Feature matching and segmentation in motion perception

Nicholas E. Scott-Samuel[*] **and Mark A. Georgeson**

School of Psychology, University of Birmingham, Birmingham B15 2TT, UK

We examined the role of feature matching in motion perception. The stimulus sequence was constructed from a vertical, 1 cycle deg^{-1} sinusoidal grating divided into horizontal strips of equal height, where alternate strips moved leftward and rightward. The initial relative phase of adjacent strips was either 0° (aligned) or 90° (non-aligned) and the motion was sampled at 90° phase steps. A blank interstimulus interval (ISI) of 0–117 ms was introduced between each 33 ms presentation of the stimulus frames. The observers had to identify the direction of motion of the central strip. Motion was perceived correctly at short ISIs, but at longer ISIs performance was much better for the non-aligned sequence than the aligned sequence. This difference in performance may reflect a role for feature correspondence and grouping of features in motion perception at longer ISIs. In the aligned sequence half the frames consisted of a single coherent vertical grating, while the interleaved frames contained short strips. We argue that to achieve feature matching over time, the long edge and bar features must be broken up perceptually (segmented) into shorter elements before these short segments can appear to move in opposite directions. This idea correctly predicted that overlaying narrow, stationary, black horizontal lines at the junctions of the grating strips would improve performance in the aligned condition. The results support the view that, in addition to motion energy, feature analysis and feature tracking play an important role in motion perception.

Keywords: motion detection; human vision; motion energy; long-range motion; feature binding; feature tracking

1. INTRODUCTION

There may be several routes to motion perception. In early work, Braddick (1974) distinguished between short- and long-range motion processes on the basis of D_{max}, the largest spatial displacement of a random dot kinematogram (Julesz 1971) which still allows the direction of apparent motion to be identified. Braddick (1974) took the existence of D_{max} as an indication that there was a short-range process in motion perception.

The short-range process was held to operate over a limited spatial range (given by the value of D_{max}) and did not function well if stimuli were presented dichoptically (Braddick 1974; Georgeson & Shackleton 1989), though recent evidence implies that dichoptic motion energy detection is sometimes possible (Carney 1997). It was contrasted with the long-range process which operates over larger displacements and does function dichoptically (e.g. Pantle & Picciano 1976). The short-range process was taken to be mediated by low-level filter mechanisms of the type proposed by Adelson & Bergen (1985) and Watson & Ahumada (1985), while the long-range process was seen as operating at a higher level involving the analysis of spatial form (Anstis 1980; Braddick 1980). However, subsequent investigation has revealed that the value of D_{max} is not constant and can vary quite widely

with, for example, element density (Lappin & Bell 1976; Morgan 1992; Eagle & Rogers 1996; Sato 1998), eccentricity (Baker & Braddick 1985) or stimulus spatial frequency (Chang & Julesz 1985).

Research has shown that variation in the interstimulus interval (ISI)—the temporal gap between successive images of a motion sequence—can produce very different percepts of the same stimulus sequence. For example, the Ternus display is a two-frame apparent motion sequence in which the first frame contains three collinear elements (usually dots or lines) equally spaced horizontally. In the second frame, the elements are shifted horizontally by the distance between each element, such that the leftmost element in the second frame appears where the central element of the first frame was located. The first and second frames are alternated to produce an impression of motion. The Ternus display has a bistable appearance when the ISI is *ca.* 40 ms and gives different motion percepts above and below this figure (Pantle & Picciano 1976). At long ISIs, group motion prevails: all the elements in the display appear to move together from side to side. At short ISIs, element motion is seen: the endmost element of the display appears to hop from one end to the other. These two types of motion have been associated with short-range (element) and long-range (group) processes (Pantle & Picciano 1976; Petersik 1989), though curiously it is the non-motion of the central elements that appears to be detected by the short-range process at short ISIs (Braddick & Adlard 1978).

The introduction of an ISI into motion sequences has proved a useful means of dissociating the short- and

[*]Author and address for correspondence: McGill Vision Research, 687 Pine Avenue West, Rm H4–14, Montréal, Québec, Canada H3A 1A1 (ness@astra.vision.mcgill.ca).

Proc. R. Soc. Lond. B (1999) **266**, 2289–2294
Received 3 June 1999   Accepted 13 July 1999

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long-range mechanisms. Using the missing-fundamental stimulus (a drifting square-wave grating, sampled at 90° phase shifts, with its fundamental frequency component removed), Georgeson & Harris (1990) showed that, at a short or zero ISI, motion was seen in the direction of the lowest frequency component (the third harmonic, which aliased to give reversed motion), while at a longer ISI motion was seen in the direction of the phase shift (the direction in which the features of the pattern were moving). The crossover between these two opposite perceived directions was around an ISI of 40 ms, consistent with the results from the Ternus display. These results suggest that, when short-range motion fails, motion perception can be supported by tracking the correspondence of image features across space–time (by 'tracking' we mean 'keeping track of' and not necessarily tracking by eye movements).

