Cue combination in the motion correspondence problem

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Image motion is a primary source of visual information about the world. However, before this information can be used the visual system must determine the spatio-temporal displacements of the features in the dynamic retinal image, which originate from objects moving in space. This is known as the motion correspondence problem. We investigated whether cross-cue matching constraints contribute to the solution of this problem, which would be consistent with physiological reports that many directionally selective cells in the visual cortex also respond to additional visual cues. We measured the maximum displacement limit ($D_{\max}$) for two-frame apparent motion sequences. $D_{\max}$ increases as the number of elements in such sequences decreases. However, in our displays the total number of elements was kept constant while the number of a subset of elements, defined by a difference in contrast polarity, binocular disparity or colour, was varied. $D_{\max}$ increased as the number of elements distinguished by a particular cue was decreased. $D_{\max}$ was affected by contrast polarity for all observers, but only some observers were influenced by binocular disparity and others by colour information. These results demonstrate that the human visual system exploits local, cross-cue matching constraints in the solution of the motion correspondence problem.

Keywords: motion correspondence; cue combination; binocular disparity; colour; contrast polarity

1. INTRODUCTION

Image motion is a primary source of information about the three-dimensional structure and motion of objects within our environment. A prerequisite to the use of this information is the solution of the motion correspondence problem. This refers to the difficulty faced by the visual system in establishing which image features from one moment to the next originate from the same physical object in space. The number of potential matches can be very large, particularly when there is a dense distribution of the image features.

In order to overcome this ambiguity, constraints are necessary in order to reduce the number of potential matches between the image features that have to be considered. These constraints have tended to be based on geometrical considerations relating to the spatial configuration of the image flow field. For example, Gestalt principles of proximity, smoothness and uniqueness (Koffka 1935; Ellis 1938) have all been applied successfully in computational approaches to the interpretation of motion (Ullman 1979; Horn & Schunk 1981; Hildreth 1983; Yuille 1983). In the current study, we consider the possibility that the visual system might also employ local image-based constraints such as the contrast and colour of features in order to reduce the severity of the motion correspondence problem. These local constraints capitalize on the fact that features in the world are rarely identical but tend to vary across a number of attributes (e.g. colour, contrast and binocular disparity). The number of potential matches to be considered in interpreting image motion would thus be dramatically reduced if motion mechanisms showed a preference for

matches between features sharing particular attributes in common.

While the use of such local matching constraints will have obvious computational advantages, it is inconsistent with a strongly modular view of visual processing in which colour, motion, form and other visual attributes are processed independently. Such a modular processing strategy is common in computational approaches to vision (Marr 1982) and has its origins in earlier anatomical and physiological studies (e.g. Zeki 1975, 1993). However, interactions between the processing of various stimulus attributes have been demonstrated in a number of psychophysical studies (Anstis & Harris 1974; Green 1986; Prazdny 1986; Nawrot & Blake 1991; Bradshaw & Rogers 1996). In the motion domain, cross-cue interactions have been shown to influence the perceived direction of motion of stimuli (Anstis & Harris 1974) and the perceived trajectories of objects (Green 1986; Prazdny 1986; Shechter & Hochstein 1990; Dawson *et al.* 1994). However, such influences are thought to be relatively unimportant in comparison to geometrical constraints (Dawson 1991), although the issue has not been explored using densely textured stimuli for which the correspondence problem is formidable due to the large number of potential matches between frames. Support for the use of multiple visual attributes in the interpretation of motion comes from reports that many individual cells in the early visual pathway show multiplex tuning, being selective for a number of stimulus attributes in addition to the direction of motion (Leventhal *et al.* 1995; Lennie 1998). For example, the majority of directionally tuned cells in cortical areas V1 and V5/MT are also selective for the binocular disparity of stimuli (Poggio & Talbot 1981; Maunsell & Van Essen 1983). Other cells in V1 are jointly tuned to the direction of motion and either colour (Leventhal *et al.* 1995) or contrast polarity (whether an

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Figure 1. Examples of the random dot stimuli used. We compared $D_{\max}$ for (b) stimuli containing a mixture of bright and dark dots with $D_{\max}$ for (a) stimuli containing only the number of bright dots of the stimuli and (c) stimuli containing the same overall number of dots but which all had the same contrast polarity. If different contrast polarities are processed independently for these stimuli, $D_{\max}$ for (b) should be similar to $D_{\max}$ for (a), which contains the same number of bright dots. If contrast polarity is unimportant then $D_{\max}$ for (b) should be similar to $D_{\max}$ for (c), which contains the same overall number of dots. (d) The number of bright dots was varied between zero and 250 and the number of dark dots was set to maintain the total number of dots at 500. In two other conditions, the elements differed in either their binocular disparity or colour.

image feature is brighter or darker than its background) (Schiller 1982; Schiller *et al.* 1986).

