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Stereoscopic depth cues can segment motion information

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Abstract. Can the motion system selectively process elements at a particular depth? We attempted to answer this question using global coherence tasks in which signal and noise elements could be given different disparities. In experiment 1 we found that, if all the signal elements had a disparity different from that of the noise elements, performance was far better than when they had the same disparity (at least for stereo-normal observers). In a second experiment we found that adding additional noise elements to the motion task had no effect if they had a different disparity (however, they had a marked effect for stereo-blind observers). We conclude that stereo disparity can be used as a segmentation cue by the motion system.

1 Introduction

Image segmentation is a goal of the early visual system that is necessary to identify things that 'belong together', in order to forms objects. The visual system appears to exploit the regularities of the physical world in order to do this. Thus the Gestalt psychologists described how 'things' that are similar seem to group together. Among the many possible dimensions on which things may (or may not) be similar are movement, colour, and stereoscopic depth — and each of these seems to be a powerful cue for such segmentation (see Braddick 1974; Stilling 1883; Julesz 1971, respectively). In natural images, objects are likely to share similarities along several dimensions. Out of my window I can view a car that is red, moving to the left, and at a particular distance from me. Can we take advantage of image segmentation along one dimension to inform segmentation along other dimensions?

This question has been approached from a number of angles. For instance, a number of experiments have been designed to establish whether irrelevant variations along one dimension will hinder detection of a target defined on another dimension (Callaghan et al 1986; Morgan et al 1992; Møller and Hurlbert 1997; Snowden 1998). For instance Snowden (1998) defined targets by a variation in the orientation of the target elements compared to the background and then added irrelevant variations in either colour or stereo depth. For targets that involved the grouping of the constituent elements (such as judgments of the shape of an area defined by these elements) large interference effects were observed suggesting that image segmentation does indeed involve information from several image dimensions.

A second approach has been to have an image where some elements are defined as signal and others as noise, and to measure the percentage signal required to perform a task. If we then give an image segmentation cue as to which elements are signal and which are noise (for instance colouring the signal elements in red and the noise elements in green), can we then selectively process the red elements and thus reduce the amount of signal elements needed? In the domain of motion perception just such an experiment was performed by Croner and Albright (1997). They employed the 'global coherence motion task' (Newsome and Paré 1988; Snowden and Braddick 1989), where a number of signal dots are moved in one direction (and the subjects' task is to identify this direction) and the remaining noise dots are moved in a random direction. They did indeed find that thresholds fell when this segmentation cue was provided [and this has been replicated by Snowden and Edmunds (in press)]. However, in seemingly related experiments, Edwards and Badcock (1994, 1996) showed that if one adds 'extra noise' to a global coherence task this extra noise disrupts performance even if it is of a different colour or polarity from those of the elements involved in the task the subjects have to perform. Again, these later findings have been replicated by Snowden and Edmunds (in press), who ruled out differences in luminance, speed, etc as possible confounds. Thus, while one set of findings appears to demonstrate that colour segmentation can be used by the motion system, another set seems to demonstrate that it cannot! A plausible explanation of the discrepancy might be that the differently coloured dots produce less masking than the same coloured dots (rather than none at all). Whilst this seems reasonable, the data do not seem to support this idea. In the studies of Edwards and Badcock the extra noise produced the same amount of masking whether or not it shared luminance/colour characteristics with the signal and noise task.

In this paper we present results from experiments that are logically identical to those of Croner and Albright (1997) and those of Edwards and Badcock (1994), save that we examine if information from stereo-depth cues, instead of those from colour, can lead to better performance on these tasks.

2 Experiment 1

In this experiment a global motion task was used, and stereo cues were added so that the signal elements and noise elements could have the same or different disparities (and therefore perceived depths). The signal elements could be assigned to a crossed or uncrossed disparity, and the noise dots could also be assigned to a crossed or uncrossed disparity, giving four conditions.

