Article

PERCEPTION

Perception
2016, Vol. 45(4) 425–442
© The Author(s) 2016
Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0301006615622323
pec.sagepub.com
SAGE

The Influence of Cast Shadows on the Detection of Three-Dimensional Curved Contour Structure

Sieu K. Khuu, Vanessa J. Honson and Kirsten L. Challinor
School of Optometry and Vision Science, The University of New South Wales, Sydney, Australia

Abstract

Cast shadows have been shown to provide an effective ordinal cue to the depth position of objects. In the present study, two experiments investigated the effectiveness of cast shadows in facilitating the detection of spatial contours embedded in a field of randomly placed elements. In Experiment 1, the separation between the cast shadow and the contour was systematically increased to effectively signal different contour depth positions (relative to background elements), and this was repeated for patterns in which the lighting direction was above and from below. Increasing the shadow separation improved contour detection performance, but the degree to which sensitivity changed was dependent on the lighting direction. Patterns in which the light was from above were better detected than patterns in which the lighting direction was from below. This finding is consistent with the visual system assuming a "light-from-above rule" when processing cast shadows. In Experiment 2, we examined the degree to which changing the shape of the cast shadow (by randomly jittering the position of local cast shadow elements) affected the ability of the visual system to rely on the cast shadow to cue the depth position of the contour. Consistent with a coarse scale analysis, we find that cast shadows remained an effective depth cue even at large degrees of element jitter. Our findings demonstrate that cast shadows provide an effective means of signaling depth, which aids the process of contour integration, and this process is largely tolerant of local variations in lighting direction.

Keywords

Contour integration, cast shadows, curved contours, depth perception, visual psychophysics

Introduction

The human visual system operates in a natural visual environment that is illuminated by a single overhead light source. Previous research has well established that the visual system is sensitive to this scene property, and visual perception has been shown to conform to

---

Corresponding author:
Sieu K. Khuu, School of Optometry and Vision Science, The University of New South Wales, Sydney 2052, Australia.
Email: s.khuu@unsw.edu.au

assumptions regarding the position of the light source (i.e., a light-from-above rule). This can be powerfully demonstrated in the perception of shadows, which are ubiquitous in visual scenes and correspond to dark-shaded regions and textures that arise from the structured interplay between opaque and three-dimensional (3D) objects and the illumination source (see Cavanagh, 2005; Dee & Santos, 2011; Mamassian, Knill, & Kersten, 1998; Yonas, 1979). Reflecting its practice in art, shadows can be considered as ''attached'' to an object and the apparent shading gradient and direction provides a powerful cue to the 3D *shape* of objects (see Khuu & Khambiye, 2012; Khuu, Moreland & Phu, 2011; Kleffner & Ramachandran, 1992; Ramachandran, 1988; Yonas, 1979), while ''detached'' or cast shadows are removed from the object and projected onto another surface or background (as in Figure 1). As cast shadows represent an occlusion of the light source by the object, the distance and position of the cast shadow provide a cue to the light source direction (e.g., the white arrow in Figure 1) and an *ordinal* representation of the 3D *position* of the object (see Dee & Santos, 2011). The usefulness of cast shadows has been long recognized and is a major feature in western art

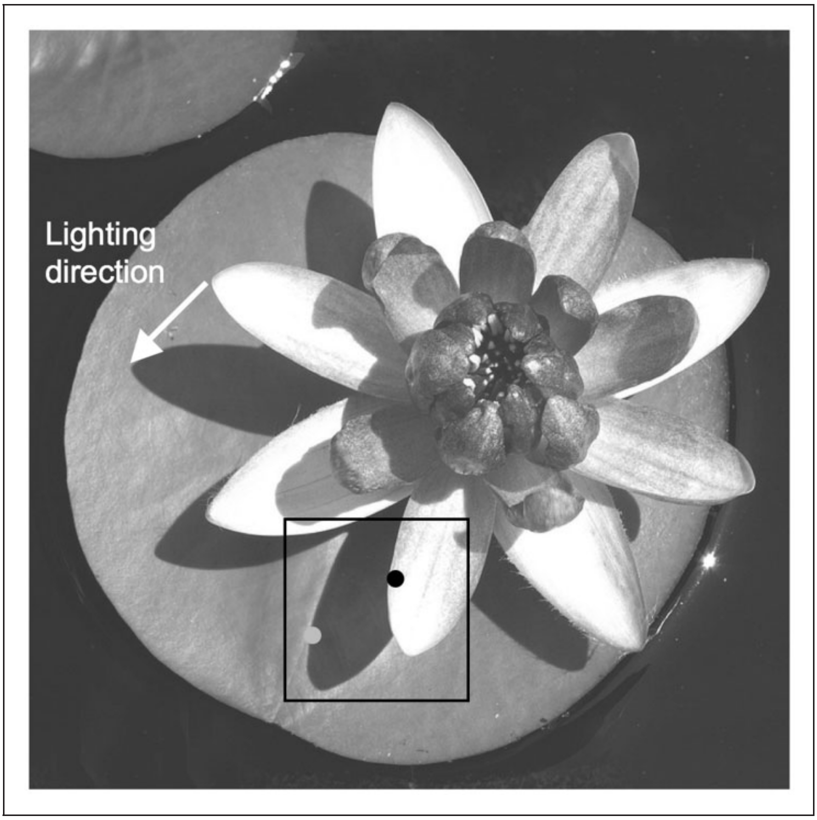

Figure 1. An example of cast shadows (in a brightly illuminated scene) providing an indication of the light source direction (white arrow indicating corresponding points between the object and its shadow) as well as the three-dimensional structure of the object (which indicates a flower raised above a lily pad). Here shaded regions in close proximity to objects are perceived as cast shadows and are used to facilitate the perception of depth and overall 3D scene structure. The framed region highlights edge structure of an object (black dot) and its corresponding cast shadow (gray dot). The perception of 3D structure will largely depend on detecting the contour structure of the object and its cast shadow.

(Gombrich, 1995; Mamassian, 2004) to define 3D spatial layout and as a means of implying “relief” in otherwise two-dimensional (2D) objects.

Previous research has well demonstrated the importance of cast shadows as a means of signaling the 3D position of objects (e.g., Allen, 1999; Hubona, Wheeler, Shirah, & Brandt, 1998), which has been shown to aid visual search (e.g., Cunningham, Beck, & Mingolla, 1996; Lovell, Gilchrist, Tolhurst, & Troscianko, 2009; Rensink & Cavanagh, 2004). Indeed, visual search times have been shown to be dependent on the position and direction of the cast shadow, with a bias in performance consistent with a light-from-above rule. Additionally, Kersten, Knill, Mamassian and Bulthoff (1996) have demonstrated that a moving cast shadow powerfully induces the illusion of motion in depth in an otherwise stationary object (see also Kersten, Mamassian, & Knill, 1997). Additionally, cast shadows have been shown to be important to the recognition of objects (see Castiello, 2001; Castiello, Lusher, Burton, & Disler, 2003) and operate without the need for the allocation of visual attention and awareness (cf. Khuu, Gordon, Balcomb, & Kim, 2014). The attribution of a cast shadow to an object (i.e., the shadow correspondence problem) is thought to operate implicitly and follows a coarse scale analysis in which an object is globally matched with its cast shadow while ignoring local variations or inconsistencies in lighting direction (Casati, 2008; Jacobson & Werner, 2004; Khuu, Khambiye, & Phu, 2012; Mamassian, 2004). Khuu et al. (2012) quantified this effect and reported that the local form of a cast shadow can largely be incongruent from the object (by as much as 60%), yet is still attributed to the object.

