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Stereopsis based on monocular gaps: Metrical encoding of depth and slant without matching contours[1]

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Abstract

It is often the case in binocular vision that one eye can see between two objects lying at different distances but the other eye cannot. We have found that the visual system is able to correctly interpret images produced this way in which a single solid rectangle in one eye is fused with two half-sized rectangles in the other eye separated by a vertical gap comprising the background. Two rectangles in depth are seen. It is as if the solid rectangle is treated as two components which each match one of the physically separated rectangles in the contralateral eye. The sign of the depth depends on which eye's view has the gap and its magnitude increases with gap width. Measured depth is found to be equivalent to real stereoscopic depth with a relative disparity equal to the monocular gap. If overall disparity differences are eliminated, between the left and the right images, variations in perceived slant of the two rectangles are still seen with increasing gap size. That two surfaces can be seen in metric binocular depth despite complete camouflage of their separation in one eye's view, suggests that stereopsis be regarded as a broad process of surface recovery not necessarily requiring image disparity at the location of the depth step. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Research on stereoscopic vision since Julesz (1960) has been focused on the matching process. Poggio and Poggio (1984) suggested that the main problem for stereoscopic theory was 'what to match' and 'how to match'. Recently, however, there has been a realisation that this may be too narrow a view, focusing too selectively on disparity specific mechanisms. As an alternative, there is now a growing appreciation that binocular vision is also heavily dependent on the processing of unpaired points and that binocular vision should be seen more generally as a surface recovery problem (Gillam & Borsting, 1988; Nakayama & Shimojo, 1990; Anderson & Nakayama, 1994), but also see von Szily (1921). Here we report another case where an unpaired component of the image plays a decisive role. Unlike previous examples, the unpaired component in our stereograms forms part of and is seen as contiguous with the background and is not in itself located in depth. Yet its presence critically influences the perceived layout of the foreground figures.

Consider a binocular viewing condition (represented in Fig. 1a) in which two rectangular planar objects of the same luminance and colour are placed side by side in the frontal plane but one (the left) is more distant than the other. When such planes are located centrally in the visual field, the left eye can see the background between them, whereas the right eye cannot because the images of the inner sides of the two rectangles are juxtaposed in that eye's view. The view each eye receives, assuming that the planes are black and the background is white, is shown in Fig. 1b. The left eye's view has a vertical gap whereas the right eye's view is solid.

Fusing these different images as stereograms (Fig. 2a,b) reveals the following: (1) two rectangles are per-

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ceived with a depth step between them; (2) the sign of the depth step depends on which eye receives the unpaired gap; and (3) the magnitude of the depth depends on the size of the gap (compare A and B).

What is striking about this demonstration is how readily the binocular visual system handles the problem of depth assignment more or less independently of conventional stereoscopic phenomena, i.e. binocular disparity and suppression. In fact, conventional theory which attributes stereopsis to the disparity of matched contours, would have to argue that we would see a slanted plane with a central white bar suppressing the congruent black region on the other eye but having no influence on perceived depth in its neighbourhood. (This hypothetical situation is shown in Fig. 1c). Instead we see two frontal plane surfaces separated by a depth step through which part of the white background can be seen. The effect is also maintained when vergence is varied (Appendix A). The nature of this finding becomes more evident if we compare the depth seen in Fig. 2a,b with that seen in a more conventional stereogram where the disparity is equal to the gap in our stereograms (Fig. 2c). The perceived depth appears similar in the two cases. Such a feat would seem to require the matching of the inner borders of the two rectangles comprising one eye's image with non-existent borders in the interior of the solid rectangle comprising the other eye's image. This rectangle appears to be somehow 'parsed' into two components which match the two physically separated rectangles in the contralateral eye. It is of some interest that the unpaired gap itself does not appear at a defined depth, but forms part of the more distant background. Thus the gap, in what we provisionally call "unpaired background stereopsis", imparts depth to adjacent regions but not to the gap itself.

It is worth considering whether the present phenomenon can be considered an extreme form of Panum's limiting case (Panum, 1858), where two lines in one eye are fused with one in the other eye and a depth difference is seen between the pair. A Panum account of our phenomenon would have to postulate that the large single rectangle in one eye is separately matched to each of the two smaller rectangles in the other eye. This is clearly not occurring. The perceived depth arising from such a match would be much greater than that seen here because the horizontal disparity would be very large; equal to the centre-to-centre distance between the two small rectangles. Enormous slants would also be apparent because of the very large width difference between each of the small rectangles and the large rectangle in the other eye. Fig. 2d illustrates the fusion required by the Panum explanation. The depth seen in Fig. 2e in which the shapes of the small and large rectangles differ, is also difficult to explain using a Panum explanation (see figure caption). Later in the paper we also shall show that the metric properties of the depth effect are incompatible with such an explanation.

To confirm our phenomenological observations we conducted an experiment to measure the magnitude of the perceived depth step as a function of monocular gap size.

