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Stereo and shading contribute independently to shape convexity–concavity discrimination

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Abstract. The present study examined the joint contribution of shading and stereopsis to the perception of shape convexity–concavity. The stimuli were the images of a synthetic convex 3-D shape seen from viewpoints leading to ambiguity as to its convexity. Illumination came from either above or below, and from either the right or the left, and stimuli were presented dichoptically with normal binocular disparity, reversed disparity, or no disparity. Participants responded "convex" more often when the lighting came from above than from below. Also, participants responded that the shape was convex more often with normal than with zero disparity, and more often with zero disparity than with reversed stereopsis. The effects of lighting direction and display mode were additive—that is, they did not interact. This indicates that shading and stereopsis contribute independently to shape perception.

Keywords: stereopsis, shading, relief perception, depth cues integration

1 Introduction

Understanding the representation of three-dimensional (3-D) objects is fundamental to theories of vision. One unresolved issue concerns the integration of different depth cues in shape perception.

It is well known that we can perceive 3-D shape from shading with the constraint that there is only one light source that illuminates the scene (Ramachandran, 1988). Shape from shading is also strongly constrained by a light-from-above prior; specifically, we assume that light comes from above, which induces depth reversal when light comes from below (Adams, 2007; Brewster, 1826; Gerardin, de Montalembert, & Mamassian, 2007; Kleffner & Ramachandran, 1992). This prior seems stronger with collimated lighting than with diffuse lighting (Langer & Bülthoff, 2000). It remains unclear whether there is also a favorite direction (left or right) with light coming from above. Sun and Perona (1998) and Mamassian and Goutcher (2001) reported a bias for light coming from above and left. Moreover, this bias correlates with handedness in the Sun and Perona study, but not in that of Mamassian and Goutcher. On the other hand, McManus, Buckman, and Woolley (2004), who reported a preference for light from above in shape judgments, also found a leftward bias when stimuli were presented for 1 s or less, but not when they were presented for an unlimited duration (ie until response).

There is also a prior for convexity in shape from shading (Hill & Bruce, 1994; Langer & Bülthoff, 2001). Liu and Todd (2004) demonstrated that the convexity prior was stronger than the lighting direction biases with two tasks in which participants had to evaluate the sign and magnitude of surface curvature of shaded images. However, another study showed that the convexity prior is indeed stronger than the light-from-above prior in children, but not in adults, in whom the light-from-above prior seems to dominate (Thomas, Nardini, & Mareschal, 2010). Furthermore, with visuohaptic experience, it is possible to modify the convexity prior for both shape judgments and the visual search task (Champion & Adams, 2007).

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It is also possible to modify the light-from-above prior in shape evaluation tasks but not in the visual search task. From these observations, Champion and Adams argued that the convexity prior can be modified at a preattentive stage of processing (at which the pop-out effect occurs in visual search), but not the light-from-above prior.

The view-from-above prior also impacts shape perception (Mamassian & Landy, 1998; Reichel & Todd, 1990). Specifically, we tend to assume that the viewpoint from which we look at the object is from above. Mamassian and Landy (2001) have studied the interaction of light-from-above and view-from-above priors to explore the mechanisms subtending the integration of priors. By varying the contrast of the cues supporting each prior to modulate their reliability, they showed that, when the light-from-above and view-from-above priors suggest opposite interpretations, the conflict is resolved according to the reliability of the cues. They concluded that the more reliable cues lead to the attribution of a higher weight to their prior constraint (eg if shading is the most reliable cue, greater weight is given to the light-from-above prior). They note in this respect that priors act like depth cues.

There is indeed evidence indicating that depth cues are weighted depending on how reliable they are. Texture is more reliable to evaluate large than small slant. Stereopsis is also more reliable with large slant, but also with short viewing distances, as well as with the slant size effect modulated by viewing distance (Hillis, Watt, Landy, & Banks, 2004; Knill & Saunders, 2003). These two cues seem to be optimally integrated and are given weights proportional to their reliability when it comes to slant discrimination and judgments (Hillis et al., 2004; Knill & Saunders, 2003). When these cues are in conflict, each receives different weights depending on which is the most informative for slant evaluation (Saunders & Backus, 2006). Norman and Todd (1995) found that, for the perception of surface corrugation in depth, when stereo and motion contradict each other, the modality showing the more effective surface curvature direction (horizontal or vertical) was perceived and the other suppressed. Furthermore, some studies have shown that, when stereopsis and monocular cues (occlusion and velocity or texture gradients) are inconsistent, the monocular cues override stereopsis (Braunstein, Andersen, Rouse, & Tittle, 1986; Stevens & Brookes, 1988). Bütlhoff and Mallot (1988, 1990) found that, for local surface evaluation, if depth cues are in conflict, edge-based stereo overrides disparate shading and nondisparate shading. Furthermore, disparate shading inhibits nondisparate shading. They also found that, when stimuli are lit from below, stereo prevents depth reversal.

