Research Report

STEREOSCOPIC SURFACE INTERPOLATION SUPPORTS LIGHTNESS CONSTANCY

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Abstract—*The human visual system has a remarkable ability to construct surface representations from sparse stereoscopic, as well as texture and motion, information. In impoverished displays where few points are used to define regions in depth, the brain often interpolates depth estimates across intervening blank regions to create a compelling sense of a solid surface. The set of experiments described here examined stereoscopic interpolation using a novel technique based on lightness constancy. The effectiveness of this method is notable because it stands as the only technique to date that unequivocally examines the perception of interpolated surfaces, and not surfaces inferred subjectively from depth information in the stimulus. Further, these data support the growing evidence that a primary function of the stereoscopic system is to define three-dimensional surface structure.*

The human visual system is adept at constructing surface representations from very sparse information, as evidenced by the formation of subjective surfaces in regions where explicit depth information is absent. This phenomenon has been studied in a variety of contexts, including motion, texture, and stereopsis. It has been argued that the visual system's facility for detecting and recognizing surfaces reflects the existence of surface-based representations that are derived from multiple sources of information (Carman & Welch, 1992; Hildreth, Ando, Andersen, & Treue, 1995; Marr, 1982). A simple example of a subjective surface is shown in Figure 1. Note that, despite the relatively large blank regions in this stereogram, observers see a solid square surface in front of a solid background. We use the term *interpolation* to refer to the assignment of depth information to these blank regions in the display to form the percept of a surface.[1]

Properties of stereoscopic interpolation have been explored using psychophysical (Collett, 1985; Glennerster, McKee, & Birch, 2002; Julesz & Frisby, 1975; Vreven & Welch, 2001; White, 1962; Wurger & Landy, 1989; Yang & Blake, 1995), computational (Grimson, 1982; Mikaelian & Qian, 2000), and physiological (Janssen, Vogels, & Orban, 2000a, 2000b; Qiu, Endo, & von der Heydt, 2001) techniques. Psychophysical experiments have provided useful information about some aspects of surface interpolation; however, the techniques used to date all provide additional information regarding the location of the interpolated surface, such as monocular figural information, the location in depth of neighboring elements, or subjective contours. For example, one popular means of examining surface interpolation is to ask observers to use a probe stimulus to indicate the perceived location in depth of an interpolated region. Observers perform this task reliably, but may base their judgments on the perceived depth of individual elements in the display; no surface interpolation is required. Surprisingly, despite the reported salience of the surface percept, there has been no objective means of assessing surface interpolation. In this report, we present a novel paradigm based on a lightness-brightness illusion that provides the first objective[2] evidence that stereoscopic surface interpolation occurs, can be evaluated empirically, and supports lightness constancy.

Lightness constancy is a well-known phenomenon in which surfaces maintain their perceived reflectance (i.e., lightness) despite changes in the intensity and direction of illumination. However, the misapplication of lightness constancy can result in striking illusions of apparent reflectance and brightness (i.e., perceived luminance). Most investigations of illusions of this type have relied on two-dimensional figural information, although there is convincing evidence that the stereoscopic depth of surfaces can influence their perceived lightness (Buckley, Frisby, & Freeman, 1994; Gilchrist, 1977; Kingdom, Blakeslee, & McCourt, 1997), as can depth from other pictorial cues (Knill & Kersten, 1991). Consider the stimulus shown in Figure 2 (from Adelson, 1993). The regions indicated by arrows are the same shade of gray, but the upper region appears darker. One explanation of this illusion (though see Todorovic, 1997, for an alternative account) is that the dark row in the bottom portion of the figure is interpreted as receiving less illumination than the other rows. This could be either because of a sharp change in the light source or a sharp change in surface slant, though the latter is more likely in the real world and is consistent with the apparent three-dimensional shape of the object.