2. Experiment 1: Perceived depth varies with unpaired gap size

2.1. Method

The stimuli consisted of horizontal black bars (8 arcmin high). In one image there were two such bars 80 arcmin long horizontally separated by a white gap of either 2.3, 3.9, 5.4 or 7.0 arcmin. The other image consisted of one solid bar which was always 160 arcmin in length (the combined width of the single bars in the

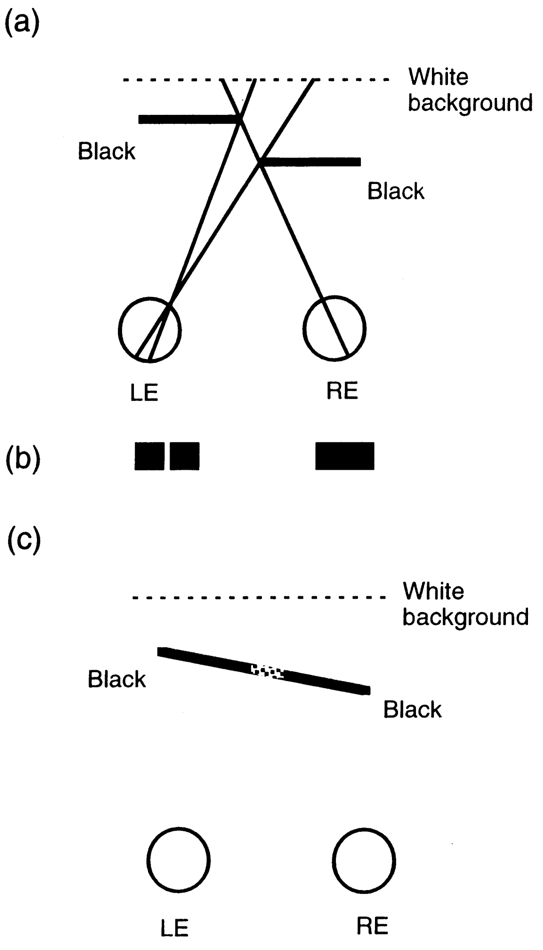

Fig. 1. (a) A bird's eye view of two eyes looking at black vertical surfaces at different depths seen against a white background. The left eye can see part of the white background through the gap between the black surfaces. The right eye sees solid black. (b) Binocular half-images produced by (a). (c) The perceptual experience of fusing (b) predicted by conventional stereopsis. The hatched region represents suppression of the black region by the white gap.

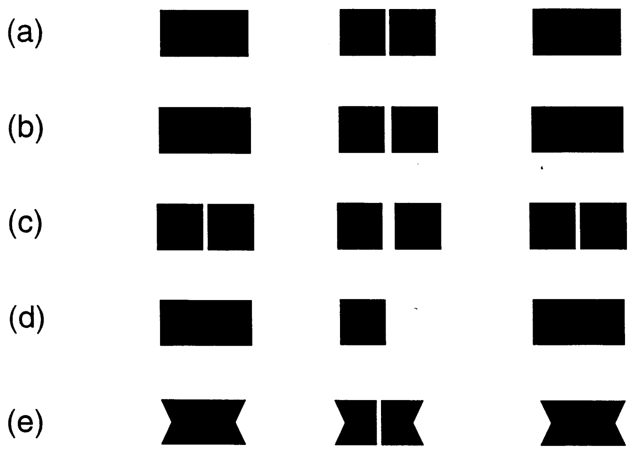

Fig. 2. (a) and (b) are two stereograms of the situation in Fig. 1 with different gap widths. They are easily fused. For crossed fusers the right rectangle appears closer when the left pair are fused. For uncrossed fusers, the left appears closer. (c) Conventional stereogram depicting two rectangles with a disparity equal to the gap used in (b). (d) One of the surface rectangles in (b) paired with the solid rectangle in the other eye. Fusion of this magnitude of disparity would be required by an explanation based on Panum's limiting case. (e) Stimuli in which the two figures in one eye are each of a different shape from the solid figure in the other eye and should be difficult to fuse as required by a Panum explanation. There is no sense of rivalry here or any sign that the visual system treats the sides of the figures as having an orientation disparity. The depth effect is easily obtained which supports the hypothesis that the solid rectangle is instead treated as two parts for the purposes of matching the two separate rectangles in the other eye.

other eye), regardless of the size of the gap in the other eye. An example of the stimulus is shown at the top of Fig. 3. All stimuli were presented on the screen of a Silicon Graphics Indy with left and right images alternating at 120 Hz and viewed through synchronised Crystal-Eyes liquid crystal shutter glasses. Viewing distance was 1 m.

The observer's task was to match the perceived depth difference between the two fused bars by means of a probe which was placed 81 arcmin below the test stimulus. The probe consisted of two adjacent horizontal lines each 160 arcmin long, centered on the gap. One of these lines could be moved vertically by moving a mouse. Observers were instructed to adjust the moveable line so that the magnitude and sign of the vertical separation of the two lines matched the perceived magnitude and sign of the depth interval between the bars. Each gap size was presented both on the left eye and on the right, and each of these eight conditions was presented once with movement of the left probe line and once with movement of the right. These 16 conditions were each replicated four times for each observer. Four observers were used. Of these, DA and DS were completely naive with respect to the phenomenon and the conceptual basis of the experiment.

2.2. Results and discussion

All observers fused the two images without difficulty. The probe settings were collapsed over the left/right probe positions to give eight settings per gap condition for each observer. Means of the settings for each observer as a function of gap width are shown in Fig. 3. Observers varied in the magnitude of depth reported. All however, showed increasing depth with increasing gap size and in all cases, the sign of the depth was consistent with the geometry of Fig. 1a.

The quantitative binocular depth response demonstrated by these results is remarkable considering that there were no matchable contours anywhere near the depth step and therefore, no disparity signal there. Conventional models of stereopsis, which depend on image matching, cannot account for this result.

In this experiment we have shown that there is a metrical variation in perceived depth which was proportional to monocular gap width. In the next experiment we ask whether the depth effect and its variation with gap width is equivalent to the effect of disparity in normal stereopsis.