As mentioned, cast shadows can be used by the visual system as an ordinal cue to the 3D position of objects. Here, cast shadows may be fundamentally informative as they might act to primarily signal the depth position of the edge or bounding *contour* of the object. As objects in the natural environment that cast shadows must be more or less solid and opaque, correspondence between an object and its cast shadow is predominantly derived from comparison between their edge structures (e.g., Casati, 2008). For example in the framed location in Figure 1, the perceived depth of the flower petal (highlighted by the black dot) might be largely derived from a comparison between its edge structure and that of its cast shadow (gray dot). Here, the ordinal depth implied by the cast shadow might function to perceptually segment the contour structure of the eave in depth, affecting its detection and recognition. Note that an exact concordance between the bounding contour of the object and its cast shadow is not necessary (e.g., Mamassian, 2004); nor is there always a perfect match as the edge structure of the cast shadow is dependent on a number of factors including the lighting direction and the orientation of the background surface (see Mamassian et al., 1998, and as is the case with many shadow matches in Figure 1). However, the exact and optimal stimulus conditions in which the visual system utilizes cast shadows remains unresolved and is the focus of some debate (see Dee & Santos, 2011).

Previous research has demonstrated that the visual system detects spatial contours by associating a train of local-oriented elements sharing a number of similar properties (e.g., Field, Hayes, & Hess, 1993; Hess & Field, 1999). The visual system’s ability to detect 2D contours is well described by the association field model proposed by Field et al. (1993) which specifies the degree to which local elements are integrated (to form a contour) based on their grouping factors such as similarity in local orientation, proximity, and position. The neural basis of contour integration is believed to reflect the network of horizontal connections between orientation-tuned units in the primary visual cortex (e.g., Bosking, Zhang, Schofield, & Fitzpatrick, 1997) and the extent to which contours are processed by the visual system reflect the statistics of the orientation structure in natural scenes (e.g., Cham, Khuu, & Hayes, 2007; Geisler, Perry, Super, & Gallogly, 2001). Where cast shadows additionally contribute to the processing of contours is that they might be used as a cue to

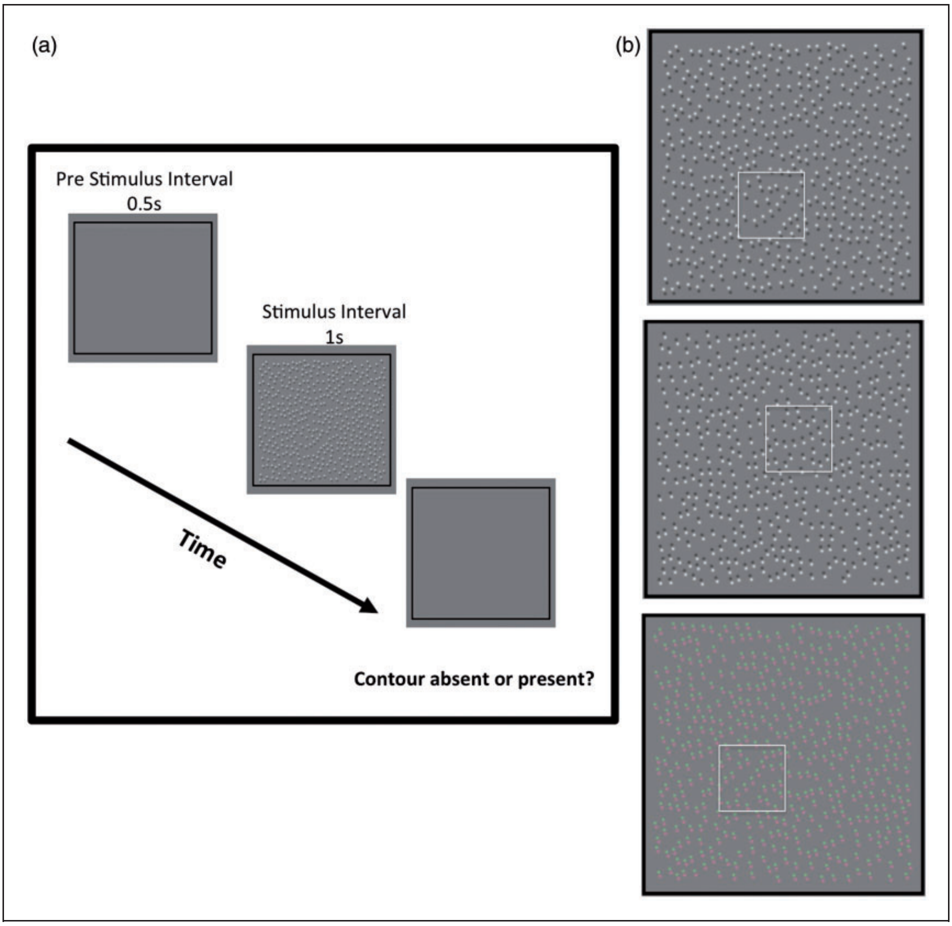

Figure 2. (a) The contour detection task. Here observers were first presented with a pre stimulus interval of 0.5 second in which the screen was blank with the exception of a square frame, and this was followed by the stimulus interval (presented for 1 second). The task of the observer was to judge whether the contour was either present or absent in the stimulus interval presentation. (b) Examples are given of contour stimuli used in the present study. Stimuli were configured such that light was from above (top panel), light-from-below (middle panel), or comprising red and green elements (bottom panel).

the depth position of contour elements. For example in the top panel of Figure 2(b), the cast shadow implies that the curved contour fragment occupies a different position in depth, as the separation between the contour and its cast shadow is greater than surrounding elements. This perceptually segments the contour from the background, allowing it to be effectively integrated by the visual system. Previous studies have well demonstrated that contour integration improves when a contour is defined by binocular disparity (see Hess & Field, 1995; Hess, Hayes, & Kingdom, 1997), but to our knowledge no study has sought to clarify whether and how cast shadows might facilitate the process of contour integration.

In the present study, we questioned the degree to which cast shadows might affect the integration and detection of spatial contours. Rensink and Cavanagh (2004) demonstrated that cast shadows can be used to identify objects using a visual search paradigm in which target and distractor elements differed in the relative orientation (i.e., the implied lighting direction) of their cast shadows. In Experiment 1, we adopted an analogous approach but sought to establish whether the visual system is able to rely on the *depth* signaled by cast shadows to aid the process of contour detection. In Experiment 2, we examined whether changing the shape of the shadow, by jittering the position of the local cast shadow elements, affects contour detection performance. As noted earlier, the visual system applies a coarse scale analysis to the processing of cast shadows and it might be expected that the visual system is largely tolerant changes in the shape of the cast shadow. For the first time, we systematically quantify the extent of change required to affect the integration of contours.