While a number of studies indicate that, when different depth cues are available, some may override the others, the more common case is cue integration. Landy and colleagues have proposed the modified weak fusion (MWF) model as a general account of how depth cues are integrated (Landy, Maloney, Johnston, & Young, 1994). According to the MWF model, depth cues are weighted according to their reliability, availability, and consistency, and they are typically integrated linearly. The model can accommodate nonlinearities, however, such as one cue vetoing another, in particular cases where cues are inconsistent or unreliable. In the same vein, Dosher, Sperling, and Wurst (1986) demonstrated that, in the perception of 3-D structure, stereo and proximity luminance covariance (ie the increase in the edge intensity as a function of the proximity to the observer) are integrated linearly.

There is biological evidence that some neuronal substrates combine the different depth cues to achieve depth perception. Indeed, Tsutsui, Sakata, Naganuma, and Taira (2001) show that, in intraparietal sulcus of the macaque, some neuron populations respond selectively to surface orientation in depth defined by a texture gradient, regardless of the texture pattern, and most also respond selectively to the surface orientation in depth defined by random dots stereograms. Liu, Vogels, and Orban (2004) found similar results with neurons of the inferotemporal cortex of the macaque that respond selectively to surface orientation in depth, no matter whether the depth information was carried by texture or by disparity.

As noted previously, a number of studies have examined how different depth cues are integrated. However, no study has yet assessed the joint processing of stereopsis and direction of lighting in the perception of shape convexity–concavity. This is the purpose of the present study, wherein the impact of stereopsis will be studied not only by contrasting normal stereo displays to zero-disparity images but also by including a reversed stereopsis condition. Reversed stereopsis is a potentially valuable test condition that has yet to be explored. Some studies have examined the adaptation effect to reversed stereopsis resulting from the long-term wearing of right–left reversing spectacles, which thus reverse the sign of binocular disparities (Ichikawa & Egusa, 1993; Ichikawa et al., 2003; Shimojo & Nakajima, 1981; Yellott & Kaiwi, 1979). This adaptation led to a depth inversion aftereffect once the spectacles were removed, and it also altered the weight of the different depth cues (Ichikawa & Egusa, 1993). Indeed, participants ended up ignoring binocular disparity altogether and using occlusion and linear perspective to a greater degree to make depth judgments than before the adaptation. Except for the studies with the hollow-mask illusion by Matthews, Hill, and Palmisano (2011), the impact of reversed stereopsis on the perception of object relief without long-term adaptation has yet to be investigated. A particular interest in using reversed stereopsis is that it maximizes the power of stereoscopic information manipulations to impact on performance. Indeed, if stereopsis, as shown by Bülthoff and Mallot (1988, 1990), helps prevent shape inversion with lighting from below, we should expect reversed stereopsis to amplify the likelihood of inversion with lighting from below and possibly to cause shape inversion even when shapes are lit from above. Reversed stereopsis implies that the crossed disparities of a concave object viewed with normal stereopsis are transformed into uncrossed disparities. Crossed and uncrossed disparities are not equal, and it has been proposed that they may be processed by distinct mechanisms (Mustillo, 1985). Since Bülthoff and Mallot (1988, 1990) worked with only crossed disparities, and no study has yet examined the integration of uncrossed disparity with other depth cues, there is a possibility that reversed stereo may not produce effects symmetrical to those of normal stereo.