3. Experiment 2: A comparison with normal stereopsis

The demonstration in Fig. 2 suggests that the depth effect achieved in the monocular gap stimulus (Fig. 2b)

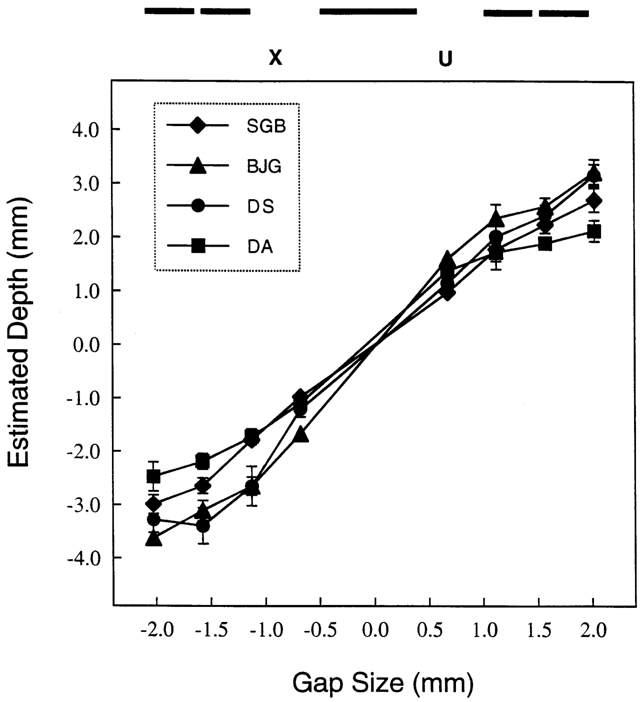

Fig. 3. The results of experiment 1. Means and S.E.s of the depth settings for each subject as a function of gap size. A free fusion version of the stimuli used is shown above the graph. Cross fusion of the left pair or uncrossed fusion of the right pair gives the appearance of the right line further back.

is similar in magnitude to that attained with normal stereopsis (Fig. 2c). As mentioned earlier, this suggests that the visual system might treat the large solid rectangle as if it were two rectangles having no (or zero) separation in that eye's view. Thus, the relative disparity of the two binocular rectangles seen in unpaired background stereopsis would be simply and metrically equal to the gap width itself. If this were indeed the case, the exact depth perceived for a range of gap sizes should be predictable. Our unpaired gap stereograms should have the same perceived depth as a normal stereogram having a relative disparity equal to the gap width. Experiment 2 explicitly tested this hypothesis—that stereopsis based on an unpaired monocular gap is geometrically identical to normal stereopsis with the same disparity using our assumed definition.

3.1. Method

The method was to match the apparent depth of two rectangles with a real binocular disparity (the stereo probe) so that they matched the apparent depth of two rectangles elicited by our unpaired gap stimulus.

The stimuli were presented on a Samtron 17-inch multisync monitor controlled by a Power Macintosh. Screen resolution was 1024 × 768 pixels. Viewing distance was 68 cm. The test stimulus for one eye was a pair of rectangles, each 87.35 arcmin wide × 174.7 arcmin high separated by a gap which varied between 2.93 and 17.49 arcmin in six equal steps. For the other eye, the stimulus was a single rectangle of the same height as those in the contralateral eye but with their combined width (174.7 arcmin). The stimulus with the gap was presented equally often in the left and right eye's view.

Directly below the test rectangles (207.2 arcmin from their bottom edge) was the stereo probe. To constitute the probe, both eyes were presented with two rectangles separated by a gap of 2.93 arcmin. These rectangles were each the same size as each of the two test rectangles separated by a gap. Disparity was introduced on any given trial by adding to or subtracting from the gap in either the left or right eye (for negative and positive disparities, respectively). Subjects controlled the disparity by means of a computer mouse. When the mouse was moved right, the disparity value increased. When it moved left, the disparity value decreased. The minimum disparity step which could be recorded was one pixel (1.46 arcmin).

The left and right views of both the test and comparison rectangles were fused by means of mirrors placed between the computer screen and the subject's eyes arranged to form a Wheatstone stereoscope. Fixation was not required. Subjects were asked to set the depth difference of the rectangles in the lower figure to match the depth seen in the rectangles of the upper figure. When satisfied with their setting they were to click the mouse button. A horizontal bar then appeared on the screen. Subjects had to position a mouse-controlled arrow cursor within this bar and click the mouse button when ready for the next trial. This ensured that they were fixating on the screen. Each combination of eye of gap and gap width was presented eight times for each subject.

Subjects used were two of the authors, (SB and BG), and JW, who was completely naive with respect to the phenomenon and conceptual basis of this experiment.