Experiment 1: The Detection of Curved Contours Defined by Cast Shadows

Experiment 1 investigated the degree to which cast shadows might facilitate the detection of contours. To provide a measure of contour detection sensitivity, we employed the methods of Field et al. (1993) in which observers were required to detect short contour fragments comprising of a small number of discrete light increment elements that followed a particular curved path (see Figure 2). The contour is embedded in a field of noise elements, which are similar in form to contour elements and act to mask the visibility of the contour. This now classic method has been typically used to understand the process of contour integration and to characterize the stimulus factors that affect the detection of contours (see Field, Hayes & Hess, 2000 for a review). To create cast shadow patterns, we employed the methods of Khuu et al. (2012) in which each element in the display was given a light decrement element partner (i.e., the cast shadow element) and the element was displaced a small distance away from its partner in a particular direction. The direction and magnitude of displacement of the cast shadow element provide an indication of the lighting direction and the implied depth position of contour elements. In Figure 2(b), all cast shadow elements are displaced in a direction that signifies light from above and this generates a perceptually 3D stimulus in which multiple increment elements appear to cast their shadow on a vertical gray background. Across different conditions, the shadow separation represented by the distance between elements forming the contour and their cast shadow partners was systematically changed. As previously demonstrated by Kersten et al. (1996), systematically increasing the separation between an object and its cast shadows resulted in the perception of the object appearing further in depth relative to the background. In Experiment 1, we examined whether increasing cast shadow separation results in a 3D "pop out" effect, which might affect the process of contour detection.

Note that to signal that the contour is perceptually further in depth, the cast shadow is physically displaced away from the contour by a small amount. Accordingly, observers might be drawn to the position to the contour in the stimulus because its "cast shadow" is further removed or separated than background elements. This 2D stimulus property alone might account for the detection of contours, and not because the visual system is detecting contours based on the implication of 3D form from its cast shadow. To address this possibility, we additionally examined contour detectability with cast shadow patterns in which the lighting direction was from below. For example in (Figure 2(b), middle panel), cast shadow elements are placed to imply that the pattern is illuminated from below. Previous studies have effectively demonstrated that such patterns are not or weakly perceptually 3D (e.g., Lovell et al., 2009; Rensink & Cavanagh, 2004) as they are not ecologically valid (i.e., do not conform with a 'light-from-above rule'), and that their detection might be largely mediated by the relationships between local elements, rather than on global properties that govern the perception of 3D structure from cast shadows (see Khuu et al., 2012). Were it the case that the physical separation of cast shadow elements is the primary cue that identifies the contour, it might be expected that contour detection performance will be similar for light-from-above and -below patterns. However, if the shadow separation is interpreted as a cue to depth, then increasing separation will improve the detection for light-from-above patterns, but not to the same degree as for light-from-below patterns.

Methods

Observers. Six observers well experienced in psychophysical experimentation participated in Experiment 1. All had normal or corrected to normal visual acuity. The relevant University of New South Wales Ethics committee gave ethics approval, and the observers gave informed consent prior to data collection with the research following the tenets of the Declaration of Helsinki.

Stimuli. The stimulus was a 20° × 20° square stimulus consisting of 480 nonoverlapping circular Gaussian elements of the form: $G(x, y) = e - (x^2 + y^2)/2s^2$ with a width of 0.25° of visual angle (see Figure 1). Gaussian elements were placed on a vertical screen with a gray background (with a luminance of 41 cd/m^2), with half the number of elements light increment (set to a Weber contrast of 0.64 at full height), and light decrement (Weber contrast of −0.64). Local elements were circular and therefore nonoriented to ensure that contour detection was based primarily on the shadow relationships between light increment and decrement contour elements and not facilitated by grouping based on their local orientation, as has been commonly investigated in numerous contour integration studies (see Field et al., 1993). Regardless, Uttal (1983) originally established that integration could effectively occur when nonoriented contour elements were used to define a contour.

Contours used in the present study comprise six elements (see Figures 2 and 4(b)) and were constructed by seeding the first light increment element in the contour to a randomly selected position in the stimulus. The second and subsequent contour elements were placed a fixed distance of 0.5° in a randomly chosen direction but placed following a constant angular offset of 10° or 30°. Thus, the angular relationship between contour elements was *co-circular*. This produced a contour fragment defined by constant curvature, with the magnitude of the angular change between elements determining the degree of curvature. Previous studies have suggested that the visual system preferentially codes curvature structure (see Kovacs & Julesz, 1993; Mathes & Fahle, 2007; Pettet, 1999; Yen & Finkel, 1998; cf. Tversky, Geisler, & Perry, 2004) as such contours are more likely to reflect the bounding contours of salient objects. If placement of contour elements resulted in it overlapping with another element or leaving the stimulus area, the contour was regenerated.

As mentioned, to create cast shadows, each light increment contour element was given a light decrement partner that was placed a fixed distance (in °) and in a particular direction away from the contour element. The magnitude of the displacement provides an indication of the *shadow separation*, while the direction of displacement provides an indication of the lighting direction. Note that in natural scenes, increasing shadow separation would lead to an increase in the size of the cast shadow and a reduction in its apparent contrast. However, such a change is negligible over the small shadow separations employed in the present study (see later) and previous studies have demonstrated that these properties are not overly critical to the perception of depth from cast shadows (see Kersten et al., 1996; Khuu et al., 2012). Additionally, these cast shadow characteristics were not included in our stimulus as they might provide an additional means of identifying the contour from noise elements. After the contour was generated, it was surrounded by randomly placed light increment noise elements which were also accompanied by a light decrement cast shadow partner that was displaced 0.09° away in the same lighting direction as contour elements. Care was taken to ensure that the density of noise elements was approximately equal (a tolerance of 2 times the dot was imposed) to the separation between contour elements to avoid the clumping of dots and large gaps in the stimulus.

The stimulus was displayed on a vertical screen with the stimulus area that was surrounded by a black (luminance: 0.2 cd/m^2, width: 0.2°) square presented with 0° disparity. As shown in Figure 2(b), this stimulus procedure produced a compelling cast shadow stimulus that depicts a fronto-parallel stimulus casting its shadow on a vertical background. Stimuli were generated using a 2.7 GHz iMAC computer using custom software written in MATLAB (version 2014b) and displayed on a linearized 27-in. LCD monitor. Observers viewed the stimulus from a distance of 60 cm in a dimly lit room.

Procedures. To measure contour detection, a single-interval forced choice procedure was used (see Figure 2(a)). Observers were initially presented with a prestimulus interval in which the screen was blank with the exception of the black square framing the stimulus area for 0.5 second, and this was followed by the stimulus interval in which a cast shadow stimulus was presented for 1 second. After this period, the stimulus disappeared from the display and observers had to judge whether a light increment contour was present or absent in the stimulus. This judgement was repeated in 80 trials in which half of the trials a contour was present in the stimulus. Whether the contour was present in the stimulus was randomized from trial-to-trial. The above-mentioned procedures were repeated for different shadow separations of 0.09°, 0.18°, 0.27°, and 0.36°, and in which the implied light source was from above and to the left (i.e., 120° in polar coordinate space) or below and to the right (300°). These conditions were repeated for contour angles of 10° and 30°. Observers performed these 16 stimulus conditions in a randomized order.