The goal of the present research was to determine if shading and stereopsis have independent (ie additive) or interactive (ie one factor modulates the impact of the other) contributions to shape perception. An experiment using a shape judgment task was used. Specifically, participants had to determine if the shape presented is convex or concave. The stimuli were the images of a convex 3-D shape seen from viewpoints that lead to ambiguity as to the convexity of the shape (figure 1). Illumination came from either above or below and from either the right or the left, and stimuli could be presented with binocular disparity, reversed disparity, or no disparity. This allowed us to determine whether shading and stereopsis are independent or interactive in their contribution to shape perception. For instance, on the basis of the findings of Bülthoff and Mallot (1988, 1990), which suggest that stereopsis overrides shading, one would predict that, when stereoscopic information (normal or reversed) is available, the impact of shading on the perception of convexity–concavity should be null or attenuated relative to zero-disparity displays. In contrast, if the effects of display mode and lighting direction do not interact, this would indicate that the two sources of information are treated independently for the determination of shape convexity–concavity.

2 Methods

2.1 *Participants*

Fourteen right-handed participants (four males and ten females) aged between 19 and 33 years old took part in the experiment. All were naive as to the purpose of the experiment, were neurologically intact, and had normal or corrected visual acuity, and a good stereo vision (assessed by the Stereo Fly test). No particular selection was applied with respect to gender or level of education.

2.2 *Material and stimuli*

The stimuli were presented over a white background on a 16 inch Compaq monitor of 1024 × 768 pixels resolution. The luminance of the screen was of 117 cd m^{-2}. Participants viewed stimuli through a mirror stereoscope by Stereo Aids, which presented the right half of the screen to the right eye and the left half of the screen to the left eye. The screen was split in half: the stimuli for the right eye were centered in the right half, and those for the left eye centered in the left half. The experiment was run on a Pentium 4 computer, and its progress and registration of the observer's performance were controlled by the E-Prime software. Participants responded by pressing the buttons of a mouse.

The stimuli were created using the 3D Studio MAX® program from Autodesk Media and Entertainment (USA) and rendered using orthographic projection. They all correspond to a unique lemon-like shape with flat extremities and a uniform gray surface which was presented from four different viewpoints (figure 1). The purpose of the flat extremity was to aid stereo matching; otherwise, the stimulus information would have been too poor to lead to a strong 3-D percept. The spatial extent of the stimuli was of 5.7 × 5.7 deg at the viewing distance of 60 cm. The shape could be lit from above right, above left, below right, and below left (22 deg left or right of a vertical line running through the object's center, and 39 deg above or below the horizontal, see figure 2). Rotations of 5.42 deg around the vertical axis were applied to the stimuli to create distinct views for the left and right eyes for the stereo and reversed stereo conditions, which simulates the effect of an interocular distance of 5.6 cm for a 3-D object viewed from 60 cm.[(1)] For the zero-disparity (ie 2-D) display condition, stimuli with the same viewpoint were presented to both eyes. The Michelson contrast of the stimuli was 0.99.

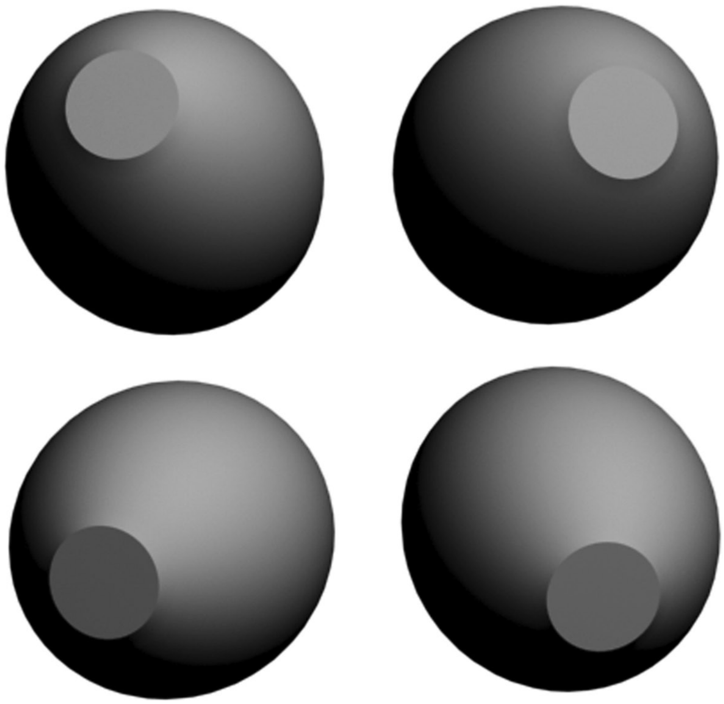

Figure 1. The four views under which the shape used in the present experiment could be displayed. The different viewpoints were created by rotating the object by 90° around the *z*-axis relative to one another.