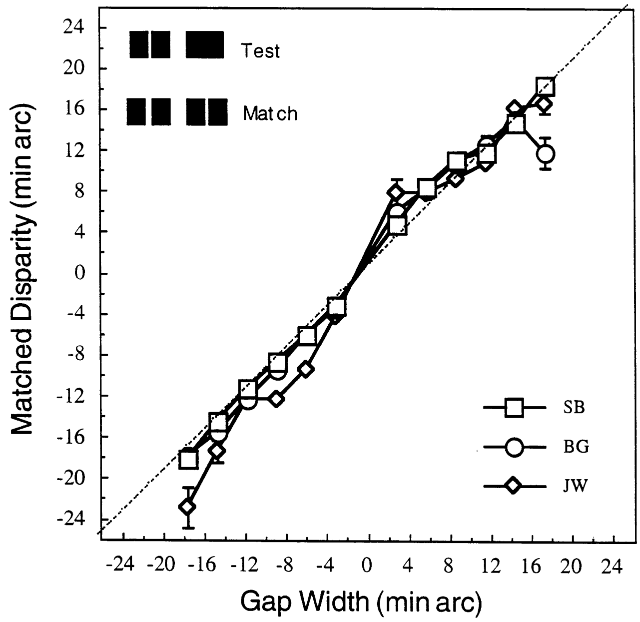

Fig. 4. The results of experiment 2. Means and S.E.s of the disparity settings of two rectangles in real stereopsis to match the apparent depth of two rectangles seen in unpaired background stereopsis. The disparity settings obtained are very close to the width of the monocular gap in the latter pair. Inset depicts examples of test and matching stimuli (see text).

3.2. Results and discussion

The results are shown in Fig. 4. If the gap is treated as a normal disparity, the results should fall on the dotted line; that is, the normal disparity set to equal the depth appearance of the monocular gap disparity should be equal to the gap width. This was found to be the case. The results were very precise as shown by the small standard errors. These data provide further very strong support for the hypothesis that the monocular gap in this case is treated as a disparity between the left and right eye views of two rectangles in depth. The precision of the data also strongly supports the view that the process by which depth is achieved is comparable to normal stereopsis.

It should be clear that the results do not support a Panum's limiting case explanation. The disparity in that case, as mentioned earlier, would be equal to the center to center distance between the two small rectangles separated by the gap (a disparity of > 87 arcmin) since the essence of the Panum explanation is that both of these rectangles would fuse with the entire solid rectangle in the other eye. It is clear that the perceived depths reported in this experiment correspond to disparities which are far below that very large magnitude.

The results are however consistent with the process postulated earlier in which the solid rectangle is 'parsed' into two parts to which each of the small rectangles in the other eye are matched. Fig. 5 shows the viewing geometry of this situation and illustrates how it predicts the binocular percept of two frontal plane rectangles, one more distant than the other[2] with the depth given by the width of visible background (gap size). There is however, a possible question concerning our interpretation which can be raised. As Fig. 5 shows, and as pointed out in the introduction, there is an overall disparity between the outer boundaries of the images in the left and right eye views in our standard stimulus. This disparity could arise either from a slant (if the uniocular gap is ignored) or from a depth step camouflaged in one eye's view (which is what is seen). The question is this. Does the gap serve to disambiguate the origin of the overall disparity and locate it at a depth step or does its presence actually elicit depth? To answer this question we conducted experiment 3 in which the overall disparity difference between the two eye's views was eliminated.

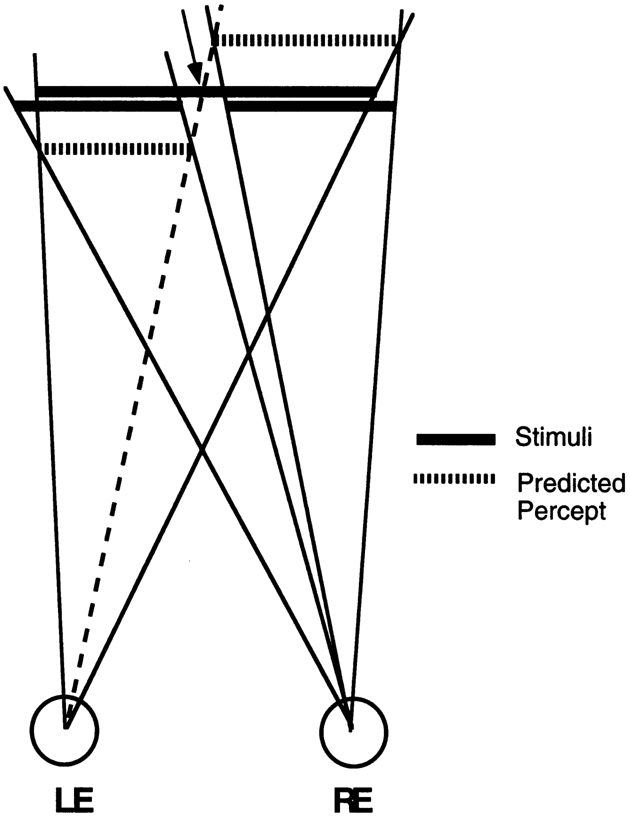

Fig. 5. The geometric basis of the depth predicted when two rectangles separated by a gap are presented to one eye (shown by the double black lines) and the other eye is presented with a solid rectangle which has the combined width of the rectangles in the other eye (shown by the single black line). The solid rectangle is assumed to be partitioned centrally (at the arrow) for matching with the two rectangles in the contralateral eye which produces a frontal plane solution. The percepts are shown by the hatched lines (see text). Other possible percepts, which do not obey the frontal plane constraint, and assume non-central partitioning of the solid rectangle, are shown in Fig. 9.

4. Experiment 3: Elimination of overall disparity between left and right eye view results in perceived slant for the two rectangles

In experiment 3, the width of the solid rectangle was made the same as the width of the two rectangles in the other eye plus the gap. If the gap in our earlier experiments served merely to locate the source of an existing disparity, all forms of apparent depth should now be eliminated since there is no disparity anywhere. Depth will still be seen however, if our previous analysis is correct; that the two rectangles surrounding the gap are each matched with a part of the solid image with the gap treated as the disparity.