2.1 *Apparatus*

Stimuli were constructed with a VSG2.2 graphics board (Cambridge Research Systems) housed in a PC computer and displayed on a Mitsubishi Diamond Pro 20X colour monitor refreshing at 120 Hz. In order to produce stereograms, presentation of individual frames was linked to a pair of 'stereo goggles' consisting of two light valves (LV050AC, Display Tech Inc.) wired in opposite polarity. The frame signal inverted on each frame; thus on even frames one of the valves was open and the other shut, whilst on odd frames the opposite relationship held. The image to each eye was therefore refreshed at 60 Hz.

2.2 *Stimuli*

Random-dot patterns were created by initially giving 800 dots random X and Y coordinates within a square of side 9.6 cm (4.8 deg from the viewing distance of 114 cm). A random-dot stereogram was then constructed by shifting all elements to be presented to the left eye by $+2$ pixels (0.048 deg) and all elements to be presented to the right eye by -2 pixels to give a crossed disparity. Elements that required an uncrossed disparity were shifted in the opposite fashion. Elements that fell beyond the initial 4.8 deg 'window' were wrapped to the other side of the display. From the viewing distance of 114 cm this simulates a physical protrusion of approximately 1.8 cm from the fixation point. In the second 'frame' of the kinematogram, elements that were chosen to be signal were displaced vertically (0.096 deg) from their position in the first frame either upward or downward, depending on the direction of motion required. Elements defined as noise were also displaced by approximately 0.096 deg in a direction chosen randomly from all possible directions (exact displacement varied across directions of motion owing to the sampling limitations imposed by pixelation). Again, any element falling outside the notional window was wrapped to the opposite side by conventional methods. In such displays it is possible that two dots could spatially 'overlap'. This could lead to artificially poor performance if noise dots were overwritten by signal dots. We therefore used an algorithm that wrote the signal dots after the noise dots, so that no signal dots were ever lost owing to occlusion by noise dots.

Each element was a dot of diameter 0.096 deg and was of yellow colour (a combination of the red and green guns with the blue gun set to zero). The luminance of each dot was drawn from a square distribution ranging from 4 to 12 cd m^{-2} (mean = 8 cd m^{-2}). Background luminance was 0.1 cd m^{-2}. Each frame of the random-dot kinematogram was displayed for 200 ms for a total presentation time of 400 ms.

2.3 *Procedure*

Each trial commenced with a fixation cross (present in the images presented to both the left and the right eye) at the centre of the forthcoming stimuli for 250 ms. This was extinguished in conjunction with the appearance of the stimulus. Subjects then gave a binary forced-choice response as to the direction of signal motion (up vs down). The level of signal for each condition was controlled from trial to trial via a QUEST procedure (Watson and Pelli 1983) tracking the 81.6% correct level and terminated after 32 trials. The starting level of the QUEST was chosen by informed guess to be well above threshold. The final maximum-likelihood estimate of this signal level was taken as the threshold measure.

On any block of trials the subject was informed as to the depth plane in which the signal would appear. Within a block of trials two conditions were randomly interleaved corresponding to the noise being in the same or a different depth plane as the signal. In total, each subject ran ten blocks (five with the signal in the front plane and five in the back plane) in a counterbalanced order to reduce any fatigue or practice effects. Data presented are the means and standard errors from these five replications. Before any data collection, each subject was given demonstrations of the stimuli and of the nature of the required task. The subjects also completed at least one practice block in each signal depth plane.

2.4 *Subjects*

In total six subjects took part in this experiment. Three subjects were recruited on the basis of their excellent stereo vision (defined as being able to read the 9th element of the Titmus stereotest and implying a stereoacuity of at least 40 s of arc), while three were recruited on the basis of their poor stereo vision (defined as being unable to read beyond the 2nd element of the Titmus stereotest and implying a stereoacuity of no less than 400 s of arc). We shall term them the 'stereo-normal' and 'stereo-blind' groups. All were naive to the aims of the experiment save for the author MCR (stereo-blind group).