We applied this logic to stereoscopically interpolated surfaces to generate the stimulus shown schematically in Figures 3 and 4. The stimulus consists of a rectangular gray field containing a horizontal darker-gray strip. Black texture elements are scattered throughout the upper and lower regions, but no elements are placed within the strip. When the upper and lower texture elements are co-planar, the strip should not be subject to the lightness-brightness illusion. However, when the upper set of elements is shifted in depth toward the observer relative to the bottom set of elements, as depicted in Figure 4b, interpolation of a slanted surface across the central gray strip could theoretically support the lightness-brightness illusion. That is, if it is assumed to receive less illumination than the upper and lower portions of the display, then some of its comparatively lower intensity will be attributed to this factor, and the region will be perceived as brighter than it is when no depth offset is present. Further, the perceived slant of the hypothetical subjective surface and the corresponding illusion

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1. A distinction has been made (see Yang & Blake, 1995) between interpolation as described here and the *propagation* of depth information from one element to another in a scene (as studied by Mitchison & McKee, 1985, 1987).

2. It is true that the brightness judgment task we used to evaluate surface interpolation is a subjective one; however, judgments in this task, unlike other tasks, cannot be based on surfaces inferred subjectively from the information in the stimuli.

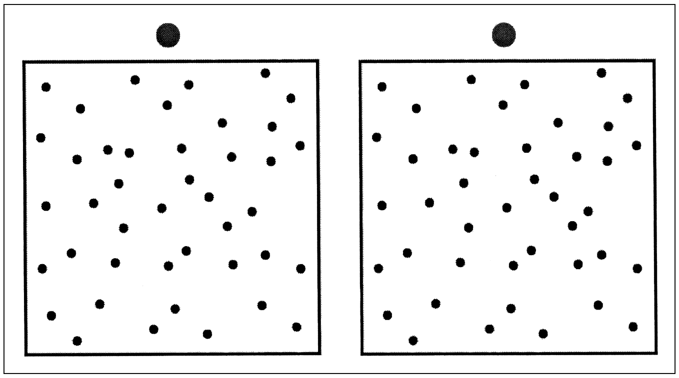

Fig. 1. A classic random-dot stereogram, viewed by crossing the eyes to align the two upper dots, and then focusing on the resultant image. Notice how the central square appears continuous and solid, despite large blank regions that contain no depth information.

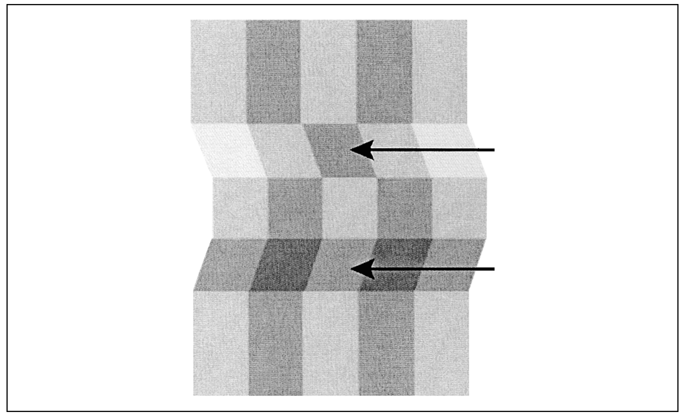

Fig. 2. Example of a lightness-brightness illusion adapted from Adelson (1993). The two patches indicated by the arrows are the same shade of gray, but the upper patch appears darker. This phenomenon has been explained with reference to the three-dimensional interpretation of this stimulus as a ridge. This interpretation suggests that the lower patch receives less illumination than the upper patch. When presented with two identical gray regions at the retina and the knowledge that one region receives less illumination than the other, the visual system apparently compensates for the reduction in illumination by increasing the perceived luminance at that location.

should increase systematically as the relative depth between the upper and lower texture elements is increased. We evaluated these predictions in the experiments that follow.

METHOD

Participants

Observers ($N = 5$) were volunteers ranging in age from 23 to 38. All had normal stereoacuity (RandDot™ stereotest) and normal or corrected-to-normal visual acuity. Four of the subjects were naive as to the purpose of the study; the 5th subject was one of the authors (L.M.W.).

