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Apparent position governs contour-element binding by the visual system

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An assumption inherent in many models of visual space is that the spatial coordinates of retinal cells implicitly give rise to the perceptual code for position. The results of the experiments reported here, in which it is shown that retinally non-visual locations of contour elements are used by the visual system for contour-element binding, lend support to a different view. The visual system does not implicitly code position with reference to the labelled locations of retinal cells, but dynamically extracts spatial position from the aggregate result of local computations. These computations may include local spatial relationships between retinal cells, but are not confined to them; other computations, including position derived from local velocity cues, are combined to code the position of objects in the visual world.

Keywords: contour; Gestalt good continuation; motion-induced apparent displacement; perception

1. INTRODUCTION

The trajectory of a moving object may be roughly estimated from knowledge of its current (or recent past) position, together with a measure of its local velocity, or it may be inferred from samples of its position over some short period of time. Neuropsychological studies and adaptation evidence point to a dissociation in human vision between mechanisms that code local velocity and mechanisms that code position. Brain injury can result in an inability to perceive motion, but can spare an ability to perceive displacement (Zihl et al. 1983), and adaptation to a moving target (e.g. a waterfall) has as an after-effect the perception of motion, in reverse direction to the target, that lacks the perception of displacement (for review, see Mather et al. 1998). In most situations of real motion of objects there will be a consistent match between changes in position—displacement—and local motion, and it is reasonable to presume that the output of mechanisms sensitive to motion and the output of mechanisms sensitive to position will also be consistent with each other.

However, MacKay’s (1958, 1961) demonstrations with stroboscopically lit, partially self-luminous, objects suggest that mechanisms sensitive to local velocity can give rise to estimates of position that do not correspond to estimates derived from mechanisms sensitive to position alone. Nijhawan (1994) in a rediscovery, and confirmation, of MacKay’s effect showed that moving objects can give rise to dissonant estimates of position by the visual system—moving objects were typically perceived as being ahead of their strobed retinal location. This dissonance in perception has been shown to be most probably the result of a reduced neural delay for moving stimuli (Whitney & Murakami 1998).

The results of experiments by De Valois & De Valois (1991) show that stationary objects that contain local-motion cues are perceived as being displaced in the direction of the motion vector. De Valois & De Valois demonstrated this perceived mispositioning by vignetting a drifting sinusoid by a stationary Gaussian; an apparent displacement of the vignette is induced. Figure 1 illustrates their finding. The motion-induced ‘illusory’ displacement of each element of a vertically aligned triplet results in perceived misalignment of the triplet, demonstrating the, perhaps partial, independence of codes for velocity and codes for position.

A question that is prompted by motion-induced perceived displacement is whether the veridical (i.e. in this case retinal) position or the apparent position, of ‘perceptually displaced’ elements, is used by the visual system for the grouping of visual elements into perceptual wholes. A powerful example of perceptual grouping is provided by fragmented contours, which are usually seen—despite fragmentation—as continuous objects. David Field and I (Field et al. 1993) created a ‘path’ stimulus paradigm, which we used to demonstrate that a subset of an array of elements is readily perceived as a contour when the contour is defined only by alignment of the elements along a smooth curve (see figure 2a). This tendency of aligned fragments to group into a perceived whole was described earlier this century as the ‘Gestalt law of good continuation’ (Wertheimer 1938); one of a set of ‘laws’ that constituted an attempt to describe and categorize the rules of perceptual organization that allow us to perceive objects as whole entities, and not simply as isolated scribbles of form and colour. Small off-axis displacements of fragments aligned along a smooth curve disrupt the ‘good continuation’ of the contour such that it is no longer perceived as an integrated whole (Field et al. 1993). This finding is illustrated in figure 2.