[(1)] Note that the optimal way to create a stereo pair would be to use two virtual viewpoints, with one horizontally displaced relative to the other in a direction parallel to the display plane. Renderings using this method were compared with those used in the experiment. The correlations for the left and right eye views were both greater than 0.99, indicating that the images were almost perfectly identical across the two rendering methods.

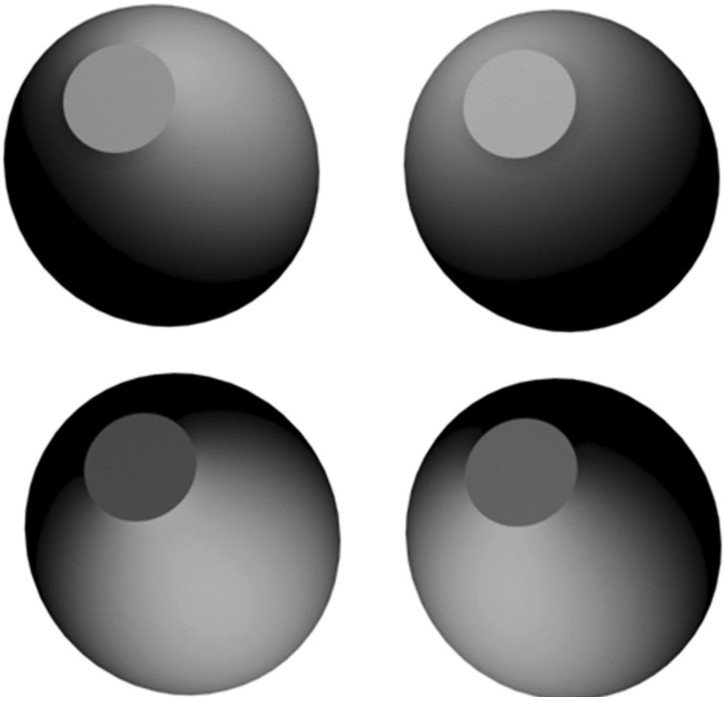

Figure 2. The four lighting directions used (ie above left, above right, below left, below right) illustrated with the top-left object of figure 1.

2.3 *Procedure*

Participants indicated whether the target was convex or concave within a 3 (display mode: 3-D, reversed 3-D or 2-D) × 2 (light from above or below) × 2 (light from the right or the left) repeated-measures experimental design. At the beginning of each trial a fixation cross was displayed for 750 ms, followed by a delay of 500 ms, followed then by the target, which lasted until the participant's response. A 500 ms white noise mask was presented immediately after the target, followed by an intertrial delay of 500 ms. Half of the participants indicated that the stimulus was concave by pressing the left button of the mouse with the right index finger and that the stimulus was convex with the right mouse button with the right middle finger. These assignments were reversed for the other half of participants. There were 30 trials per condition. Each stimulus was presented with each illumination direction and display mode seven or eight times, with the rule that the shapes would be presented at least seven times each, and that two of them were selected randomly to be presented an eighth time to equal 30 trials. This gave a total of 360 experimental trials divided in three blocks of 120 trials. In each block there were 10 trials for each condition. The order of the blocks was random. The trials were presented in a random sequence within each block. Twenty practice trials were presented prior to the experimental trials. The dependent variable was the rate of "convex" responses.