Stimuli and Apparatus

A Macintosh G4 computer running Matlab™ software and the VideoToolbox (Pelli, 1997) was used to create the stimuli and present them on a Clinton™ 21-in. Monochrome monitor. Stereographics™ shutter glasses were used to present stimuli stereoscopically at a frame rate of 60 Hz per eye.[3] Observers were seated 1 m from the screen, and their head position was stabilized using a combination head and chin rest. The test and comparison stimuli were presented in rectangular windows (5.7° × 8.5°) cut 5.7° apart in a cardboard occluder, as illustrated in Figure 3. In both stimuli, sparse, randomly positioned black dots (diameter = 5.2′) on a light-gray background were scattered above and below a central midgray, horizontal strip (5.7° × 1.3°). In the test stimulus, the luminances of the background and the horizontal test strip were 33.0 and 21.9 cd/m^2, respectively. The luminance of the background in the comparison stimulus was varied in blocks of trials (28.7, 31.5, 34.4, or 37.4 cd/m^2), so that it could not be used as a reference for the observer's brightness settings. Thin black horizontal lines that provided no disparity information marked the horizontal boundaries of the central strip. Before horizontal positional jitter was added to the texture elements, their center-to-center spacing was 0.31° (vertical) and 0.91° (horizontal). Random horizontal jitter was added to each element with a maximum offset of 0.37°. In the test stimulus (on the left side of the display), the dots in the upper and lower portions of the display were displaced in depth in opposite directions, creating the percept of two offset fronto-parallel planes (Fig. 4b). The comparison stimulus was identical in form, but all elements were in the plane of the screen (Fig. 4a). The occluder ensured that the vertical edges of the horizontal strip were not visible and so provided no depth information. The display was carefully configured to ensure that all regions of the stimulus appeared to lie behind the occluder.

In Experiment 1, the texture elements abutted the edge of the horizontal strip, and the separation in depth of the two planes was 0, 1.7, 3.3, 6.7, or 10 cm. In Experiment 2, the vertical separation between the upper and lower sets of texture elements varied from 1.3° to 3.9° while their relative depth was either 0 or 10 cm. Figure 4c illustrates an intermediate vertical separation with a depth offset between two halves of the stimulus.

Procedure

Observers viewed the target and comparison patterns simultaneously and on each trial were asked to match the perceived luminance (i.e., brightness) of the horizontal strip on the right to that of the horizontal strip on the left. Note that the subjects' task was a brightness match. We therefore refer to the resultant distortion as a lightness-brightness illusion. There was no time limit imposed on each trial, although observers were discouraged from making prolonged adjustments. Test conditions cycled quasi-randomly, as did the luminance of the upper and lower regions and the initial luminance of the comparison strip. Observers were not directed toward any specific interpretation of the stimulus, although all reported seeing a slanted surface joining the upper and lower regions.

3. To render cross talk between the two eyes' views imperceptible, we used a fast-phosphor monochrome monitor and low-contrast stimuli.