If contours are constructed of elements, where each element is a Gaussian-vignetted drifting sinusoid, that are aligned along the axis of a smooth curve, then the result shown in figure 1 predicts that the motion of the sinusoid will induce an apparent off-axis displacement of each element. This displacement will be similar to the physical off-axis displacement illustrated in figure 2b, and may, as a consequence, disrupt the perceptual salience of the contour. However, the prediction that arises from the view that the metric of visual space is derived from the positions of retinal cells—a view that can be traced to the ‘local sign’ hypothesis of Lotze (1852)—and is subsequently mapped in an orderly topographic fashion through the visual pathway, is that the positions of objects are coded according to their retinal coordinates. It can be...
argued that this metric is available regardless of appearance; compelling evidence comes from experiments where the size or position of objects is distorted perceptually, but the ‘illusory’ distortion is not reproduced in the control of action (Milner & Goodale 1995). Thus, which position of the elements, their motion-induced apparent position or their retinal position, is used by the visual system in the assembly of contours (often thought of as a relatively ‘high-level’ task, e.g. Rock (1984)), and hence makes explicit the shape of objects?

2. METHODS AND RESULTS

Figure 2 presents examples of the stimulus arrays for a contour-detection experiment where the task of the observers was to determine in each trial which of a sequentially presented pair of arrays contained a contour. One array was made up of 256 elements quasi-randomly arranged in position and orientation, the other was made up of 256 elements of which 244 were quasi-randomly arranged, and 12 formed a ‘path’ aligned along a smooth contour. The right panels of figure 2 present examples of the arrays; each array contains the aligned set of elements—the path—that is shown in isolation in the left panels. The arrays were made up of ‘dynamic’ elements, all of which in the experimental condition were Gaussian-vignetted drifting sinusoids. The perceived displacement of the elements that is induced by the drift of the vignetted sinusoids is so dramatic that the array of ‘dynamic’ elements resembles a carpet of insects moving around the surface of the array in every direction. Indeed, a casual observer needs to view the array for some time to convince him/herself that the elements themselves are, in fact, stationary, and that it is only the sinusoid that drifts.

The results of the experiment, presented in figure 3, show that detection of contours constructed from vignetted drifting sinusoids improves when the contour elements are progressively misaligned, to some optimal displacement from alignment, in a direction opposite to the sinusoid’s direction of motion. Contour-detection performance peaks when the elements are physically misaligned by more than a quarter of their visible width. Thus, when the visual system binds the elements to give rise to the perception of a contour, it uses the motion-induced ‘illusory’ position of elements of the contour—where the results of the alignment experiment (figure 1) suggest that they appear to be—and not their retinal locations. The displacement of contour elements from physical alignment that is required for optimal contour detection, about 1.0 σ for observer A.H., is larger than the displacement from physical alignment required for a triplet of elements to be perceived as aligned, about 0.35 σ (compare the results in figure 1 with those in figure 3; ‘σ’ refers to the standard deviation of the Gaussian vignetted).

3. DISCUSSION

The salience of contours, such as the ones formed by the stimuli used in the experiment reported here, illustrates the operation of an ‘organizing principle’ of the visual system that may be a consequence of relatively low-level binding operations that may occur in primary and secondary areas of the visual cortex (Spillmann & Werner 1996; Grossberg et al. 1997). Contour assembly, using fragments that are apparently displaced due to a local-motion signal, is achieved with contour fragments whose positions correspond to their apparent, local-motion induced, location,
not with fragments whose positions correspond to their actual retinal location. The distortions in visual location that are induced by a local-motion signal cannot be explained with reference to high-level visual processing since the visual system’s use of the displaced positions for contour assembly indicates that motion-induced apparent displacement precedes ‘binding’ operations. Because the measure used in the experiment—contour detection—is an indirect measure of visual alignment, the results of the experiment provide strong evidence that the visual system’s spatial metric incorporates local-motion cues. The findings illustrate the powerful influence of local-motion signals on position information, not only in determining perceived position, but also in shaping the input to the mechanisms that link or bind elements into objects. These results add to and extend existing evidence for the non-separability of form and motion (e.g., Burr et al. 1986), and challenge a commonly accepted view of modular analysis by the visual system where different attributes, such as form and motion, are thought to be analysed through non-communicating independent modules.