The functional significance of this cortical organization might be that local image cues are used in the analysis of retinal motion. To test this, we developed a variation on a commonly used motion task. Two-frame motion sequences were generated from a pattern of randomly positioned dots, which were moved vertically between frames. The perception of apparent motion in such random dot kinematogram (RDK) stimuli gradually breaks down as the magnitude of the displacement increases. For displacements greater than a critical value (referred to as $D_{\max}$ in the literature) observers are unable to determine the correct direction of motion (Braddick 1974). An important determinant of $D_{\max}$ is the number of elements in the display. As the number of elements decreases, $D_{\max}$ increases due to the number of potential matches between the two frames being reduced. The ability of observers to detect motion in these stimuli is therefore limited by the correspondence problem (i.e. which of the large number of elements in frame 1 corresponds to a single element in frame 2) (Morgan & Fahle 1992; Todd & Norman 1995; Eagle & Rogers 1996).

We measured the $D_{\max}$ for RDKs in which the elements differed in their contrast polarity, binocular disparity or colour. For the contrast polarity condition, the elements were either brighter or darker than their background. The relative number of bright to dark elements was varied between blocks of trials while keeping the total number of elements constant (see figure 1). If information regarding contrast polarity is used in the processing of motion then we predict that $D_{\max}$ will vary with the ratio of bright to dark elements. Specifically, if the motions of bright and

dark elements are processed separately, then $D_{\max}$ should only depend on the density of bright elements in our displays despite the fact that the overall number of elements was unchanged between stimuli. Alternatively, if contrast polarity information is not used in motion processing then $D_{\max}$ should be unaffected by changes in the proportion of bright to dark dots as the total number of dots does not vary. Similar predictions can be made for stimuli containing elements differing in binocular disparity or colour.

2. METHODS

(a) Stimuli

The stimuli were two-frame kinematograms in which the images were displaced vertically between frames. Each stimulus subtended 10.67 arc deg × 8 arc deg; each dot was a square array of pixels subtending a 5 arc min × 5 arc min. All dot patterns contained between ten and 500 dots. For the stimuli containing identical dots, the number of dots was varied between ten and 500. For the stimuli containing mixed elements, the number of dots of one type was varied between ten and 250 while the number of dots of the other type was adjusted to make the total number of dots 500 in all cases. Two-frame motion sequences were generated by shifting the dots vertically *en masse*. Dots that were shifted outside the patch window by this displacement were wrapped around vertically and given a new horizontal coordinate. Each frame was presented for 224 ms with no inter-frame interval.

For the contrast polarity condition, the dots were presented on a uniform grey (6.32 cdm⁻²) background. The luminances of the bright and dark dots were 49.4 and 0.8 cdm⁻², respectively. The bright and dark dots therefore had an equal Michelson contrast of 0.77 (defined as $(L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$, where $L_{\max}$ and $L_{\min}$ are the dot and background luminances, respectively and $L_{\max}$ is the brighter and $L_{\min}$ the darker of the two values). Although this definition of contrast is only strictly applicable to densely textured patterns that are spatially homogenous (Campbell & Robson 1968), dark and light dots have equal perceived contrast when matched in this way (Burkhardt *et al.* 1984; Whittle 1986). In the binocular disparity condition, the dots were presented on a black (0.4 cdm⁻²) background and had a luminance of 37.8 cdm⁻². The dots were either presented with zero disparity or with a crossed disparity of 10 arc min so as to appear in front of the fixation plane. In the colour condition, the dots were either red or green (with Commission Internationale de L'Éclairage chromaticity coordinates of (0.618, 0.348) and (0.293, 0.589), respectively) and were presented on a black (0.4 cdm⁻²) background. The red and green dots were perceptually isoluminant, the isoluminance point being established individually for each observer using the minimum motion technique (Anstis & Cavanagh 1983).

(b) Procedure

The observer's task was to decide whether the pattern of dots had moved upwards or downwards for each trial. No feedback was given regarding the accuracy of their responses. A block of trials consisted of 20 trials at each of seven displacement values. The observers performed four blocks of trials for each condition, making a total of 80 trials for each displacement value in each condition. The $D_{\max}$ for each condition was defined as the displacement that produced 20% errors after interpolation of the data points (Baker & Braddick 1982).