Fig. 6a shows the viewing geometry of this new stimulus. It is assumed that the solid rectangle (shown by the black line) is (as appeared to be the case in previous experiments) treated as two equal parts which unite with the two rectangles (shown by the double lines) on the other eye. It should be noted that the viewing geometry now requires that the perceived binocular surfaces be slanted, since the rectangles in the image with the gap are narrower than the halves of the solid rectangle with which they are assumed to be matched. Fusion of Fig. 6b shows that the appropriate depth step is still seen in this case and is, as predicted, accompanied by an apparent slant of the fused rectangular segments towards the eye with the gapped image. The wider the gap the greater the foreshortening of the rectangles surrounding the gap relative to the halves of the solid rectangle in the other eye and therefore, the greater the predicted slant should be. The presence of slant in this situation and its quantitative relationship to gap size was confirmed in experiment 3. It should be emphasised that slant seen when the left and right eye images are of the same overall size cannot be due to disparity in the images since there is none. Slant is

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[2] Fig. 5 also predicts that the further rectangle will appear larger than the nearer one. This size difference was reported by subjects and can be perceived when Fig. 2b is fused.

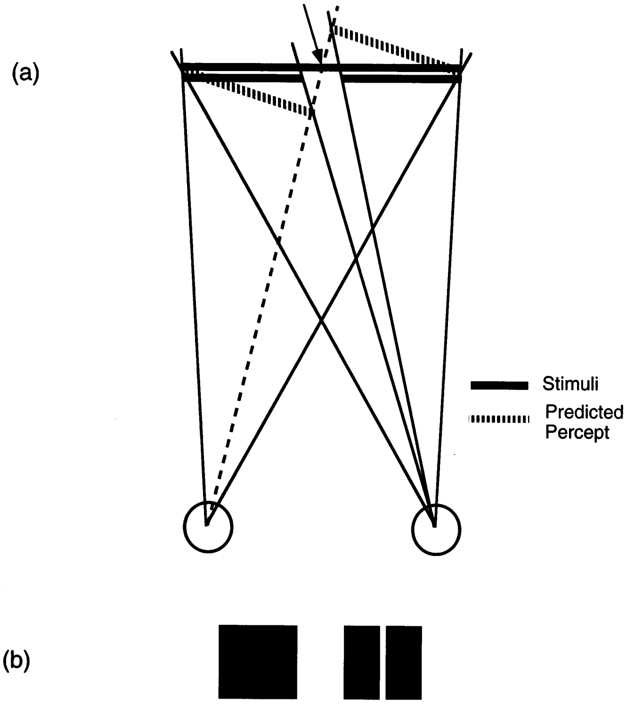

Fig. 6. (a) The geometric basis of the depth and slant predicted when two rectangles separated by a gap are presented to one eye (shown by the double black lines) and the other eye is presented with a solid rectangle which has the combined width of the rectangles plus the gap in the other eye (shown by the single black line). The solid rectangle is assumed to be partitioned centrally (at the arrow). This means that the resulting half rectangles are each wider than the congruent explicit rectangle in the other eye. The predicted percepts are shown by the hatched lines. (b) Images which satisfy the conditions illustrated in (a). When fused these images are perceived as slanted towards the eye with the gap. (see text)

however, predicted by the process we have already described, in which the gap elicits a parsing of the solid rectangle into two regions, which in this case do not precisely match in width the two smaller rectangles in the other eye.

4.1. Method

There were two rectangular segments on one eye, each 94 arcmin wide × 193 arcmin high, separated by a gap of either 3.6, 7.2 or 10.8 arcmin. The solid image in the other eye was the combined width of these rectangles (188 arcmin) in half the trials and 188 arcmin plus the gap width in the remaining trials. This allowed comparison to be made of the degree of slant perceived in the new condition, where the width of the solid rectangle includes the gap, and the condition used in previous experiments, where it does not. The stimuli were presented using the same apparatus as in Experiment 1. Viewing distance was 1 m. Each observer was presented with each of the three gap widths combined with each of the two solid image conditions. Each of these six conditions was presented both with the gap on the left eye's image and the gap on the right eye's image (12 conditions in all). There were three sessions per observer with each of the 12 conditions shown three times per session in random order. Observers were required to judge the slant of the rectangle on the left on each trial by means of a probe line placed 30 mm below the bottom of the test display and centred on the left image. The probe line could be rotated by a lateral movement of the mouse. The probe consisted of a 23 mm long line of variable orientation (0–360°) which pivoted in the centre of a fixed horizontal line (45 mm long). Observers were asked to set the frontal plane angle between these two lines to match the perceived slant in depth of the rectangular segment. Clockwise deviations were scored as negative and counter-clockwise deviations positive. Three observers were used. SAM was completely naive with respect to the phenomenon and the conceptual basis of the experiment.

4.2. Results and discussion

The results are shown in Fig. 7. First, consider the data for the case where the outer boundaries of the left and right half images are the same and where we predict a perceived slant proportional to gap width. As predicted (see filled circles), there is a strong relationship between gap width and slant and it is appropriately signed according to which eye viewed the gap[3]. Contrast this with the perceived slant seen with stimuli more similar to that used in Experiments 1 and 2 (open circles). Despite some noticeable slant in two (BJG and SAM) but not in the third observer (SGB), it is clear that overall, the slant perceived is much reduced. This is just the reverse of what would be predicted on the basis of the overall disparity present per se. These results, as well as informal observations of Fig. 6b, show that the depth response to an unpaired gap occurs without explicit disparity of any kind between the images.