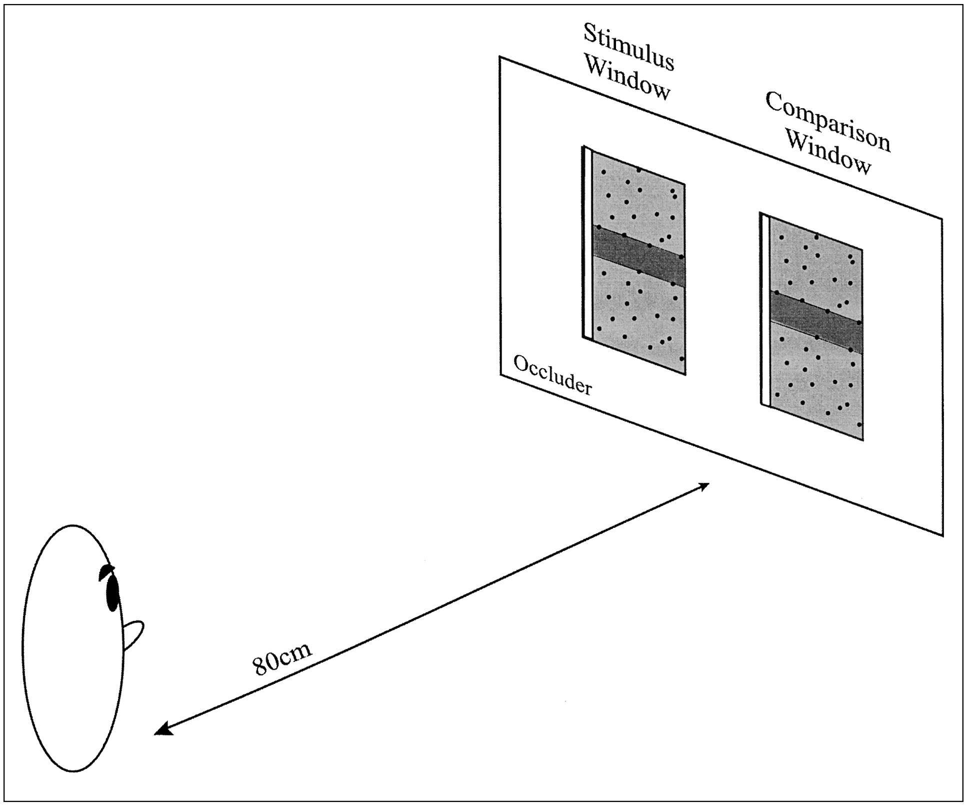

Fig. 3. Schematic of the experimental setup. The white frame represents an occluder with two adjacent windows through which the observer viewed the test and comparison stimuli. The subject sat 80 cm from the occluder, which was placed 20 cm in front of the screen. The task was to adjust the perceived brightness of the central horizontal strip in the comparison stimulus (right) to match the perceived brightness of the same region in the test stimulus (left). In the slant-matching task of Experiment 2, the comparison stimulus was dark gray except for four rows of dots that were arranged to match the dimensions of the horizontal strip.

RESULTS

Experiment 1

The magnitude of the illusion was quantified for each test condition by calculating the percentage change in luminance setting from the zero-depth condition. The independent variable (the relative depth of the two sets of elements) was converted to the geometrically specified surface slant to aid subsequent interpretation. The individual and group data are shown in Figure 5. As predicted, there was an illusion, and it varied directly with the separation in depth between the upper and lower surfaces (larger separations created a stronger illusion).

We examined the extent to which the data can be explained by the visual system applying Lambert's law to achieve lightness constancy. Lambert's law is described by Equation 1:

$$I_e = I_a R + I_p R\cos(\theta + \alpha), \tag{1}$$

where I_e is the intensity of illumination at the eye, I_a is the ambient illumination, R is the surface reflectance, I_p is the point illumination, θ is the surface normal, and α is the elevation of the point source of illumination. Hypothetical setting data were computed as in Equation 2 choosing values for I_a, I_p, R, and α:

$$I_{hyp} = I_{e\ veridical} + (I_{e\ veridical} - (I_a R + I_p R\cos(\theta + \alpha))). \tag{2}$$

Values for θ were those specified by the disparity-defined surface slant. It can be seen in Equation 2 that setting errors, deviations from the target-strip luminance $I_{e\ veridical}$, result when the surface is assumed to be illuminated to some extent by a directional source. We obtained values for the four parameters in Equation 2 that best described each observer's settings in a least squares sense. Observed and hypothetical data were then expressed as illusion magnitude, given as a percentage of the target-strip luminance. The resulting fits (dashed lines in Fig. 5) were consistent with the proposal that subjects used a physical model of illumination in judging the brightness of the interpolated region. This is an intriguing possibility that warrants further experimental evaluation.

The results of Experiment 1 show that in the test stimuli used, a slanted surface is interpolated between the two sets of textures, and that this surface is subject to a consistent lightness-brightness illusion well described by Lambert's law. As a first step toward defining the