Results and Discussion. We applied signal detection theory to derive the criterion independent sensitivity index (d') from the proportion of hits and false alarm rate for the different stimulus conditions. This provided a measure of the accuracy of the observer to detect the contour. The average sensitivity of the six observers is shown in Figure 3 plotted as a function of the shadow separation and separately for the two lighting directions. In Figure 3, results for detecting contours in which the curved contour angle was 10° and 30° are shown in the left and right panels, respectively. Consistent with previous observations and the predictions of the association field model, contours with smaller curvature are better detected (i.e., overall higher sensitivity) than contours with larger angles ($F(1, 78) = 16.512$, $p < .0001$). The association field model ascribes that contours in which the angular difference between pairwise elements is small are easier to detect than those in which the contour angle is larger (see Field et al., 1993). To establish the effect of lighting direction and shadow separation on contour sensitivity, a repeated measures two-way analysis of variance (ANOVA) was conducted separately for both contour angles. This analysis observed for both contour angles a main effect of lighting direction (10°: $F(1, 40) = 25.17$, $p < .0001$; 30°: $F(1, 40) = 24.28$, $p < .0001$), as well as shadow separation (10°: $F(3, 40) = 13.53$, $p < .0001$; 30°: $F(3, 40) = 10.72$, $p < .0001$). Additionally, no significant interaction effect was observed (10°: $F(3, 40) = 3.21$, $p = .0617$; 30°: $F(3, 40) = 2.65$, $p = .069$) which indicated that the effect of changing shadow separation on contour sensitivity was the same for both lighting directions.

A number of findings are evident in Figure 3. First, contour detection performance is superior for light-from-above patterns as compared with light-from-below patterns. This was

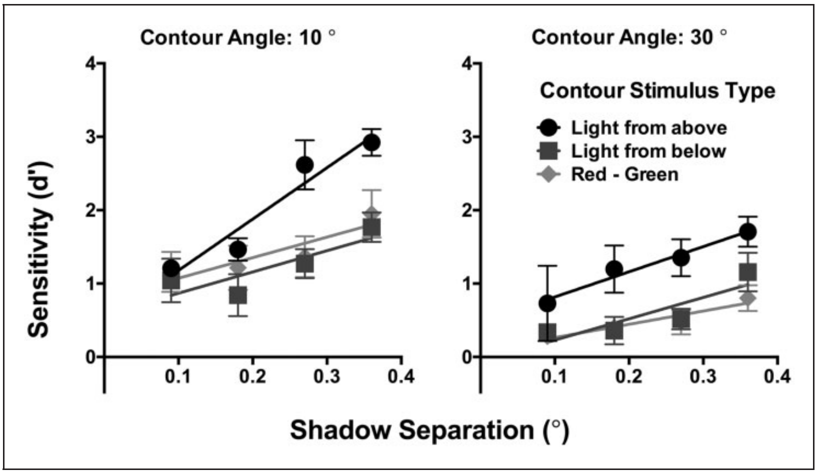

Figure 3. Contour detection sensitivity (averaged across six participants) for different stimulus types (represented by different symbols) plotted as function of two-dimensional distance between the contour and its cast shadow. Error bars signify 1 standard error of the mean. Solid lines represent line of best fit for the different pattern types (10°: light-from-above: $Y = 6.998 \times x + 0.475$, light-from-below: $Y = 2.896 \times x + 0.579$, red-green: $Y = 2.801 \times x + 0.7927$; 30°: light-from-above: $Y = 6.542 \times x - 0.225$, light-from-below: $Y = 2.906 \times x - 0.060$, red-green: $Y = 1.809 \times x + 0.083$).

evident for both contour angles. This detection advantage is consistent with the visual system adopting a "light-from-above rule," and we argue that the light decrement elements are perceived as cast shadows, which is used to cue the 3D position of the contour. Here the cast shadow implies that the contour is at a different ordinal position in depth relative to background elements, which facilitates its detection and integration by the visual system. Conversely, cast shadows in light-from-below patterns might not be perceptually 3D (as they are not ecologically valid) leading to poorer contour detection with performance mediated by a different process. Second, increasing the shadow separation improved contour detection performance, but note this improvement is most evident for light-from-above patterns, where larger separations are effective in signaling larger depth differences (as noted by Kersten et al., 1996). To provide an indication of this effect, linear regression analysis applied to the two lighting direction conditions and contour angles (line of best fit [average $R^2 = 0.86$], shown as solid lines in Figure 3) indicated that the effect of changing the shadow separation on contour detection sensitivity was significantly greater (10°: $F(1, 36) = 7.33$, $p = .0103$; 30°: $F(1, 36) = 10.47$, $p = .0026$) for light-from-above patterns than for light-from-below patterns as indicated by the difference in their slope values—see figure captions for values. Finally, the difference in performance between the two pattern types additionally suggests that cast shadows are an effective cue for light-from-above patterns and detection is not simply mediated on the local 2D separation between contour and cast shadow elements (see supplementary experiment later). Note that it is possible that cast shadows provide a means of identifying the contour *without* it providing a 3D cue. However were it the case, it might be expected that increasing shadow separation *will lead to* poorer contour detection performance. This is because increasing shadow separation will mean that contour and cast shadow elements will be more effectively masked by background noise elements which will reduce the ability of the visual system to effectively pair the contour with its cast shadow.

Importantly, in the present study, we report the opposite effect such that increasing shadow separation improved contour detection performance, which likely signifies that the cast shadow is perceived as 3D in form. This agrees with previous studies that have demonstrated the effectiveness of increasing shadow separation in signaling greater depth separations (see Kersten et al., 1996; Khuu et al., 2014).

Our finding of poorer sensitivity to light-from-below patterns suggests that the cast shadows in these stimuli are not used to infer 3D structure, and performance might be alternatively determined by the visual system detecting the *physical* separation between contour and shadow elements (e.g., Khuu et al., 2012; Rensink & Cavanagh, 2004). It could be argued that such patterns might provide a weaker 3D signal (than light-from-above patterns), and the slight improvement with increasing shadow separation reflects this stimulus property. However, the approach of Experiment 1 did not allow us to verify these two possibilities. To investigate this issue, we adopted the approach of Khuu et al. (2012) and compared contour detection performance between cast shadow patterns and contour stimuli comprising of elements that were differentiated or segregated based on perceptually isoluminant red and green colors (see Figure 2(b), bottom panel). Because red-green patterns are not defined by a polarity difference (as with cast shadow patterns), they are not perceptually 3D in form but nevertheless share the same structural configuration as the cast shadow patterns used in the main experiment. As there is no cast shadow, the detection of red-green patterns must accordingly be primarily facilitated by the physical separation of red and green elements associated with the curved contour. If the detection of light-from-below patterns was mediated by separation between contour and shadow elements, it might be expected that detection performance will be similar to red-green patterns. As in Experiment 1, the supplementary experiment was repeated in which the separation of red and green elements forming the contour was systematically increased and repeated for contour angles of 10° and 30°.