In Fig. 8 we show that the visual system is able to combine appropriately three rectangles in one eye with narrow vertical gaps between them and one solid rectangle in the other eye. The reader can use this figure to directly experience the effect of varying the width of the solid rectangle (see figure caption).

It is clear from these observations that unpaired background stereopsis occurs in the absence of any conventional disparity. It is also clear that the visual system is able to arrive at a sophisticated resolution of

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[3] The slant is symmetric for one subject (SGB) but asymmetric for the other two (BJG and SAM). Asymmetry is consistent with partitioning of the solid image at a location other than the middle. This would have the effect of making one binocular rectangle appear more fronto-planar but the other one less fronto-planar than for central partitioning.

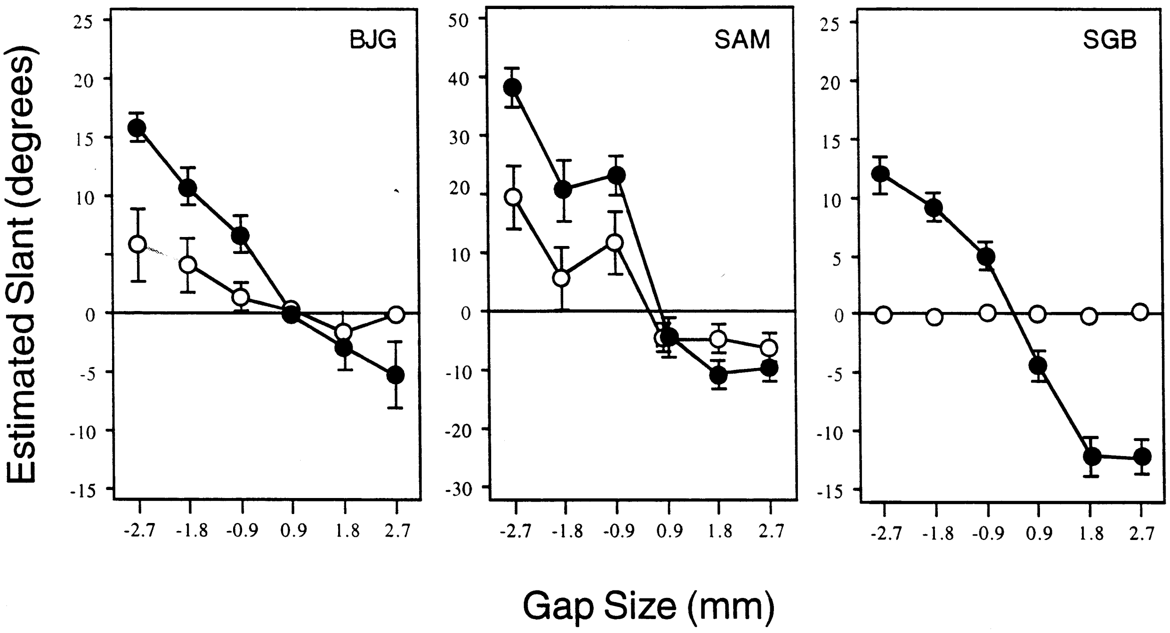

Fig. 7. The results of experiment 3. Mean slant settings for each subject for each gap size for the condition in which the width of the solid rectangle included the gap (filled circles) and the condition where it did not (open circles).

binocular stimuli, including appropriately graded slant, without the matching features normally considered essential for stereopsis.

5. General discussion

5.1. Novelty and significance of this finding

We think our results present a significant puzzle and possible challenge to our current understanding of stereopsis and depth perception. The prerequisite for conventional stereopsis, the pairing of image elements, one from each eye, is clearly not fulfilled for 'unpaired background' stereopsis. Furthermore, the distance of the monocular gap from any contours in the contralateral eye far exceeds the known range of stereo mechanisms, and even if the contours of the gap were to pair with such remote contours, the depths predicted do not agree with those we obtained. Thus, we cannot call upon the presumed coding properties of disparity selective neurons (Poggio & Fischer, 1977) to 'explain' the proper sign and the continuous gradations of depth perceived, all in the absence of any other cues to depth.

Recently there has been growing interest in seeing the problem of stereopsis more broadly; as a process of surface recovery rather than simply one of disparity coding or depth interpolation. Several observations have played a role here. First is the existence of 'daVinci' stereopsis (Kaye, 1978; Nakayama & Shimojo, 1990), indicating that unpaired image points can lead to reliable orderings of depth in relation to fused regions according to the geometrical constraints posed by occlusion. Second is the facilitation of normal stereoscopic depth perception by the presence of unpaired regions (Gillam & Borsting, 1988). Following this were new reports on the critical role of unpaired image regions in a wider variety of contexts. It was found for example that the monocular image may cause a subjective contour to be located at the intersection of the monocular and binocular regions (von Szily, 1921;

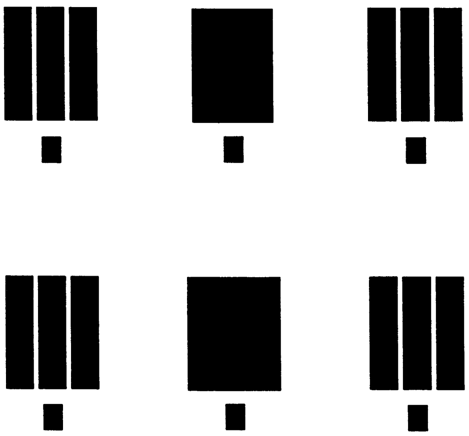

Fig. 8. Sets of three rectangles which can all be simultaneously fused with the solid rectangle in the other eye. In each case, fusion of the left pair reverses the depth relations seen when the right pair is fused. In (a) the solid image is the combined width of the three rectangles. The rectangles are seen as flat surfaces at successively increasing depths. In (b) the solid image is the combined width of the three rectangles plus the two gaps. The rectangles all look slanted, but at the same depth (like venetian blinds). The bases of these percepts are shown in Figs. 5 and 6, respectively.