Figure 2. Stimulus arrays from the contour-detection experiment. (a) Contour constructed from fully aligned elements. On the left, contour path alone; on the right, contour path embedded in background ‘noise’. All elements of the path are aligned along a smooth curve. (b) Contour path constructed from non-aligned elements. All elements of the contour path are displaced away from the axis of the contour. The Gaussian-vignetted sinusoid of contour and background elements either drifted or counter-phased, in incoherent phase, in each of two conditions. In the experimental drifting-sinusoid condition, 12 contour elements were either all displaced in the direction opposite to the direction of drift of the sinusoid, or all displaced in the same direction as the drift. The direction of drift of the sinusoid of each contour element was randomly allocated; however, no more than two adjacent elements of the contour drifted in the same direction. The direction of drift of the sinusoids of the background elements was randomly allocated. In the counterphasing control condition the sinusoids of all elements—contour and background—counter-phased at the same temporal frequency. The demonstration shown in (b) corresponds to a condition where contour-elements are misaligned off the axis of a smooth curve. The off-axis displacement shown is 4°; a level of misalignment from a smooth curve that renders the contour path utterly undetectable when embedded in background elements (right panel). In the experiment all elements, background and contour, were made up of drifting or counterphasing Gaussian-vignetted sinusoids—drift speed/counterphase frequency, 4.7 Hz; display update, 37.5 Hz; screen refresh rate, 75 Hz; dimensions of the elements were as described in figure 1. All elements were constrained in position to a 16 x 16 grid. Background elements had random orientation and position, within the limitations imposed by the 16 x 16 grid. The array of 256 elements subtended 8° visual angle. A two-alternate forced-choice procedure was used in the experiments; the observer chose which of two sequentially presented arrays contained a contour. One presentation consisted of background ‘noise’ elements alone, the other consisted of 12 contour elements embedded in ‘noise’ elements, as shown in the right panels. The angular difference between each of the 12 elements aligned along a contour was ± (40 ± (0° 12))°. Each presentation was a 1.0 s (half-height to half-height) raised Gaussian-ramped temporal window. Further details on the construction of the stimulus arrays have been published elsewhere (Field et al. 1993).
The findings presented here are not consistent with simple models of spatial localization that have as their basis the simple transference through the visual pathway of the retinotopic position of retinal cells. Nor are they consistent with simple, and naive, structural isomorphism speculations on cellular anatomy and the shape of contours. The findings are, however, consistent with the emerging view that the majority of receptive fields of cells in the geniculostriate pathway are space–time inseparable, with many cells having spatio-temporally tuned receptive fields that will allow for summation along a velocity trajectory (DeAngelis et al. 1995; Burr & Ross 1986). They are also compatible with recent findings that suggest that visual space is dynamically remapped for image stabilization (e.g. Motter & Poggio 1990) and other findings that imply a plasticity in visual space prior to saccadic eye movements (e.g. Ross et al. 1997).

It may not be too fanciful to suggest that the metric for spatial vision is the dynamical result of a number of different low-level computations, and that the explanation for the ‘illusion’ of apparent displacement induced by a local-motion signal is that a normally useful computation produces a misleading output when the visual system is presented with a visual image that has unlikely spatio-temporal statistics.

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REFERENCES


Figure 3. Results of contour-detection experiments. (a) Contour detection as a function of element offset from alignment with a smooth curve, where contour elements consist of Gaussian-vignetted drifting sinusoids. Offset dimension is scaled to the size of the elements—\( \sigma \) of the Gaussian vignette. The results of two observers are plotted; each datum plots the percentage correct and \( \pm 1 \) s.e.m. for 1000 two-alternate forced-choice trials; all conditions were interleaved in blocks of 50 trials. Observer L.M. was naive to the aims and manipulations of the experiment. The round symbols show detection performance as a function of offset of elements from a smooth curve, where the offset is in the opposite direction to the direction of drift of the sinusoid (i.e. offset is counter to motion-induced displacement). The square symbols show detection performance where the offset is in the same direction as the direction of drift of the sinusoid. These results indicate that the position of the elements that results in optimal contour-detection performance occurs when the elements are physically displaced from alignment along a smooth curve by about \( \sigma \) for observer A.H. and 1.5\( \sigma \) for observer L.M. (b) Contour detection as a function of element offset using Gaussian-vignetted counterphasing (i.e. non-drifting) sinusoids. The symbols show detection performance as a function of offset of contour elements from a smooth curve. As expected, performance simply deteriorates monotonically as offset increases, since no apparent displacement is induced by the counterphasings sinusoids.