2.5 *Results*

Mean thresholds for the three stereo-normal observers are presented in figure 1a. For all subjects in both conditions (signal in front plane or signal in back plane) thresholds were considerably lower if the noise was presented in the other plane than when it was presented in the same plane. The size of the effect was approximately 1 log unit. Hence it appears that stereo depth can be used as a segmentation cue by the motion system in a manner similar to that described by Croner and Albright (1997) for colour or luminance polarity. We would also like to note that Croner and Albright (1997) refer to 'unpublished observations' implying that they have performed an experiment very similar to this with similar results.

Mean thresholds for the three stereo-blind observers are presented in figure 1b. Thresholds for these observers were similar in the two conditions and therefore suggest that it was indeed stereo information that allowed the stereo-normal observers to improve in the different condition rather than any experimental artifact.

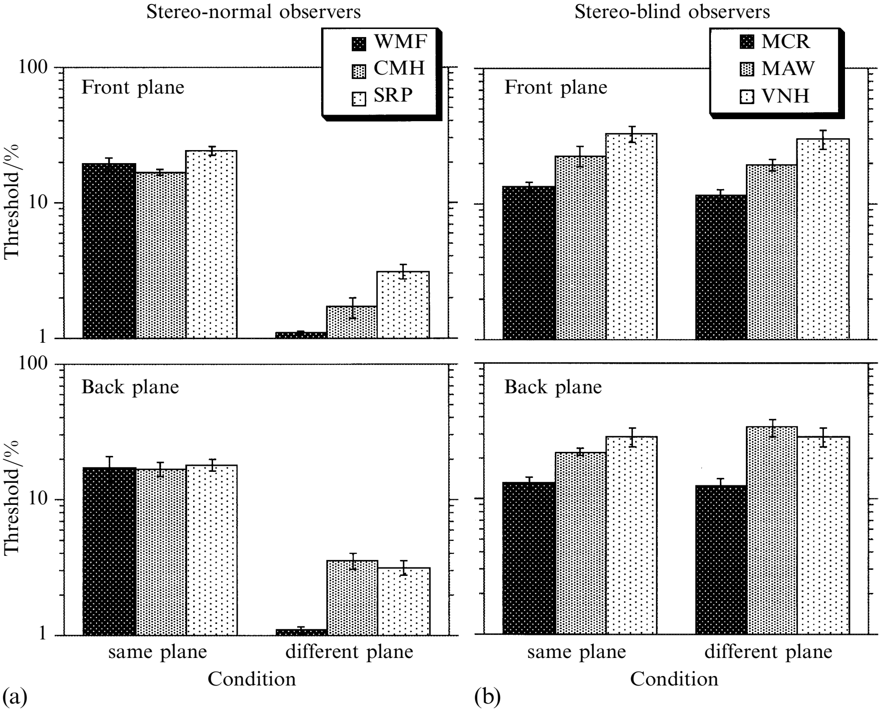

Figure 1. Thresholds of the identification of the direction of motion are plotted (a) for three stereo-normal observers and (b) three stereo-blind observers against the conditions (whether the noise had the same or opposite disparity to the signal) for experiment 1. In each case the upper panel depicts the results when the signal was in the front plane, and the lower panel when the signal was in the back plane. Error bars represent ±1 SEM.

3 Experiment 2

The logic of this experiment is analogous to that of the experiments of Edwards and Badcock (1994, 1996). A global motion task is defined by 400 elements and a threshold percentage of dots required to reliably discriminate the two opposite directions is measured—this is termed the 'no noise' condition. We can now add in 400 extra noise dots to this task. Note that these dots are all noise with no signal. If these dots are indistinguishable from the other dots defining the global coherence task, thresholds should rise. Whereas, if the extra noise is not 'seen' by the motion calculation, thresholds should not change.