With the advent of the distinction between first- and second-order processing it has been argued that the short-range–long-range dichotomy is no longer useful (Cavanagh & Mather 1989; Cavanagh 1991). Conversely, a defensive action has been launched to argue instead that it is the distinction between first- and second-order processes that is superfluous (Petersik 1991, 1995). Others have identified the analysis of first-order stimuli with a short-range process and second-order stimuli with a long-range process (e.g. Chubb & Sperling 1989). However, it is possible to dissociate short- and long-range mechanisms using only second-order stimuli by masking features and noting the differences in second-order motion direction discrimination at short and long ISIs (Smith 1994). This finding implies that both the short-range–long-range and first-order–second-order distinctions are useful.

Lu & Sperling (1995) used a display in which, as with the missing-fundamental stimulus, the motion energy and features of a stimulus did not move in the same direction. Experiments using the pedestal-plus-test display revealed three kinds of motion analysis: first order, second order and feature tracking (Sperling & Lu 1998). The third of these corresponds to the long-range process and it now seems that the terms 'long range' and 'feature tracking' are interchangeable.

The rigidity of the division of motion mechanisms into short range, long range, first order and second order remains unclear. Cavanagh (1991, 1992) suggested a 2×2 classification by identifying two motion processes (active and passive) and two stimulus factors (first order and second order). The active process involves attention to stimuli moving around the visual field and the passive process involves low-level, local motion mechanisms. There are four possible pairings of process and factor, and Cavanagh (1991) assigned all pairings except the passive–first-order combination to the long-range motion category. This division of motion processing into active–passive and first-order–second-order pairings is a useful one and can be accepted without subscribing to Cavanagh's (1991, 1992) particular labelling of the individual pairings. For example, it may be that the passive and active motion processes could be relabelled as the short- and long-range processes, respectively.

Here, using the fact that it is possible to dissociate short- and long-range mechanisms by varying the ISI, a novel stimulus sequence was used to probe the short-

versus long-range dichotomy. The experiments presented below reinforce the idea that there is a long-range (or feature-tracking) mechanism which is sensitive to the similarity across time of those features which it tracks and that it has a longer memory than the short-range process. Thus, any complete picture of motion processing must include not only first- and second-order pathways, but also mechanisms responsible for feature tracking (Culham *et al.* 1998).

2. EXPERIMENT 1: FEATURES INFLUENCE MOTION PERCEPTION

We constructed a stimulus sequence from two vertical sinusoidal gratings drifting in opposite directions (left and right), temporally sampled at 90° intervals of phase. Each grating was divided into horizontal strips of equal height and these strips were then spatially interleaved so that alternate strips in the composite stimulus were moving to the left and right in a four-frame apparent motion sequence. The two constituent gratings were assembled into the composite stimulus sequence in two ways: aligned and non-aligned (see figure 1). In the aligned configuration (figure 1*a*), the two constituent gratings have phase sequences over time of 0–90–180–270° and 0–270–180–90°, resulting in a situation where adjacent strips are either 0° or 180° out of phase in each frame. In the non-aligned configuration (figure 1*b*), the two constituent gratings from which the strips sequence is constructed have phases 0–90–180–270° and 270–180–90–0°, resulting in a stimulus where adjacent strips are 90° out of phase with each other in all frames.

Thus, both sequences were derived from the same smooth relative motion, but sampled in different temporal phases. The sampling creates an alternation of long and short bars in the aligned sequence (figure 1*a*), but a succession of uniformly short bars in the non-aligned case (figure 1*b*). If spatial features play a role in motion perception, then the mismatch between features might disrupt the motion of drifting horizontal strips in the aligned sequence but not in the non-aligned sequence. Such an outcome would not be trivial, for in terms of local motion energy the strips of each sequence are the same. Indeed these experiments grew out of earlier ones showing that, when the ISI was zero, the perception of interleaved strips of motion in opposite directions was readily obtained with sequences composed of alternating gratings and plaids, similar to the aligned condition (Scott-Samuel & Georgeson 1996; Scott-Samuel 1997). The alignment of features did not appear to impede motion perception at zero ISI and so our interest here centred on the longer ISIs where feature-based motion might prove to be the dominant factor.