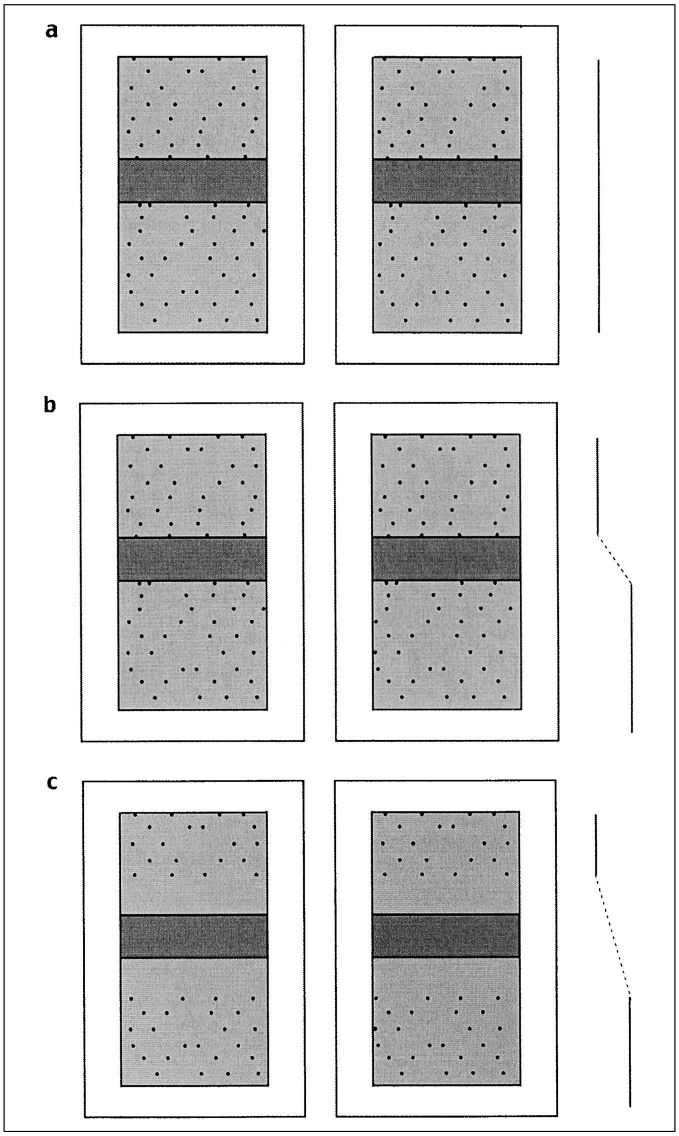

Fig. 4. Stereogram illustrations of the test stimuli, with depth profiles indicated (lines to the right). To view each stereo pair, align the white frames surrounding the two images by crossing your eyes. Dotted lines represent possible interpolated surfaces. In the experimental setup, the comparison stimulus (not shown here) was always frontoparallel, as shown in (a). In Experiment 1, the upper set of elements in the test stimulus was displaced in depth toward the observer, and the lower set was displaced by the same amount in the opposite direction (b). In Experiment 2, the separation of the upper and lower texture elements was varied, as illustrated in (c). Because of luminance and geometric artifacts introduced by the printing process, the lightness-brightness illusion is not likely apparent in this figure.