In this experiment we measured motion thresholds for the global motion coherence task in both the front and back planes. We then added extra noise dots in either the front or back planes. We expect that when the extra noise is in the same plane as the global coherence task then thresholds must rise. The question of interest is whether extra noise dots in a different plane also cause a rise in thresholds, and, if so, do they do so by the same amount as the dots in the same plane?

3.1 *Methods*

These were as similar as possible to those in experiment 1. There were six conditions. Condition 1 was a global coherence task consisting of 400 dots, all in the front plane—we term this the 'no noise' condition. In condition 2 a further 400 noise dots were added to the display (ie 400 dots, each moving in a random direction) in the same plane as the global coherence task. In condition 3 these 400 noise dots were added in the other plane. The remaining three conditions were similar, save that the global coherence task was in the back plane. Again the trials were blocked so that conditions where the global coherence task was in a particular plane were interleaved. Subjects were therefore aware (and were informed) which plane contained the signal. Subjects performed at least one practice block in each condition before data were collected. Again, each data point presented is the mean and standard error of five measurements.

Once again three stereo-normal and three stereo-blind observers were recruited. All were naive except the authors RJS (stereo-normal) and MCR (stereo-blind).

3.2 *Results*

Results for the stereo-normal observers are presented in figure 2a. Despite the quite different baseline performance of the subjects, the pattern of results is similar across observers. Extra noise in the same depth plane increases thresholds (close to the amount predicted for maintaining a constant overall signal-to-noise ratio), whereas extra noise in the other depth plane does not alter thresholds. This is true for both depth planes for the global coherence task.

Results for the stereo-blind observers are presented in figure 2b. Extra noise in either depth plane now increases thresholds (close to the amount predicted for maintaining a constant overall signal-to-noise ratio). Again, this suggests that the lack of interference from the extra noise dots in the different plane in the stereo-normal observers is not an artifact.

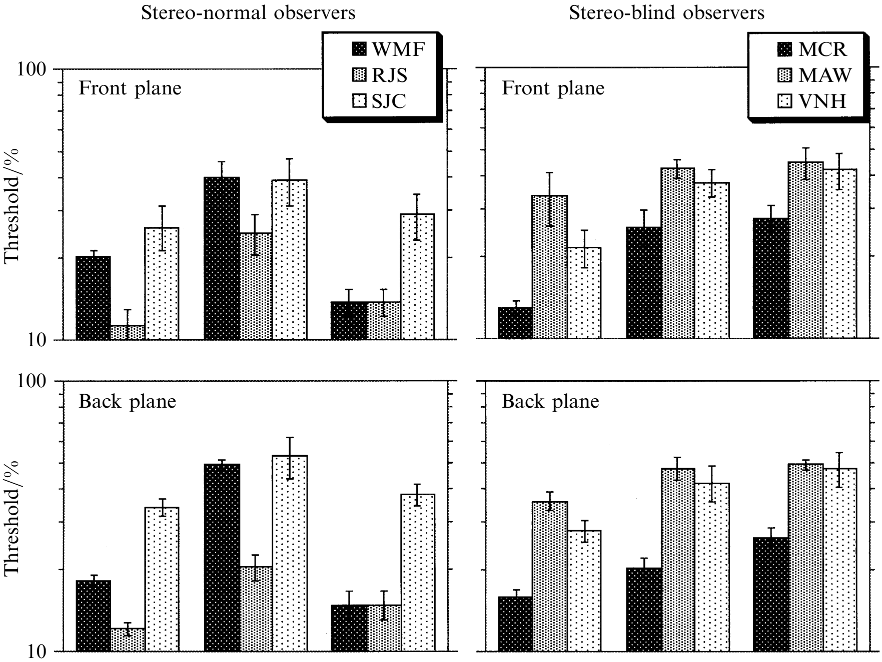

Figure 2. Thresholds of the identification of the direction of motion are plotted (a) for three stereo-normal observers and (b) three stereo-blind observers against the conditions (whether no additional noise was added, additional noise was added in the same plane as the global motion task, or additional noise was added in the opposite plane to the task) for experiment 2. In each case the upper panel depicts the results when the signal was in the front plane, and the lower panel when the signal was in the back plane. Error bars represent ±1 SEM.