3 Results

A three-way within-subject ANOVA including the factors of display mode (3-D, reversed 3-D, and 2-D), illumination from above or below, and illumination from left or right was carried out on the rates of "convex" judgments (figure 3.) Main effects of display mode ($F_{2,26} = 16.81$, $p < .001$, $\eta^2 = 0.56$) and illumination from above or below ($F_{1,13} = 6.68$, $p < 0.05$, $\eta^2 = 0.34$) were obtained. The display mode effect indicates that participants responded "convex" more often when the stimuli were shown with normal disparity than with no disparity ($F_{1,13} = 6.45$,

$p < .05$, $\eta^2 = 0.33$), and when the stimuli were presented with no disparity than with reversed disparity ($F_{1,13} = 10.89$, $p < 0.01$, $\eta^2 = 0.46$). The illumination above–below effect indicates that participants judged the stimuli as convex significantly more often when they were lit from above than from below. We found no other significant effect (with all Fs < 1). Indeed, the effect of illumination from left or right ($F_{1,13} = 0.01$, $p = 0.95$, $\eta^2 = 0.001$) was far from significant. Most importantly, the interaction of lighting from above or below × display mode ($F_{2,26} = 0.23$, $p = 0.80$, $\eta^2 = 0.02$) was also far from significant, thereby indicating the additivity of these factors. The effect of lighting from above or below was significant and of constant magnitude, regardless of whether the stimuli were presented with stereopsis ($F_{1,13} = 6.22$, $p < 0.05$, $\eta^2 = 0.32$, mean difference of 0.08; SD = 0.12), reversed stereopsis ($F_{1,13} = 5.08$, $p < 0.05$, $\eta^2 = 0.28$, mean difference of 0.08; SD = 0.14), or no disparity ($F_{1,13} = 4.77$, $p < 0.05$, $\eta^2 = 0.27$, mean difference of 0.10; SD = 0.17).

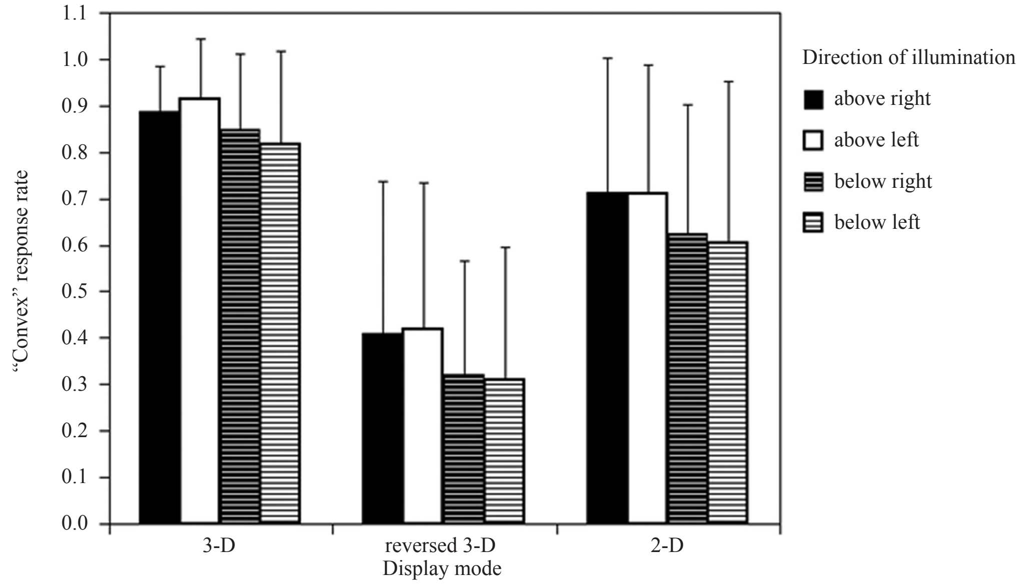

Figure 3. The rates of "convex" responses as a function of the above–below and left–right directions of illumination and of display mode.

4 Discussion

The results show that stereopsis and lighting from above or below both influence shape judgments. Thus, participants responded that the shapes were convex more often when the stimuli were presented with stereopsis than with no disparity, and when the stimuli were presented with no disparity than with reversed stereopsis. Also, participants responded "convex" more often when the lighting came from above than from below. However, whether the stimuli were lit from the right or the left did not affect responses. The effects of display mode and lighting from above or below were precisely additive ($F < 1$).

4.1 *The integration of depth cues*

The absence of statistical interaction between the effects of display mode and lighting, and the fact that the effect sizes of the above–below lighting direction were almost exactly the same in the three display mode conditions (ie the difference across display modes is less than the standard deviation of the effect size for lighting direction) indicate that stereopsis and shading combine in an accumulative way. In other words, they are integrated linearly. These findings are consistent with the MWF model (Landy et al., 1994), which postulates that depth cues are integrated linearly, as well as with the data of Dosher et al. (1986), which showed that stereo and proximity luminance covariance are integrated linearly.