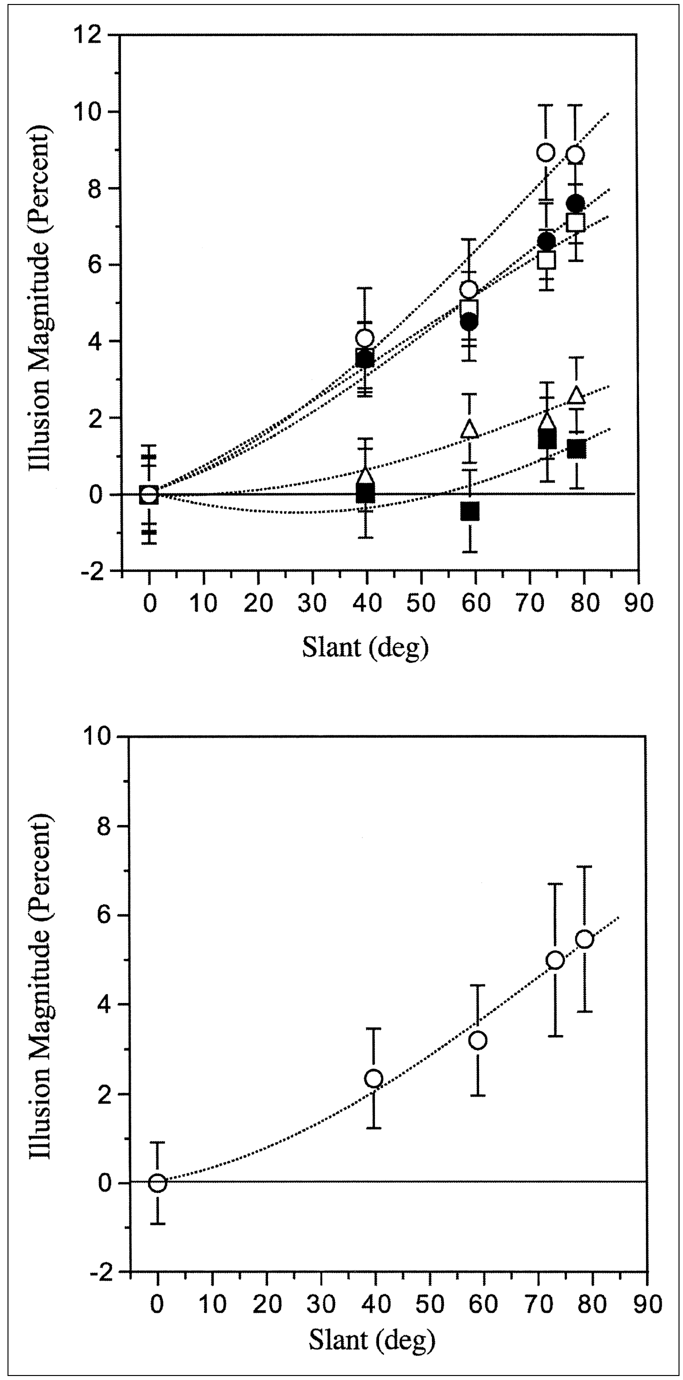

Fig. 5. Magnitude of the lightness-brightness illusion in Experiment 1. The top panel shows results for individual subjects; each symbol represents a different subject and a total of 16 observations. The bottom panel shows the group average. In both panels, larger illusion magnitudes reflect increasingly high (i.e., brighter) gray-value matches. Note that depth on the abscissa was converted to slant to aid interpretation of the data. The dotted lines show the best-fitting function based on the Lambertian model. Error bars represent ±1 *SEM*.

range of this interpolation process, in Experiment 2 we increased the separation between the upper and lower texture elements. The resulting stimuli were highly ambiguous, and therefore could provide important insight into the flexibility and scope of stereoscopic interpolation. We also examined matched slant for these patterns to determine whether the apparent slant of the strip varied with separation in a manner consistent with the disparities in the stimulus, and if the matched slant covaried with the brightness settings in the expected (i.e., approximately linear) way.

Experiment 2

In Experiment 2, we gradually increased the edge-to-edge separation of the upper and lower sets of texture elements (see Fig. 4c). As in Experiment 1, there were many valid interpretations of the stimulus. One possibility was that subjects would continue to interpolate a planar surface connecting adjacent upper and lower elements. If so, the matched slant of the interpolated surface would be expected to vary inversely with separation, as would the amount of the lightness-brightness illusion. However, if the percept of a slanted surface was lost, the illusion would also disappear.

We found that there was a gradual reduction in illusion magnitude with increasing separation (Fig. 6), and that interpolation of a slanted surface and the resulting illusion was maintained up to the maximum separation tested (3.9°). To confirm that subjects did perceive slant in the ambiguous horizontal strip, we also assessed perceived slant more directly using a matching task in which the test stimulus was identical to that described in the Method section and the comparison stimulus consisted of four horizontal rows of dots positioned within the region corresponding to the horizontal strip in the comparison stimulus window. Observers were asked to match the perceived slant of the subjective surface on the left with that of the rows of dots on the right. We found the matched slant to be consistent with the intensity data for all subjects. That is, observers who showed a considerable lightness-brightness illusion in Experiment 2 also made large slant settings. However, 1 observer, who exhibited no illusion at a separation of 0.5°, made small slant settings at this point. Further, we found that matched slant and the illusion covaried linearly, as expected ($r^2 = .96$).