4 General discussion

In both of the paradigms we have employed it appears that depth information derived from retinal disparity could be used to segment the information available to the motion system that performs the global coherence task. In this discussion we shall compare these results to others that have used the same paradigms but employed colour and polarity as the segmentation cues, discuss psychophysical evidence from other paradigms that bear upon this issue, and attempt to place the findings within current knowledge of the physiology of the primate motion system.

4.1 *Depth versus colour/polarity as a cue to segmentation*

Logically similar experiments to those presented here have been reported in which colour and polarity have been used as segmentation cues. Croner and Albright (1997) show that such cues are effective in the paradigm used in experiment 1 where the signal and noise have unique identities, whereas Edwards and Badcock (1994, 1996) have shown that the same cues are ineffective in the paradigm used in experiment 2 of the present study. Snowden and Edmunds (in press) replicated both of these findings and argued that the paradigm where signal and noise have unique identities may produce artifactually lower thresholds, as the subject may be able to selectively attend (covertly) to some small section of the display where a signal dot appears. This strategy is not available in the later paradigm (or at least is greatly reduced). In support of this argument Snowden and Edmunds (in press) show that a manipulation that increases the size of the attentional window (by presenting the stimuli in the near-periphery) abolishes this effect. Thus they conclude that segmentation based on colour or polarity is not available in this global coherence task. Clearly such an attentional strategy is also available to our observers (at least those with stereo vision) in experiment 1. However, the usefulness of stereo-depth cues persisted in experiment 2. If this technique eliminates the potential artifact of attention to a particular location (as it appeared to do for the colour and polarity cues), this suggests that the systems that solve the global coherence task have available to them an image representation that contains information about the depth of elements.

4.2 *Other paradigms*

Hibbard and Bradshaw (1999) have reported results from a somewhat similar paradigm to that used in the present experiments. They presented random-dot kinematograms that contained coherent motion in either a single direction or in two opposing directions. Motion coherence thresholds were larger for the two-surface stimulus than for a single surface (see also Snowden 1989, 1990; Verstraten et al 1996). However, the difference disappears if the two surfaces are presented at different disparities. This result seems in agreement with those presented here. Other work by this group (Hibbard et al 1999) compared coherence thresholds for conditions where the signal and noise were in the same plane or where the signal and noise were on different planes and showed a large difference in thresholds (as in our experiment 1). However, if the noise dots were scattered across many planes (whilst the signal remained on one plane), no such change was found. It appears that segregation of the image into distinct perceptual surfaces is a necessary condition for selective processing of some subset of the elements.

Interactions between depth and motion have been explored in other paradigms (Nawrot and Blake 1989; Qian et al 1994; Bradshaw and Rogers 1996; Bradshaw and Cumming 1997). For example Anstis and Harris (1974) have shown that the motion aftereffect is contingent on binocular disparity. They adapted subjects to clockwise rotation in the front plane interspersed with anticlockwise rotation in the back plane. On subsequent testing, patterns presented in the front plane appeared to rotate anticlockwise and those in the back plane clockwise. Thus there appears to be some segmentation of the motion signals based upon their retinal disparity. All these lines of evidence support the notion that stereo depth is important in motion processing. Is there evidence to support the contention that colour does not play a similar role? Similar experiments to those of Anstis and Harris (1974) have been performed for colour and motion. Favreau et al (1972) demonstrated that after adapting to, say, a red spiral expanding and a green spiral contracting the motion aftereffect depended on the colour of the test spiral (being the opposite of the motion viewed for that spiral in the adaptation phase). This evidence suggests that colour does play a role in segmenting motion information. However, further experiments by Anstis and Harris (1974) showed that the disparity-contingent motion aftereffect was much stronger than the colour-contingent one and 'won out' when the two were pitted against one another. Perhaps then the difference between colour and retinal disparity is not qualitative but quantitative in nature.