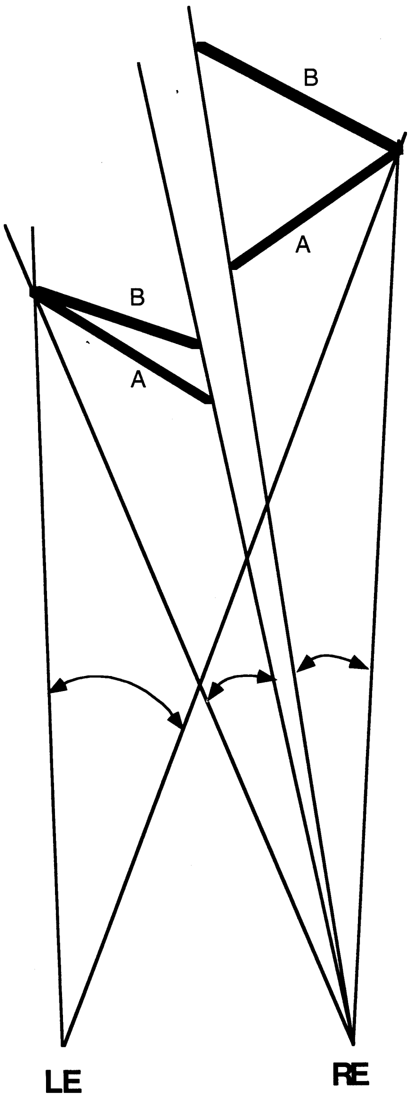

Fig. 9. Showing that two equal angles separated by a gap in one eye combined with a solid angle of their combined size in the other eye could arise from an infinite variety of pairs of objects at different depths and slants. Two of these arrangements are shown- one labelled A, the other B. The frontal plane solution is shown in Fig. 5.

Nakayama & Shimojo, 1990; Anderson, 1994; Anderson & Nakayama, 1994; Anderson & Julesz, 1995). All of these results were of importance because they indicated that 'matching and or pairing' might not be the primary event in stereopsis; that the registration of unpairedness may have precedence in determining how matching is to proceed. Unpaired background stereopsis adds considerable credence to this claim. A process of breaking camouflage by using information from the other eye to infer a contour can be nothing like existing models of the matching process.

Da Vinci stereopsis refers to the case in which a monocular region of a fused binocular array is perceived in depth relative to the binocular region. In the case of unpaired background stereopsis on the other

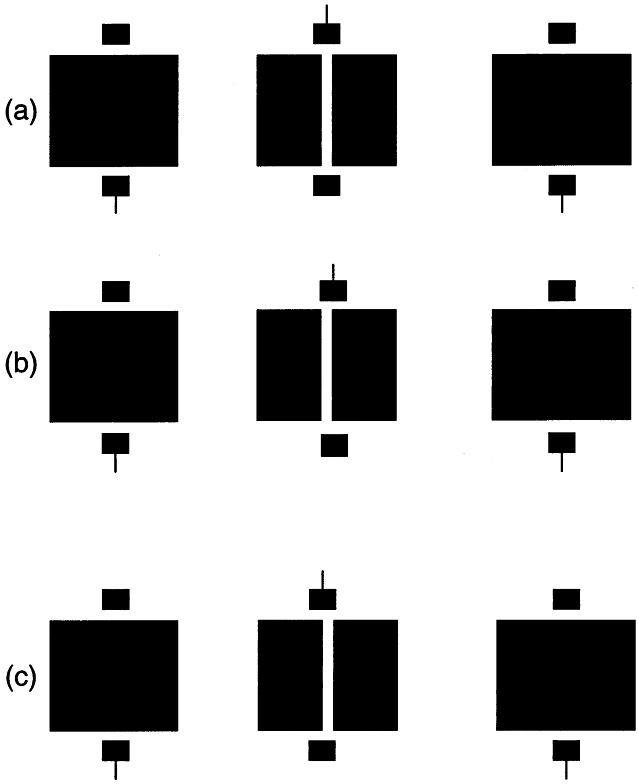

Fig. 10. Showing that the sign of the apparent depth at the gap does not depend on fixation (see text). Crossed fusers should fuse the left pair and uncrossed fusers the right pair of each set.

hand, depth is not seen in the monocular part of the image (which is the featureless background) but in the binocular parts (the rectangles) relative to each other. The two images through which the background is visible fuse fully with the one image in the other eye in which there is no visible background. This superficially resembles Panum's limiting case, which also involves the fusion of two images with one. We have shown above that the present phenomenon differs from Panum's limiting case. We believe it is a novel phenomenon[4] in which the two rectangles in one eye each appear to fuse with part of the solid rectangle in the other eye. The parts are not present in the monocular image but are generated by the binocular context. In experiment 2, results were shown to be metrically consistent with fusion of each of the rectangles separated by background with half of the solid rectangle in the