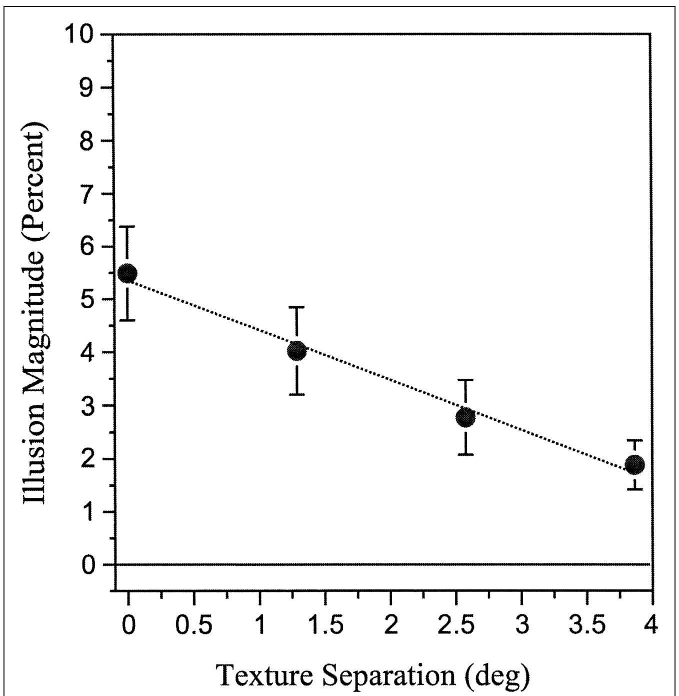

Fig. 6. Magnitude of the lightness-brightness illusion in Experiment 2 (calculated as in Experiment 1), averaged across the 5 subjects. Results are plotted as a function of the distance between the leading edge of the upper and lower sets of texture elements. The solid line represents expected results if no illusion occurred. Error bars indicate ±1 *SEM*.

An important aspect of the results of this experiment is the range of separations over which surface interpolation was maintained. Previous estimates of the upper limit of disparity interpolation range from 0.03° (Westheimer, 1986) to 0.3° (Yang & Blake, 1995). In our study, the maximum separation between the upper and lower textures was 3.9°, and even at this separation there was evidence of the interpolation of a slanted surface. Therefore, we propose that existing estimates of the upper limit for disparity interpolation underestimate the capacity of the disparity interpolation process. This discrepancy can be attributed to differences in stimulus configuration, for example, element size and spacing. Attempts to estimate the upper bounds on interpolation must be interpreted with care, and with specific reference to the stimulus configuration employed.

DISCUSSION

Initially, it may seem surprising that the visual system constructs a surface representation from such limited stereoscopic information. Indeed, the prevailing viewpoint in the stereoscopic literature is that the stereoscopic signal is used to estimate the relative depths of isolated points in a scene. However, some investigators have emphasized the role that stereoscopic signals play in promoting accurate surface perception (Anderson, Singh, & Fleming, 2002; Koenderink & van Doorn, 1976). This change in emphasis is supported by experiments that demonstrate surface interpolation from degraded patterns such as illusory figures (Ramachandran & Cavanagh, 1985; Vreven & Welch, 2001). Furthermore, experiments on visual attention have revealed that attention cuing by a stereoscopic stimulus is advantageous only if the cued region defines a surface in depth (Marrara & Moore, 2000). Recent single-unit recording studies also lend support to a surface-based model of stereopsis by showing that neurons as early as area V2 encode (at least) disparity gradients (Qiu et. al., 2001). Further, there is compelling evidence that single neurons in a subarea of the inferotemporal cortex respond selectively to stereoscopically defined surfaces with specific directions of curvature (Janssen et al., 2000a, 2000b).

In summary, the experiments described here provide the first evidence of stereoscopic surface interpolation that does not depend on a judgment of subjectively inferred surfaces. Further, we demonstrated that this paradigm, based on a lightness-brightness illusion, can be used to examine the nature of the interpolation process. This form of surface interpolation is robust, and (for the configuration we used) extends over at least 3.9°. In recent experiments, we have demonstrated that the properties of surface interpolation via other depth cues, such as motion parallax, also generate a reliable lightness-brightness illusion (Duke & Wilcox, 2002). Thus, this paradigm will prove valuable for the empirical study of texture- and motion-based surface interpolation and how these cues are combined in the visual cortex to form a common representation of surfaces in the environment.

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