Perceptual isoluminance for red-green patterns was established using heterochromatic flicker photometry. Observers were presented with a single Gaussian element (with a radius of 2°), which alternated in color from red to green at 20 Hz. The contrast of the red stimulus (CIE 1931 $x = 0.62$, $y = 0.33$) was held constant (Weber 0.64) and observers, using method of adjustment, altered the contrast of the green stimulus (CIE 1931 $x = 0.28$, $y = 0.59$) until perceptual flicker was minimized. This process was repeated 3 times for each observer, and the results averaged and used to individuate the stimulus for each observer. Previous studies (e.g., Bilodeau & Faubert, 1997) have well established that the perceptual isoluminance point does not greatly change within the central 20°of visual angle, which is the same as our stimulus area. Additionally, it has been previously established that contour detection with luminance and colored defined stimuli are similar which allows for their comparison (see McIlhagga & Mullen, 1996; Mullen, Beaudot, & McIlhagga, 2000).

The results of this supplementary experiment are shown in Figure 3 as solid diamonds which represent d′ values plotted as a function of the shadow separation. For red-green patterns, increasing the separation between red and green elements improved contour detection sensitivity as indicated by the significant slopes values ($p\text{s} < .0001$) associated with the line of best fit for both contour angles. To compare the results between the three different pattern types across the different element separations, a two-way repeated measures ANOVA was performed separately for the two contour angles. This analysis again observed significant main effects of shadow separation (10°: $F(3, 60) = 12.20$, $p < .0001$; 30°: $F(3, 60) = 16.24$, $p < .0001$) and pattern type (10°: $F(2, 60) = 11.42$, $p < .0001$; 30°: $F(2, 60) = 18.68$, $p < .0001$), as well as significant interaction effects (10°: $F(6, 60) = 1.82$,

$p = .01$; 30°: $F(6, 60) = 2.67$, $p = .0232$). Tukey post-hoc comparisons (corrected for multiple comparisons at an alpha = 0.05) indicated that contour sensitivity to red-green patterns was significantly lower than from light-from-above patterns for separations greater than the background noise elements (i.e., at separations equal to and greater than 0.25°, $ps < .021$) but were not significantly different from light-from-below patterns regardless of the separation between elements ($ps > .142$).

The findings of the supplementary experiment indicated that contour sensitivity for light-from-above patterns increased with the shadow separation far more than light-from-below and red-green patterns (consistent with the adoption of a light-from-above rule), while sensitivity to red-green and light-from-below patterns were similar suggesting perhaps common process underlies their detection. Particularly contour sensitivity might be mediated by detecting the local 2D separation between contour and cast shadow elements, rather using this signal to imply 3D form. This agrees with the findings of a number of visual search studies that have investigated the detection of cast shadow stimuli. For example, Rensink and Cavanagh (2004) have shown that visual search times are longer when detecting upright cast shadow stimuli as compared with inverted cast shadows. They argued that longer search times are required for upright stimuli as they are ecologically valid and extra processing is required to implicitly derive their 3D structural configuration. Inverted patterns are detected quicker (as they are not ecologically valid) and less likely to be considered as a 3D cast shadow stimulus, and with detection-mediated local structural differences.

In summary, Experiment 1 demonstrated that cast shadows can be effectively utilized to signal the 3D position of a spatial contour, and increasing the shadow separation improved contour detection sensitivity. However, this was dependent on the lighting direction with a detection advantage observed for light-from-above patterns (over light-from-below and red-green patterns), which suggests that the detection of cast shadows conforms to a light-from-above rule.

Experiment 2: The Effect of Cast Shadow Form on Contour Detectability

In Experiment 1, we established the importance of cast shadows in facilitating the detection and integration of spatial contours. An important step in this process is the ability of the visual system to accurately attribute the contour with its cast shadow (the so-called *shadow correspondence problem*, see Mamassian, 2004). Note that the homogeneous lighting configuration of Experiment 1 ensured that the structural form or shape of the contour and its cast shadow was exactly the same, and this shape concordance might have facilitated the inference of 3D structure. However, previous research has shown that the visual system can be insensitive to local changes in the point-to-point relationship between an object and its cast shadow (see Casati, 2008; Khuu et al., 2012; Lovell et al., 2009; Mamassian, 2004). Tolerance to local inconsistencies in lighting direction and shadow might suggest that the visual system applies a coarse scale analysis to solve the cast shadow correspondence problem (see Mamassian, 2004). In Experiment 2, we aimed to quantify the degree to which local inconsistencies in lighting direction affect the ability of the visual system to rely on cast shadows to cue the 3D position of a contour. In particular, we were interested in how systematically changing the shape of the cast shadow stimulus (by randomly permuting the local position of the shadow elements) affects contour detection. As in Experiment 1, we measured and compared detection performance between shadow patterns in which the general lighting direction was from above and below.

Methods

The observers, methods, and procedures were the same as in Experiment 1. However, only contours of 10° curvature were examined. Cast shadows were constructed such that a small degree of "jitter" was added to the position of cast shadow elements. The following steps (outlined in Figure 4) were used to systematically change the shape of the cast shadow. As in Experiment 1, light increment contours were constructed and assigned a random position in the stimulus, and then shadow elements were assigned to each contour element, and they were displaced a fixed distance of 0.36° to an initial position (indicated by the red spot in Figure 4(a)) consistent by a particular initial "primary" lighting direction. Experiment 1 demonstrated that this shadow separation was sufficient to improve contour detection sensitivity for light-from-above patterns. Subsequently, shadow elements underwent additional displacement in which they were shifted a fixed distance (denoted by r° in visual angle) away from the initial position in a particular random direction (given by θ°). Accordingly, cast shadow elements could be potentially relocated to any position (e.g., black dots in Figure 4(a)) on the circumference of a circle (indicated in Figure 4(a) by the black dashed circle, with a radius of r and the position coinciding with primary lighting direction at the center of the circle) with their new local lighting direction indicated by the white dashed lines intersecting the contour element and the new cast shadow element position. These procedures advantageously allowed for the systematic and structured deviation in the position of cast shadow elements (from its original location, which corresponded to the cast shadow form corresponding with the primary lighting direction) by simply changing the magnitude of r.

Mamassian (2004) noted that the visual system matches cast shadows using a "centre of mass" computation. To ensure that the global position of the cast shadow did not significantly change (when r is systematically increased) the position of alternating cast shadow elements was counterbalanced. This was achieved by first selecting a random position (θ°) for a particular cast shadow element, and then assigning the next element in the cast shadow to the polar opposite direction. This procedure was repeated until all elements in the cast shadow were assigned a direction. This ensured that there were an equal number of cast shadow elements (in magnitude and position) on either side of the original or average cast shadow position (dotted curve line in Figure 4(b)) and thus there was no net deviation in the global cast shadow position to one side.

To provide a schematic representation of this cast shadow permutation process, two examples are given in Figure 4(b) in which in which $r = 0^\circ$ and $r = 0.18^\circ$. Note that when r is 0°, cast shadow elements are completely aligned with contour elements consistent with the primary lighting direction, while an r of 0.18° produced local variations in the position of cast shadow elements away from the primary lighting direction position.