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[4] A phenomenon which appears to be somehow related to ours is Kumar's (Kumar, 1995) report that if two rectangles are separated by a gap which has identical width in the two eyes but which differs in luminance, a depth effect can be seen. Although Kumar attributes this effect to occlusion, it is not clear to us just how occlusion would produce identical gaps in the two eyes but with a luminance difference. It could be that when the luminance differences becomes very great, the rectangle with the low luminance gap is treated as solid but Kumar does not demonstrate or analyse the case which is our concern here in which rectangles in depth produce no gap in one eye.

other eye; resulting in the perception of two frontal plane rectangles separated in depth. When the width of the solid rectangle is greater than the sum of the widths of the two rectangles in the other eye, consideration of the viewing geometry indicates that any partitioning will lead to slant in one or both of the fused rectangles. The presence of this slant was confirmed in experiment 3. We have not considered cases in which the solid rectangle is smaller in width than the sum of the widths of the two rectangles in the other eye. This would be produced by a spatial arrangement in which the images of the two rectangles in depth are separated in one eye's view but have overlapping images in the other eye's view. The geometry and perceptual outcomes in this situation will be the subject of a future paper.

There are other distinctive characteristics that make unpaired background stereopsis particularly worthy of mention. First, and most important is the convincing absence of a plausible set of matching contours in the other eye that could account for the depth seen as some variant of normal stereopsis. Second, is the metrical coding of depth; the fact that perceived depth is graded with monocular unpaired gap width in the absence of any plausible matches that could account for these gradations. We describe these two points in the light of previously published reports of daVinci stereopsis.

Nakayama and Shimojo (1990) indicated that some form of daVinci stereopsis could be metrical, that the perceived depth of an unpaired vertical line adjacent to a binocular region would vary when its horizontal distance from the binocular region was varied. Nakayama and Shimojo did not claim, however, that the perceived depth was mediated by a distinct process independent of normal stereopsis, and the depth seen is consistent with the view that the unpaired line's depth can be predicted from double or Panum matching (Ono, Simono & Shibuta, 1992; Gillam, Blackburn & Cook, 1995).

Nakayama and Shimojo (1990) also described a second aspect of daVinci stereopsis, reporting that unpaired regions could give rise to a subjective surface hovering in front of the background. Not reported in the paper, however, were their failed attempts to show a graded depth of the subjective surface with increasing widths of the monocular points, a finding that led them to believe that some aspects of da Vinci stereopsis were more qualitative, not metrical as is conventional stereopsis.

In this context, Liu, Stevenson and Schor's (1994) claim regarding daVinci stereopsis was of considerable interest. They reported that a phantom surface, similar but not identical to that reported by Nakayama and Shimojo (1990), could be perceived as graded in depth with an increase in the width of a monocular region, suggesting metrical depth without the presence of ordinary stereopsis. Gillam (1995) disputed this claim by noting that the horizontal edges in Liu et al.'s stereogram could be responsible for the depth perceived. In a follow up paper, Liu, Stevenson and Schor (1997) while disagreeing with the specifics of Gillam's point, acknowledged that their original stimulus did contain information such that the disparity of obliquely oriented Gabor filters in each eye could supply the needed disparity information to account for the depth seen. As such, it became clear that metrical depth without any matching had not been demonstrated.

In a later development Gillam and Nakayama (1999) used stereograms similar to those presented by Liu et al., but designed to eliminate all disparity information. They showed that metrical depth for a phantom figure bounded by subjective contours can be obtained from unpaired points alone, uncontaminated by conventional stereopsis. Yet the depth obtained was not precisely related to the width of the unpaired region. As in most cases of da Vinci stereopsis, (Nakayama & Shimojo, 1990) the stimulus poses only a one sided constraint in determining perceived depth. The present report goes further in showing that perceived depth on the basis of an unpaired region can be comparable in accuracy to conventional stereopsis. Why should background stereopsis be more accurate than other forms of stereopsis from unpaired regions? Depth is after all unconstrained here too in that the solid rectangle could be made up of a wide range of objects at different depths with different slants (Fig. 9). It appears that the visual system finds a frontal plane solution if one exists. The stimuli we used in experiment 2, where stereoscopic accuracy was found, are consistent with a frontal plane solution and importantly the only one possible. With this constraint the gap/disparity completely determines the depth[5].

We have only begun to determine the parameters of binocular images which give rise to depth and slant perception in this paradigm. We could for example vary the relative overall widths over a much wider range or place the gap asymmetrically. It is possible that not all conditions will produce depth consistent with simply treating the gap as a disparity.

Finally, it should be noted that the resemblance between background stereopsis and regular stereopsis could be learned by association. Normally, when an array such as shown in Fig. 1a is viewed, there would be texture on the two objects which would have disparity equal to the gap size. In addition, the width of the monocular gap would be the same as the difference in widths of the binocular gaps revealed by a small lateral head movement.

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[5] A frontal plane solution is consistent with the lack of perspective in the stimuli and perhaps more importantly represents a better 'generic view' (Nakayama & Shimojo, 1992) in that the images of frontal plane rectangles will alter less with lateral changes in viewpoint than those of slanted rectangles.

Appendix A

The stereograms shown in Fig. 10 have fixation bars and nonius lines (a) in the center of the figure (b) in the further plane and (c) in the nearer plane. These stereograms were presented to ten naive subjects. All reported the same depth effects (the rectangle on the side of the gap as further) in all cases. This rules out fixation as a critical factor in the effects reported here.

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