Figure 2. (a) $D_{\max}$ plotted against the number of image elements for stimuli containing only bright elements on a dark background. $D_{\max}$ increased as the number of elements was decreased. (b) The slope of the log of $D_{\max}$ against the log of either the total number of dots (the dot density condition) or the number of dots differing on a particular attribute (the remaining three conditions). The results are given separately for each observer. These trends were tested for significance using Page's *L*-test and are significant except where indicated by an asterisked legend.

(c) Apparatus

For the experiments in which the stimulus elements differed in contrast polarity or colour, the stimuli were presented on a Sony Trinitron 17 in colour monitor driven by a Macintosh 7500 at a viewing distance of 112 cm. At this distance, each pixel in the 640 × 480 display subtended 1.25 arc min. A 51 pixel × 384 pixel central portion of the screen was used to display the stimuli such that the horizontal and vertical extents of the stimuli were 10.67 and 8 arc deg, respectively. For the experiments in which the stimulus elements differed in binocular disparity, the stimuli were presented on two Apple 12 in monochrome monitors driven by a Macintosh 7500 and arranged in a

standard, Wheatstone, stereoscope configuration. The monitors were viewed through two first-surface mirrors set at $\pm 45^\circ$ to the median plane. The viewing distance was 114 cm. At this distance, each pixel in the 640 × 480 display subtended 1 arc min and the horizontal and vertical extents of the display were again 10.67 and 8 arc deg. All experiments were performed in a darkened room.

(d) Observers

Two of the authors plus three other individuals who were experienced psychophysical observers but unaware of the aims of the experiment participated in the experiments. All observers had normal colour vision and stereoacuity of better than 30 arc.

3. RESULTS

The results for our condition in which $D_{\max}$ was measured for patterns that contained only bright elements against a dark background are shown in figure 2a. Here, we found that $D_{\max}$ increased as the number of elements was decreased from 500 to ten (Morgan & Fahle 1992; Eagle & Rogers 1996). This increase in $D_{\max}$ with decreasing number of elements was linear when the results were plotted on log-log axes. This trend was significant for all observers (Page's *L*-test, $p < 0.01$).

For each of the remaining conditions, the random dot patterns contained a fixed number of elements of which a subset differed from the remainder in terms of their contrast polarity, binocular disparity or colour. The number of elements in this subset was varied and, in each case, a regression of the log of $D_{\max}$ onto the log of the number of elements in the subset was performed. The slopes of these regressions are shown in figure 2b plotted individually for each observer. For all observers, varying the proportion of bright elements to dark elements had a significant effect on $D_{\max}$ (Page's *L*-test, $p < 0.01$), that is, as the number of bright elements decreased, the direction of motion could be reliably reported for progressively greater displacements. For the remaining two conditions, marked individual differences in the results were found. When the subset of dots was defined with a different disparity, a significant increase in $D_{\max}$ was found for three of the five observers (N. S. S., M.F.B. and P.B.H.) (Page's *L*-test, $p < 0.01$). When the subset was defined with a different colour, a significant increase in $D_{\max}$ was found for two of the observers (N. S. S. and S. J. W.) (Page's *L*-test, $p < 0.05$). However, the size of the effect was much less for the colour condition than that which was observed in the disparity case.

4. DISCUSSION

It has been proposed that $D_{\max}$ is limited by the number of elements in a display because, for dense distributions of elements, many false matches have to be considered before a correct match can be selected (Morgan & Fahle 1992; Eagle & Rogers 1996). Each of the stimulus manipulations employed in the current study provides additional information which may be used to reduce the number of potential matches. In each case, this additional information increased the range of displacements over which the direction of motion could be

detected in a similar fashion to that observed when the number of potential matches is actually reduced by reducing the dot density. Individual differences in the extent to which this information was used were evident, with some of the cues producing an improvement in performance for some observers only. The contrast polarity, binocular disparity and colour of image features can all therefore be used to solve the motion correspondence problem. These results are inconsistent with a strong dissociation between the processing of motion and other attributes (cf. Stoner & Albright 1993; Schiller 1996; Lennie 1998).