Procedures

In Experiment 2, we measured contour detection performance (using the methods of Experiment 1) with cast shadow contours in which we systematically permutated the cast shadow shape by changing the position of local cast shadow elements. As in Experiment 1, contours were placed in a random field of noise elements with their accompanying shadow displaced in the primary lighting direction at a fixed distance of 0.09°. Note that separation was smaller than that defining the cast shadow contour (which was set to 0.36°), which (as demonstrated in Experiment 1) allowed the contour to be readily detected from its background.

In separate conditions, position of cast shadow elements was displaced to random positions with r set to 0°, 0.045°, 0.09°, 0.135°, and 0.18°. This was repeated for cast shadow patterns in which the primary lighting direction was from above as well as below.

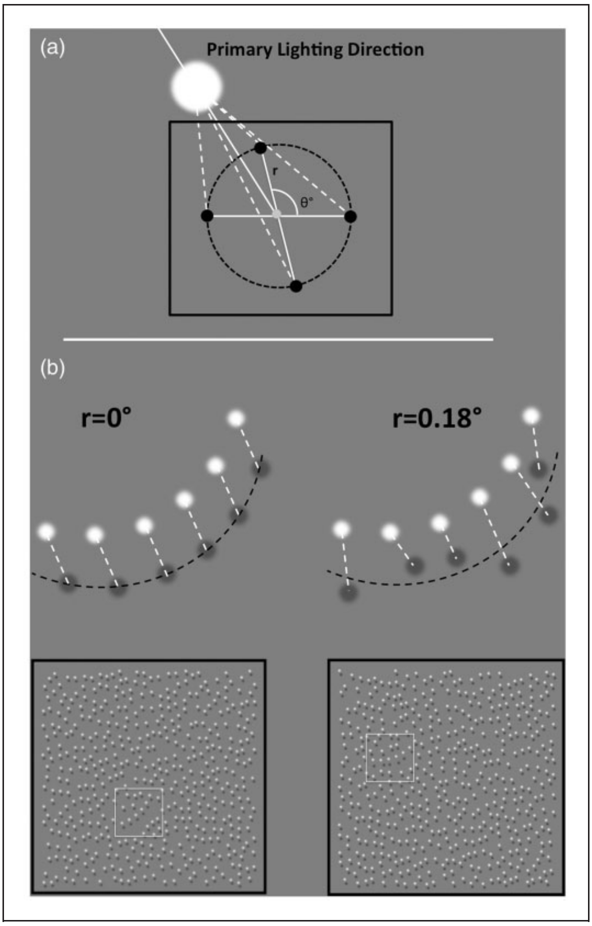

Figure 4. A schematic representation of the way in which the shape of the cast shadow was changed by randomizing the position of cast shadow elements. (a) Cast shadows elements were initially displaced to a position consistent with a particular primary lighting direction (gray dot) and then underwent subsequent displacement (r°) in a random direction (θ°). All possible cast shadow positions fall on a circle (with a radius equal to r°). These new shadow positions are consistent with lighting directions (dashed white lines) that are slightly permuted from the primary lighting direction. (b) Examples are given of permuted cast shadow forms. When $r = 0^\circ$, there is no permutation in shape and the cast shadow is identical to the contour and the position of local elements are consistent with the primary light source direction (indicated in the figure by the curved dashed line). However, when $r = 0.18^\circ$, the local position of shadow elements were randomly displaced away from the primary lighting direction, which affected the global shape of the cast shadow. Below each permuted cast shadow forms are examples of the stimuli used in Experiment 2.

Results and Discussion

Contour detection sensitivity (d') is plotted in Figure 5 as a function of the random displacement of the cast shadow element (r°) away from the primary lighting direction for conditions in which the cast shadow represented light-from-above (circles) and below (squares). A two-way repeated measures ANOVA was conducted to examine the effect of changing the displacement of local cast shadow elements and lighting direction on contour detection sensitivity. This analysis revealed significant main effects of both lighting direction

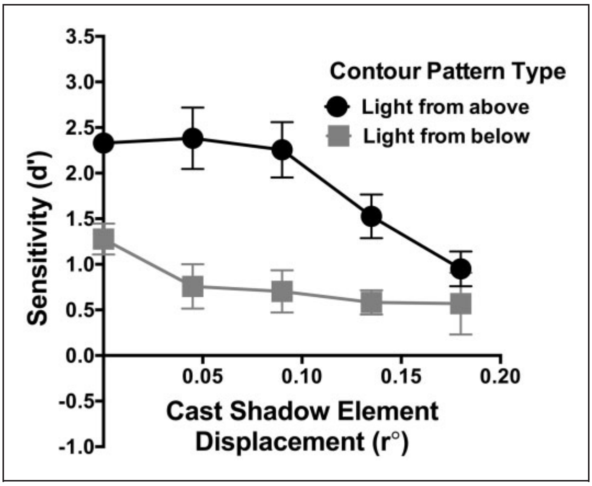

Figure 5. Contour sensitivity (d') plotted as a function of the cast shadow element displacement ($r°$). Error bars represent 1 standard error of the mean. Results for patterns in which the lighting direction was from above and below are represented by circles and squares, respectively.

($F(1, 50) = 50.97$, $p < .0001$), as well as cast shadow displacement ($F(4, 50) = 6.04$, $p = .0005$), but there was no significant interaction effect ($F(4, 50) = 2.18$, $p = .0850$).

A number of findings are evident in Figure 5. First, replicating the results of Experiment 1, contour detection sensitivity was superior for light-from-above than light-from-below configurations, particularly at small cast shadow displacements. Second, increasing the random displacement of cast shadow elements reduced contour detection sensitivity, but the extent of this effect is clearly different for the two pattern types. For light-from-below patterns, contour sensitivity monotonically reduced with the random displacement of local cast shadow elements, which might be expected if the visual system detected such patterns by relying on the local separation between contour and shadow elements. Randomly displacing the local position of cast shadow elements would reduce the effectiveness of this method of identifying the contour.

For light-from-above patterns, contour sensitivity was initially unaffected by the local displacement of cast shadow elements (up to 0.09°) and only decreased at the largest cast shadow displacements used in the present study. Indeed, Tukey post-hoc comparisons tests demonstrated that contour sensitivity to light-from-above patterns were significantly higher than light-from-below patterns for all cast shadow element displacements of 0°, 0.045°, 0.09°, and 0.135° (ps $< .0166$) but were not significantly different for a displacement of 0.18° (ps $> .451$). These findings suggest that for light-from-above patterns, the visual system is very much tolerant to local inconsistencies in the position of cast shadow elements (and consistent with a coarse scale analysis), and the cast shadow ceases to provide an effective cue to the location of the contour only at large displacements. It is possible that at large displacements the form of the cast shadow no longer resembles or is sufficiently different from the contour, which impairs or prevents their association and thereby implication of 3D form.