Further evidence for the roles of colour and stereo depth in motion perception arises from experiments using a 'visual search' paradigm. It is well established that a single item with motion different from that of other items in a display is very salient and 'pops out'. Operationally this is defined as the reaction time to detect this element being independent from the number of other elements. However, time taken for the detection of an item defined by the conjunction of two features (eg shape and colour) increases with the number of other items (Treisman and Gelade 1980). An exception to this 'rule' was reported by Nakayama and Silverman (1986). They found that an item defined by its motion and stereo depth could be detected independently of the number of other items. In essence, Nakayama and Silverman suggest that the subjects can selectively search (in parallel) just one depth plane to find the item with the odd motion. Of further interest is that Nakayama and Silverman also tested conjunctions of colour and motion. Here search increased with the number of elements, suggesting that subjects could not selectively process only items of one colour (at least not in parallel). These results therefore resemble those of the present study and our related one (Snowden and Edmunds, in press) in the domain of colour and polarity: subjects can selectively process motion information from one depth plane but not of only one colour.

4.3 *Physiology*

The primate brain seems to have a highly specialised pathway for the processing of visual motion information (see Snowden 1994). Within this pathway, the middle temporal area (MT—also known as V5) seems to play a central role. It has been implicated in a number of motion tasks, including the global motion coherence task used in the present experiments (for a review see Movshon and Newsome 1992). The cells of area MT show a sensitivity not only to direction and speed of motion but the majority also have a sensitivity to binocular disparity (Maunsell and Van Essen 1983). A possible role of this disparity tuning has recently been elucidated by Bradley et al (1995). Motion in directions away from the preferred direction of an individual neuron serves to reduce the neuron's response to its preferred direction (Snowden et al 1991), suggesting interactions between elements sensitive to different directions of motion. Bradley et al found that these interactions mainly occur only when the two motion surfaces share the same disparity (depth) and not when they are at different disparities. One is therefore tempted to suggest that such neurons would also be able to 'ignore' noise that is presented at a different disparity from that of the signal and so mimic the psychophysical results reported here.

The input of colour information to area MT has a more controversial history. It would now appear that many neurons of area MT do receive some input from signed chromatic contrast (for reviews see Dobkins and Albright 1993; Logothetis 1994), so potentially there is information about the colour, and therefore segmentation by colour, available at this level. Whether such neurons can use this cue to selectively process only one colour could be established by experiments similar to those of Bradley et al (1995) or by employing the techniques of the current paper [though once again the effects of attention may be important in the response of such neurons—Treue and Maunsell (1996)].

5 Conclusions and speculation

We have demonstrated how the use of stereo depth can aid in motion-processing tasks by segmenting noise so that its interference is reduced (or eliminated). In similar experiments we suggested that colour and luminance polarity did not achieve this. If this evidence for the different roles of stereo depth and colour is accepted, we can then speculate why this difference could occur. One possibility is that one of the primary aims of segmentation processes is to form surfaces. The depth information in our display clearly gave the impression of two surfaces. It may then be possible to selectively process only one surface, perhaps through an attentional mechanism (Duncan 1984; Nakayama and He 1995). Our (Snowden and Edmunds, in press) colour variations did not give the same powerful impression of two surfaces that in turn may provide a limited ability for such attentional mechanisms to selectively process just one set [though there is some limited evidence for attention to colour in complex displays (Brawn and Snowden 1997, in press)]. Perhaps other variations (in other dimension or indeed in colour) that do give the impression of discrete surfaces will also aid in this segmenting the signal from the noise.

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