However, our results may appear inconsistent with those of Bülthoff and Mallot (1988, 1990), who showed that edge-based stereo can override disparate shading and shape from shading in the evaluation of local surface depth. An attenuated or eliminated impact of above–below lighting direction on the perception of convexity–concavity could have been expected in the present results when stereoscopic information was available. We found only additivity of the effects, which may be due to a difference in the nature of the tasks required of the participants. Whereas we required a categorization of shapes as either convex or concave, the task used by Bülthoff and Mallot (1988, 1990) was one of local surface depth evaluation with objects that were either flat or had variable degrees of convexity. We believe that the markedly different constraints on the task and the nature of the stimulus interpretation required is probably what led to the difference in how depth information was used. In fact, Bülthoff and Mallot (1988) admitted that edge-based stereo vetoing disparate shading and shape from shading could occur only locally (as in their task) and not in global perception. What has been found here is that shading and stereo are integrated linearly when it comes to perception of global shape relief.

Our results appear inconsistent with the studies showing that monocular cues may override stereopsis (Braunstein et al., 1986; Stevens & Brookes, 1988) since the direction of illumination information carried by shading did not alter the effect of display mode. It should be noted, however, that the monocular depth cues studied in Braunstein et al. and in Stevens and Brookes are occlusion and velocity or texture gradients, in contrast to shading in the present study. This may thus suggest that different monocular depth cues differ in the degree to which they contribute to the interpretation of shapes in depth. A mitigating factor that may also be important in determining the contribution of different depth cues is the type of stimuli used. Thus, the stimuli used by Braunstein et al. and in Stevens and Brookes are line drawings, in contrast to the shaded objects used here.

It is important to note that, in the normal stereo condition, when the shape was lit from above, the convex response rate was of 91%, but this rate did not fall to 9% with the shape presented with reversed stereopsis and light from below. Indeed, in this condition the convex response rate was of 32%. Thus, the results with reversed stereo are not the mirror image of those in the normal stereo condition. The convexity prior may be a factor in this asymmetry.

Perhaps more importantly, in the reversed stereo condition the binocular disparities in the display were uncrossed, whereas they were crossed in the normal stereo condition. Patterson et al. (1995) showed that perceived depth is more accurate and sensitive with crossed than with uncrossed disparities. However, their display durations were much shorter than ours (around 100 ms vs 2732 ms). With their small stimulus duration, it is impossible for participants to change their vergence angle while exploring the stimuli. In contrast, with the long stimulus exposures used here, vergence changes that alter the sign of binocular disparities may have occurred. Thus, it is not entirely clear whether the findings of Patterson et al. apply to account for the asymmetry observed here between normal and reversed stereo. Possibly more relevant, Tam and Stelmach (1998) found an asymmetry in stereoanomaly between crossed and uncrossed disparities. Indeed, they report that uncrossed disparity results in a greater number of participants failing to perceive stereoscopic depth than crossed disparity, and this with display durations as long as 1000 ms. In fact, at this stimulus duration the difference between crossed and uncrossed disparities had long reached an asymptote, such that one should expect the same result with protracted stimulus exposures. This robust asymmetry between crossed and uncrossed disparities is congruent with the hypothesis that they are processed by different systems (Mustillo, 1985). Also supporting this view, Ishigushi and Wolfe (1993) demonstrated a difference in stereo capture between crossed and uncrossed disparities. Thus, while crossed disparity led to strong stereo capture, uncrossed disparity led to unstable representations. The authors accounted for this finding by suggesting that the two kinds of disparities play a different role in surface reconstruction and that they differ in their perceptual representation.

The asymmetry reported here between normal and reversed stereo thus agrees with previous relevant findings in the literature and with the accounts proposed by Mustillo (1985) and by Ishigushi and Wolfe (1993). Regardless of the specific reasons for this asymmetry, it remains that shading and stereo contribute independently to the perception of relief. In relation to this issue, it is interesting to note that, since crossed and uncrossed disparities seem to be processed by different mechanisms (Mustillo, 1985) and that uncrossed disparity leads to unstable perception of depth (Ishigushi & Wolfe, 1993), one might have expected shading to have a greater impact with reversed than with normal stereo. This possibility was tested and rejected by the present study.