General Discussion

In the present study, we investigated the ability of the visual system to rely on cast shadows to detect contours embedded in a field of randomly placed noise elements. Here, the perceived

3D position signaled by the cast shadow might provide a means of identifying the contour, which affects its integration by the visual system. In Experiment 1, we reported that increasing shadow separation improved sensitivity to detecting contours. However, this effect was dependent on the lighting direction. We report superior sensitivity for light-from-above patterns compared with when it was below or for red-green patterns in which there is no cast shadow. This finding negates the possibility that contours were simply identified based on the local 2D separation between the contour and its cast shadow. The findings of Experiment 1 suggest that the visual system adopts a light-from-above rule and cast shadow patterns that conform to this heuristic are utilized as an ordinal cue to the depth position of the contour. The results of Experiment 1 are consistent with the findings of Kersten et al. (1996) who demonstrated that a moving cast shadow could induce illusory object motion in depth. While the cast shadows in our study were stationary, the effect of increasing shadow separation across different stimulus conditions is comparable to Kersten et al., as contours were perceived to be at larger depth separations, which facilitated their detection. Our findings and those of Kersten et al. suggest that cast shadows can be effectively utilized as a cue in the localization of objects in 3D space and agree with previous studies that have shown that the contour integration is highly dependent on depth cues such as binocular disparity (see Hess & Field, 1995).

The effectiveness of cast shadows in facilitating the perception of 3D structure naturally leads to the question of whether processing is preattentive. Previous research (e.g., Elder, Trithart, Pintilie, & MacLean, 2004; Lovell et al., 2009; Rensink & Cavanagh, 2004) using visual search has demonstrated that cast shadows might be preattentive and are processed quickly (100 millisecond) to provide a means of segmenting an object from a field of distractors. These findings agree with observations made of visual neglect patients who were able to utilize cast shadows presented in their field of neglect to aid in the recognition of objects (see Castiello, 2001; Castiello et al., 2003). Our results are consistent with this conclusion as we demonstrated that cast shadow stimuli might be implicitly processed to provide a means of identifying the position of the contour. This obviously facilitates contour integration and recognition and improves with larger shadow separations as the cast shadow signals the contour to be further in depth. These results are consistent with the notion that the analysis of cast shadows reflects low-level implicit processing, which contribute (along with other depth cues, e.g., see Allen, 1999; Hubona et al., 1998) to the identification and segregation of objects in the visual scene; note however that some cast shadow illusions do require visual awareness (see Khuu et al., 2014). Rensink and Cavanagh (2004) further argued that after this process cast shadows are ignored so that they do not interfere or disrupt the recognition of objects. However, it is debatable whether the observed insensitivity to cast shadow form might simply reflect a coarse scale analysis of cast shadows as has been demonstrated in the present study and elsewhere (see Jacobson & Werner, 2004; Lovell et al., 2009; Mamassian, 2004). It is worth noting that our study is *the first* to explicitly examine the influence of cast shadows on the processing of contour integration and detection, and while our findings are largely consistent with previous reports further work is needed to provide conclusive evidence for whether common processes govern how cast shadows are detected and utilized by the visual system.

It should be noted that the cast shadow elements themselves are unlikely to feature directly in the contour integration process. According to the association field model (see Field et al., 1993), local contour elements are associated based on grouping principles such as similarity in orientation, good continuation, proximity, and luminance polarity. As the contour and cast shadow elements are of different polarities, they are unlikely to be processed by a common contour mechanism. Indeed, it has been well demonstrated that the visual system does not combine opposite polarity signals (which are mediated by separate On- and Off-pathways see Badcock, Clifford, & Khuu, 2005; Field, Hayes, & Hess, 2000) at local stages of visual processing to derive local form information. However, as demonstrated in the present study, more complex associations might be made between opposite polarity elements (as they are judged to be cast shadows) to infer 3D position and not local orientation. Here it is possible that separate contour analyses might be performed for increment and shadow elements and then associated to infer 3D structure. Where this is achieved in the visual system remains unclear, though the use of contour stimulus pioneered in the present study and neural imaging will be very informative in highlighting brain areas involved in the computation of 3D object structure from cast shadows. A possible candidate area is primary visual cortex as previous studies have shown that the spatial representation of form resembles perceived rather than actual form (see Fang, Boyaci, Kersten, & Murray, 2008).

In Experiment 2, we demonstrated that the visual system comfortably tolerates changes in the apparent shape of the cast shadow when the position of local cast shadow elements is randomly displaced. Cast shadows were effective in cueing the 3D position of the contour even when the form of the cast shadow differed from the object. These findings agree with previous studies that have demonstrated that the visual system is largely insensitive to local discrepancies in the image in matching cast shadows (e.g., Casati, 2008; Khuu et al., 2012; Mamassian, 2004). Mamassian (2004) revealed this by showing that the perceived lighting direction of impossible shadows (i.e., objects with incongruent cast shadow form) was derived using a global "centre of mass" match between an object and its shadow rather than local discrepancies.

It has been argued that the visual system employs a coarse scale analysis to match cast shadows to provide a quick and efficient method of providing an *overall* indication of the 3D position of objects (e.g., Rensink & Cavanagh, 2004). The representation of precise point-to-point local matches might not be desirable because this process would be computationally exhaustive, and the depth information from cast shadows is usually limited. Note that the accurate representation of the 3D position of an object signaled by a cast shadow is dependent on accurate estimates of factors such as the observer viewpoint, spatial scale, lighting direction, and background surface position and orientation (Mamassian et al., 1998). Without specifically coding of these factors and in the absence of other identifying depth cues, the actual depth (signaled only by a cast shadow) of the object is largely ambiguous and limited to *ordinal* representations (i.e., whether an object is in front of a surface, but not its actual depth location) of depth position. Alternatively and to overcome this problem, the visual system might derive a measure of metric depth by relying on other cues such as stereopsis as the magnitude and direction of binocular disparity is well correlated with the depth position of an object. Cast shadows (in addition to other depth cues) might contribute to this process (e.g., see Allen, 1999), as has been modeled by cue combination models (e.g., see Clark & Yuille, 1990).

We observed contour detection sensitivity decreased with large shadow displacements (see Figure 5). A possible explanation for this is while a coarse scale analysis is used to match an object with its cast shadow, at large shadow displacements the global shape or form of the cast shadow becomes unidentifiable (with the object), and the cast shadow matching processing becomes less effective. Note that the recovery of the contour shape of the cast shadow is likely to be driven by a contour integration process, which (as mentioned earlier) is governed by associative principles such as good continuation and smoothness. Large displacements or permutations in the local position cast shadow elements will obviously effect the integration of cast shadow elements, which might mean that it is not detected by the visual system, and therefore, do not provide an effective cue to signal the 3D position of the contour. Future studies that examine the possibility of a link between the conditions effective for derivation of 3D form from cast shadows and contour integration might be fruitful.

In conclusion, the present study demonstrated that cast shadows provide an effective means of signaling the depth position of objects. We note that they can be used to signal the position of spatial contours, which in turn facilitates their detection and integration. Finally, the matching of cast shadows to extract 3D form is likely to follow a coarse scale analysis that ignores local inconsistencies in the implied lighting direction.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported by an Australian Research Council (ARC) Discovery Project grant (grant number: DP110104713) to S. Khuu.

References

Allen, B. P. (1999). Shadows as sources of cues for distance of shadow-casting objects. *Perceptual and Motor Skills*, *89*, 571–584.

Badcock, D. R., Clifford, C. W., & Khuu, S. K. (2005). Interactions between luminance and contrast signals in global form detection. *Vision Research*, *45*, 881–889.