However, before this conclusion can be drawn it is necessary to rule out the possibility that the changes in the spacing of the simple image features introduced by our experimental manipulations could also explain the results. We tested whether changing the proportions of bright and dark elements in the contrast polarity condition affected the mean separation between like-signed zero crossings in the output of a spatial bandpass filter in such a way that could account for the effects we report. This measure was used as it has provided a good description of the effects of element size and density on $D_{\max}$ (Morgan 1992; Morgan & Fahle 1992): other simple features such as luminance peaks would give similar results (Eagle & Rogers 1996). We found that, while altering the proportions of the light and dark elements had some effect on the spacing of the zero crossings, this effect was considerably smaller than that of varying the element density. The change in separation between zero crossings cannot therefore explain the results we obtained, which were of equal magnitude for the two manipulations. The effects of colour and binocular disparity can also not be accounted for in terms of the density of simple stimulus features since neither manipulation altered the monocular luminance distributions of our patterns. It might also be argued that, in the contrast polarity condition, the motions of bright elements in the display are processed preferentially, perhaps because of differences in the salience of the bright and dark dots. We think this is unlikely since the dots were matched for Michelson contrast and, therefore, perceived contrast for these types of stimuli (Burkhardt *et al.* 1984; Whittle 1986). More importantly, we repeated the experiment for one observer (P.B.H.) using stimuli containing small numbers of dark elements and found similar improvements in performance.

The use of local image-matching constraints has also been demonstrated in the solution of the related binocular correspondence problem (the problem of which features in the left and right eyes' image originate from the same location at one particular time), where it has been shown that matches are preferred between image features sharing a common contrast polarity or direction of motion (Harris & Parker 1995; Bradshaw & Cumming 1997).

It is often assumed that the analysis of image motion occurs in two stages (see, for example, Braddick 1993). First, local estimates of velocity are obtained within small areas of the image and these in turn are combined in a second stage in order to compute global aspects of the optic flow within larger regions of the image. Interestingly, cross-cue interactions do not in general appear to

be useful in the discrimination of direction in global motion stimuli, which are composed of 'signal' elements that move in a specific direction and 'noise' elements that move in random directions (Edwards & Badcock 1994, 1996; Oli & Kingdom 1998; Hibbard & Bradshaw 1999; Hibbard *et al.* 1999; Snowden & Rossiter 1999). The perception of coherent motion in such stimuli requires the spatial integration of motion estimates from signal dots across the image. When signal dots are distinguished from noise dots by using an additional, local cue such as colour, sensitivity to motion can be improved (e.g. Croner & Albright 1997, 1999; Van der Smagt & Van de Grind 1999). However, in these circumstances it has been argued that motion processing is qualitatively different to the usual processes underlying the integration and segmentation of motion signals (Edwards & Badcock 1996; Croner & Albright 1999) as it may rely on the attentional allocation of resources to a restricted area of the retinal image in which the target motion is concentrated (Roitman & Shadlen 1997; Snowden & Edmunds 1999). Such a strategy would not be effective for the stimuli used in the current study, since no improvement in performance could be obtained by focusing attention on any particular region of the image. This is because the target motion is carried by all the dots in our stimuli, in contrast to global motion stimuli in which the target motion is carried by individual signals dots spatially distributed within a large number of noise dots.

The differences between the results reported here and those from studies that have looked at the perception of global motion coherence suggest that measures of $D_{\max}$ and motion integration and segmentation relate to different aspects of motion analysis. While it is difficult to determine the physiological locus of any psychophysical result, there is strong evidence that global motion relies on the activity of cells in area MT (Newsome & Paré 1988), which are not strongly selective for contrast polarity or colour (Zeki 1974; Saito *et al.* 1989). In contrast, the effects reported here may be the psychophysical correlate of the fact that many cells in area V1 are jointly tuned for the direction of motion and other stimulus attributes. Interestingly, Harris & Parker (1995) also found that 'on' and 'off' signals are processed independently at the stage of binocular matching but not at the stage of spatial integration of binocular disparities. The usefulness of contrast polarity information in the early and late stages of processing thus appears to be similar for motion processing and binocular stereopsis.

$D_{\max}$ was clearly influenced by the contrast polarity, binocular disparity and colour of the stimulus elements. The effects of contrast polarity were shown by all observers. This result is in keeping with other studies, which have demonstrated independent processing of on and off signals in the detection of motion (e.g. Wehrhahn & Rapp 1992; Edwards & Badcock 1994). However, the effects of colour and binocular disparity were only shown by a subset of the observers tested here. These results may reflect individual differences in the use of particular stimulus attributes in the interpretation of motion. It is interesting to note that the observers showing an effect of colour were not the same as those showing an effect of binocular disparity.

The matching constraints shown to be used here reflect the known tuning properties of single cells in the early visual pathway. For example, many directionally selective cells in area V1 are also tuned to opposite contrast polarities, binocular disparity or colour. The results reported here suggest that one possible functional role of this joint tuning is to allow local image-based constraints to be employed in the solution of the motion correspondence problem.

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