4.2 *Lighting direction priors*

Our results indicate that stereopsis does not affect the light-from-above prior. Thus, when stimuli were lit from above, they were perceived as convex more often than when they were lit from below, regardless of display mode. The effect of the above–below lighting direction observed here is consistent with the findings of Adams (2007), Connor (2001), Gerardin et al. (2007), and Kleffner and Ramachandran (1992), who all showed that shape perception is constrained by the light-from-above prior.

The left–right lighting direction had no effect on convexity judgments. This is in agreement with the results of experiment 1 by McManus et al. (2004), and with the notion that shape perception is not guided by a light-from-the-left prior. However, these results contradict those of Sun and Perona (1998) and of Mamassian and Goutcher (2001) as well as those of experiment 2 by McManus et al., which suggested a lighting-from-the-left prior. It appears that exposure duration may be the factor responsible for these inconsistent results. In the present experiment the stimuli remained visible until the participant's response, as in experiment 1 by McManus et al., which showed no leftward bias. The mean response time, and thus exposure duration, in the present experiment was of 2732 ms, and of 2068 ms in McManus et al. In contrast, exposure durations were shorter in the experiments that showed a leftward bias. Indeed, stimuli were presented for 120 ms in Mamassian and Goutcher, less than 500 ms in Sun and Perona, and between 200 and 1000 ms in experiment 2 by McManus et al. It is possible that longer exposure durations lead the participants to adopt a different response strategy since they have more time to analyze the available information. Sun and Perona found a strong correlation between handedness and the preferred lighting direction. This suggests that hemispheric laterality could be implicated in the leftward bias. Under this assumption, perhaps longer exposure durations leave more time for interhemispheric information transfer, which eliminates any potential lateralization effect that may otherwise occur with shorter durations. This could explain why short and long exposure durations are associated with different outcomes regarding the effect of left–right lighting direction.

Another feature of the present results is the relative magnitude of the effects of display mode and of shading on the frequency of "convex" responses. Overall, this frequency is increased by 20% with normal stereo relative to 2-D presentations and decreased by 30% with reversed stereo in comparison with 2-D displays. These effects are of a much greater magnitude than the overall impact of above–below lighting direction, which differed by 9% in the rate of "convex" responses. This suggests that, in the present experimental context, stereoscopic information carried a greater weight for the interpretation of shapes in depth than shading. This finding is congruent with the notion of the relative dominance of stereo over shading for the perception of 3-D shapes that we may retain from the studies of Bülthoff and Mallot (1988, 1990) discussed above.

It is possible, however, that the relative importance of different depth cues varies according to the strength of the signal they offer. For instance, had we used the same object as in the present study but with a greater simulated distance, binocular disparities would have been smaller and this could have reduced or even eliminated the dominance of stereo over above or below lighting. Alternatively, maybe the same effect could be obtained with a manipulation of above or below lighting that involves greater position disparities between the two light sources. These issues will need further studies to be elucidated.

4.3 *Convexity prior*

We may note also that with 2-D displays participants responded "convex" on more than 50% of trials, even with lighting from below. We interpret this finding as further support for the observations of Langer and Bülthoff (2001) demonstrating a bias towards an interpretation of shapes as convex. Furthermore, these findings suggest, in support of previous results by Liu and Todd (2004), that the bias for convexity is stronger than the bias for the above or below direction of illumination.

It is also important to note that, in the normal stereo condition, when the stimuli were lit from above, the rate of convex responses was of 90% instead of 100%, as we might have expected. We note, however, that the depth information carried by the stimuli was rather impoverished. Indeed, the only available depth cues were binocular disparity, whose informativeness was probably advantaged by the flat extremity on the shapes, and shading. It is possible that with so little information some ambiguity remained about the convexity of the stimuli, even with normal stereo and lighting from above.

5 Summary

The goal of the present research was to determine if shading and stereopsis have independent or interactive contributions to shape perception. An experiment using a shape judgment task (ie to determine if the shape is convex or concave) was designed. The results show that the effects of display mode and lighting direction are additive—that is, they do not interact. This indicates that stereopsis and shading have their own independent contributions to shape perception. In other words, each depth cue appears to be processed independently and to affect convexity–concavity judgments to a degree that is independent of the direction suggested by the other cue.

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