Bilodeau, L., & Faubert, J. (1997). Isoluminance and chromatic motion perception throughout the visual field. *Vision Research*, *37*, 2073–2081.

Bosking, W., Zhang, Y., Schofield, B., & Fitzpatrick, D. (1997). Orientation selectivity and the arrangement of horizontal connections in tree shrew striate cortex. *Journal of Neuroscience*, *17*, 2112–2127.

Casati, R. (2008). The copycat solution to the shadow correspondence problem. *Perception*, *37*, 495–503.

Castiello, U. (2001). Implicit processing of shadows. *Vision Research*, *41*, 2305–2309.

Castiello, U., Lusher, D., Burton, C., & Disler, P. (2003). Shadows in the brain. *Journal of Cognitive Neuroscience*, *15*, 862–872.

Cavanagh, P. (2005). The artist as neuroscientist. *Nature*, *434*, 301–307.

Cham, J., Khuu, S. K., & Hayes, A. (2007). Contour curvature in natural images: Statistical analysis and psychophysics. *Perception (Supplementary)*, *36*, 156.

Clark, J. J., & Yuille, A. L. (1990). *Data fusion for sensory information processing systems*. Boston, MA: Kluwer.

Cunningham, R. K., Beck, J., & Mingolla, E. (1996). Visual search for a foreground object in continuous, naturalistic displays: The importance of shadows and occlusion. *Investigative Ophthalmology & Visual Science*, *37*, S299.

Dee, H. M., & Santos, P. E. (2011). The perception and content of cast shadows: An interdisciplinary review. *Spatial Cognition & Computation*, *11*, 226–225.

Elder, J. H., Trithart, S., Pintilie, G., & MacLean, D. (2004). Rapid processing of cast and attached shadows. *Perception*, *33*, 1319–1338.

Fang, F., Boyaci, H., Kersten, D., & Murray, S. O. (2008). Attention-dependent representation of a size illusion in human V1. *Current Biology*, *18*, 1707–1712.

Field, D., Hayes, A., & Hess, R. F. (1993). Contour integration by the human visual system: Evidence for a local "association field". *Vision Research*, *33*, 173–193.

Field, D., Hayes, A., & Hess, R. F. (2000). The roles of polarity and symmetry in contour integration. *Spatial Vision*, *13*, 51–66.

Geisler, W. S., Perry, J. S., Super, B. J., & Gallogly, D. P. (2001). Edge co-occurrence in natural images predicts contour grouping performance. *Vision Research*, *41*, 711–724.

Gombrich, E. H. (1995). *Shadows: The depiction of cast shadows in western art*. London, England: National Gallery Publications.

Hess, R. F., & Field, D. (1999). Integration of contours: New insights. *Trends in Cognitive Sciences*, *3*, 480–486.

Hess, R. F., & Field, D. J. (1995). Contour integration across depth. *Vision Research*, *35*, 1699–1711.

Hess, R. F., Hayes, A., & Kingdom, A. A. (1997). Integrating contours within and through depth. *Vision Research*, *37*, 691–696.

Hubona, G. S., Wheeler, P. N., Shirah, G. W., & Brandt, M. (1998). The relative contributions of stereo, lighting, and background scenes in promoting 3D depth visualization. *ACM Transactions on Computer-Human Interaction*, *6*, 214–242.

Jacobson, J., & Werner, S. (2004). Why cast shadows are expendable: Insensitivity of human observers and the inherent ambiguity of cast shadows in pictorial art. *Perception*, *33*, 1369–1383.

Kersten, D., Knill, D. C., Mamassian, P., & Bulthoff, I. (1996). Illusory motion from shadows. *Nature*, *379*, 31.

Kersten, D., Mamassian, P., & Knill, D. C. (1997). Moving cast shadows induce apparent motion in depth. *Perception*, *26*, 171–192.

Khuu, S. K., & Khambiye, S. (2012). The influence of shape-from-shading information on the perception of global motion. *Vision Research*, *55*, 1–10.

Khuu, S. K., Khambiye, S., & Phu, J. (2012). Detecting the structural form of cast shadows patterns. *Journal of Vision*, *12*, 1–14.

Khuu, S. K., Gordon, J., Balcomb, K., & Kim, J. (2014). The perception of three-dimensional cast-shadow structure is dependent on visual awareness. *Journal of Vision*, *14*, 1–16. http://www.journalofvision.org/content/14/3/25. DOI:101167/14.3.25

Khuu, S. K., Moreland, A., & Phu, J. (2011). The role of shape-from-shading information in the perception of local and global form in glass patterns. *Journal of Vision*, *11*, 20, 1–13. Retrieved from http://www.journalofvision.org/content/11/7/20, doi:10.1167/11.7.20

Kleffner, D. A., & Ramachandran, V. S. (1992). On the perception of shape from shading. *Attention, Perception & Psychophysics*, *52*, 18–36.

Kovacs, I., & Julesz, B. (1993). A closed curve is much more than an incomplete one: Effect of closure in figure-ground segmentation. *Proceedings of National Academic Science USA*, *93*, 15508–15511.

Lovell, P. G., Gilchrist, I. D., Tolhurst, D. J., & Troscianko, T. (2009). Search for gross illumination discrepancies in images of natural objects. *Journal of Vision*, *9*, 37, 1–14. Retrieved from http://journalofvision.org/9/1/37/, doi:10.1167/9.1.37

Mamassian, P. (2004). Impossible shadows and the shadow correspondence problem. *Perception*, *33*, 1279–1290.

Mamassian, P., Knill, D. C., & Kersten, D. (1998). The perception of cast shadows. *Trends in Cognitive Sciences*, *2*, 288–295.

Mathes, B., & Fahle, M. (2007). Closure facilitates contour integration. *Vision Research*, *47*, 818–827.

McIlhagga, W. H., & Mullen, K. T. (1996). Contour integration with colour and luminance contrast. *Vision Research*, *36*, 1265–1279.

Mullen, K. T., Beaudot, W. H., & McIlhagga, W. H. (2000). Contour integration in color vision: A common process for the blue-yellow, red-green and luminance mechanisms? *Vision Research*, *40*, 639–655.

Pettet, M. W. (1999). Shape and contour detection. *Vision Research*, *39*, 551–557.

Ramachandran, V. S. (1988). Perception of shape from shading. *Nature*, *331*, 163–166.

Rensink, R. A., & Cavanagh, P. (2004). Influence of cast shadows on visual search. *Perception*, *33*, 1339–1358.

Tversky, T., Geisler, W. S., & Perry, J. S. (2004). Contour grouping: Closure effects are explained by good continuation and proximity. *Vision Research*, *44*, 2769–2777.

Uttal, W. R. (1983). *Visual form detection in 3-dimensional space*. Hillsdale, NJ: Lawrence Erlbaum.

Yen, S. C., & Finkel, L. H. (1998). Extraction of perceptually salient contours by striate cortical networks. *Vision Research*, *38*, 719–741.

Yonas, A. (1979). Attached and cast shadows. In C. F. Nodine (Ed.), *Perception and pictorial representation* (pp. 100–109). Westport, CT: Praeger Publishers.