increase in taper thresholds between the 30° and 60° stimuli (2° and 6° of taper from perspective, respectively).

Experiment 1 also showed that the PSE became increasingly tapered down (negative) as the distance of the inclined trapezoid increased above 100 cm. This effect can be accounted for as follows.

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To begin with, suppose that an observer underestimates the top-away inclination of a rectangle. The linear perspective of the image will be larger than it should be for the underestimated inclination. Consequently, downward (negative) taper must be introduced into the stimulus to make it appear rectangular. Conversely, the PSE was tapered up (positive) at the nearest distance of 50 cm, suggesting a possible overestimation of inclination of the surface at this distance.

Experiment 2 showed that, as expected, the inclination of a rectangle was underestimated at a distance of 300 cm relative to nearer distances.

While it is possible that a systematic underestimation of inclination could result from mis-registration of angular disparity, the literature suggests that the bias more likely arises in the scaling of angular disparity by distance. Convergence and accommodation of the eyes provided the only information for the distance of our stimuli. However, Fig. 5 shows that, as distance increases beyond one metre, vergence does not change much (neither does accommodation). It therefore becomes increasingly difficult to distinguish between two distances as distance increases. There is general agreement that judgments of linear distance based on convergence are overestimated at near distances and underestimated at far distances (Owens and Leibowitz, 1978, Morrison and Whiteside, 1984: Viguier et al., 2001). Gogel (1969) produced evidence that, in the absence of distance information other than vergence, observers tend to perceive objects at a specific distance, an effect he called the "specific distance tendency". One would predict the least bias in registered distance at this specific distance (Gogel, 1969). For the taper data from Experiment 1 the smallest bias was at the 100 cm condition. Equivalently this is where the effective distance curve crosses the veridical curve in Fig. 11. As effective distance obtained from inclination matches was always less than true distance in Experiment 2, a similar null bias point cannot be found. A specific distance of about 100 cm is somewhat nearer than Gogel's estimate of around 200 cm (Gogel and Tietz, 1973). It is also nearer than the mean value of 150 cm reported by Owens and Leibowitz (1976), who associated the specific distance with dark vergence state. On the other hand it is slightly further than the 50-60 cm of Tresilian et al. (1999) who attributed the specific distance tendency to a general contraction bias around the mean of a set of stimuli under uncertainty.
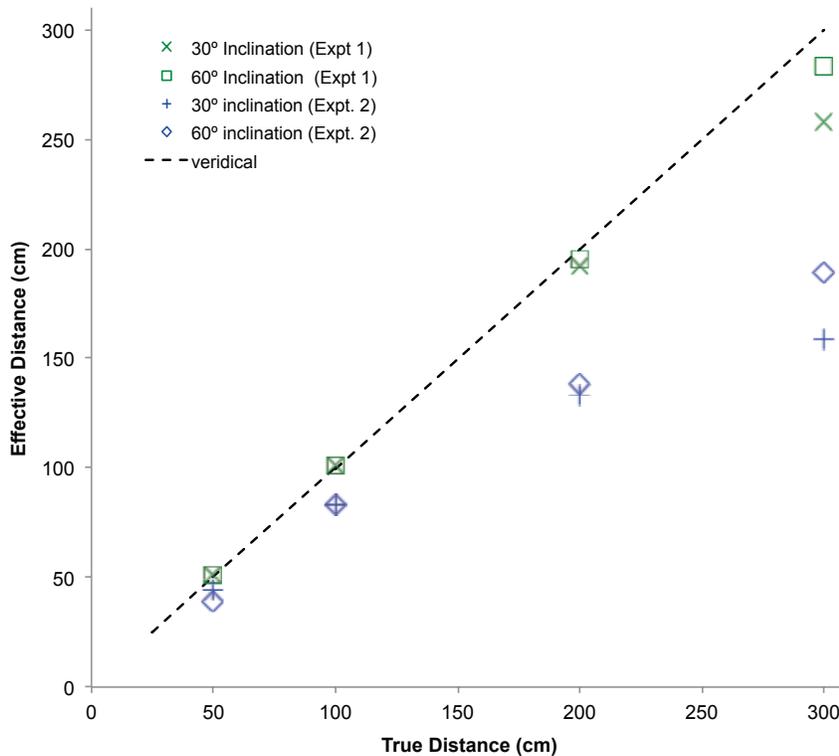
Fig. 11. Effective distances as estimated from taper settings in Experiment 1 and from inclination matches in Experiment 2, as a function of inclination and actual viewing distance. See text for details.

The next step is to ask how an underestimation of distance produces an underestimation of inclination. Table 1 shows that as the distance of an inclined rectangle is reduced the angular disparity produced by its left and right sides increases. Suppose that the distance of a rectangle inclined top-away is underestimated. The angular disparity will indicate a smaller inclination at the underestimated distance than it would at the actual distance. This will cause the inclination of the rectangle to be underestimated. Note that misperception of the linear perspective of our stimuli cannot account for the effect of perceived distance on perceived inclination because, for each inclination, linear perspective did not change with distance.

We can summarize the above argument as follows (note that an analogous argument predicts that positive taper must be introduced when distance is overestimated). (1) When convergence and accommodation of the eyes are the only cues to distance, near distances are overestimated and far distances are underestimated. (2) If the distance of an inclined rectangle is underestimated, the unchanged angular binocular disparity will be less than it should be for that perceived distance. This produces underestimation of the inclination of the rectangle. (3) If inclination is underestimated, the unchanged perspective of the image of a rectangle will be larger than it should be for that perceived inclination. Consequently, downward (negative) taper must

be introduced into the stimulus to make it appear rectangular.

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