(a) *Method*

Stimuli were generated by a PC with custom-written Pascal software and displayed via a Cambridge Research Systems VSG2/2 8-bit framestore on a gamma-corrected Eizo Flexscan 9060S monitor with a frame (refresh) rate of 60 Hz. The use of two palette chips together gave the system the equivalent of 12-bit luminance resolution, that is the full 8-bit grey scale was available even at fairly low contrasts. The mean luminance of the display was 70.5 cd m^{-2} and its
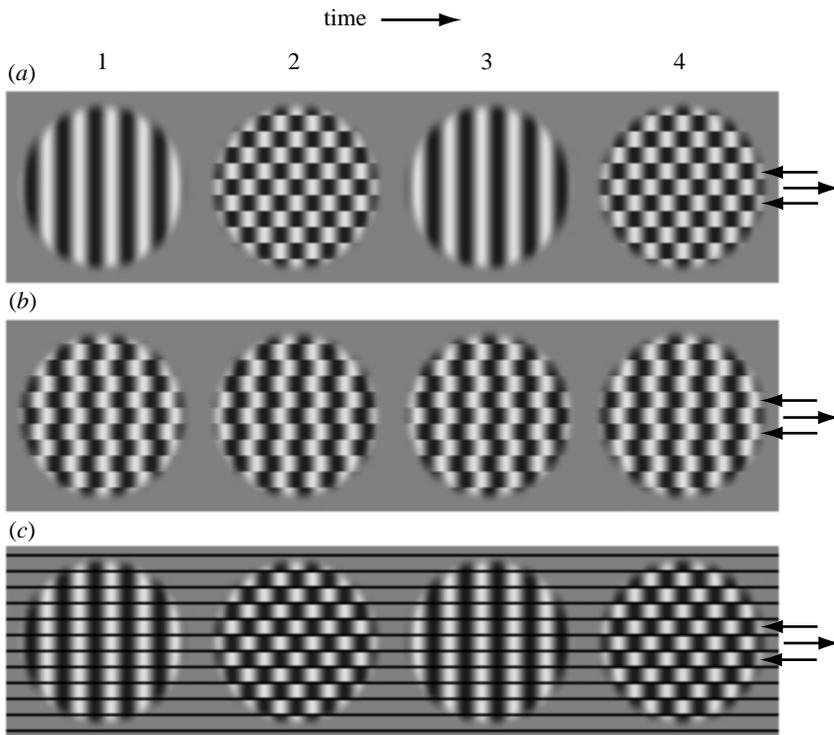
Figure 1. Three strips sequences. The (*a*) aligned and (*b*) non-aligned sequences compared; the four frames of the two sequences used in experiment 1 are shown with black arrows showing the direction of motion of the central three strips. (*c*) The aligned sequence with added horizontal bars used in experiment 2.

linearity was calibrated with a Minolta LS-110 photometer. Contrast was expressed as Michelson contrast, $100(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} and L_{min} were the maximum and minimum luminances, respectively.

Both the aligned and non-aligned versions of the strips sequence were used and the height of the strips was equal to half the horizontal period of the constituent vertical gratings. The ISI was varied randomly across trials from 0 to 116.7 ms in steps of 16.6 ms. During the ISI a uniform field was displayed at the mean luminance. There were 48 trials per observer for each of the 14 conditions (aligned and non-aligned versions at seven ISIs). Each stimulus frame in the sequence was displayed for 33.3 ms, corresponding to a drift temporal frequency of 7.5 Hz at zero ISI. Two cycles of the four-frame sequence were displayed in each trial and the grating contrast was fixed at 20%. The overall display size was 512 pixels × 512 pixels giving a horizontal spatial frequency of 1.0 cycle deg^{-1} and field size 4.5° at a viewing distance of 214 cm. The height of the strips was 0.5°, well above the minimum height needed for visibility of the interleaved motions (Scott-Samuel & Georgeson 1996).

The observers had to indicate the direction of motion of the central strip of the stimulus sequence (left or right) in a single-interval, binary-choice task with feedback. This direction was varied randomly from trial to trial. A fixation point was provided at the centre of the display and cursors at each side indicated the height of the central strip the direction of motion of which was to be judged. The observer's head was held in position with a chin and forehead rest. Viewing was binocular, with both observers (the authors) using their usual spectacle correction.

(b) Results: mismatched features disrupt long-range motion

The results for two subjects are shown in figure 2, plotted as the percentage of correct direction judgements

as a function of ISI. The non-aligned sequence gave almost perfect direction discrimination for the motion of the strips across all ISIs for both subjects. However, performance on the aligned sequence was 100% correct only for very short ISIs (0–17 ms). At longer ISIs of *ca.* 50 ms, one subject (N.S.S.) was at chance and the other (M.A.G.) reported movement in the direction opposite to the phase shift of the sequence. Motion reversal has previously been reported at ISIs of *ca.* 50 ms for random-dot kinematograms (Shioiri & Cavanagh 1990) and square-wave gratings (Braddick 1980) and was attributed to a biphasic impulse response of the short-range process. Two-pulse experiments have been modelled successfully using such a biphasic impulse response at detection threshold (Watson & Nachmias 1977) and above threshold (Georgeson 1987). At the longest ISIs the aligned performance was at or above chance (50–75% correct), but well below the non-aligned performance (100% correct).

The difference in performance for the two sequences is very striking when we recall that the two displays were identical except for the choice of starting point for the sampling of the motion; both sequences are sampled versions of the same continuous motion display. In a control experiment, the display sequence consisted of a single (long) grating stepping to the right or left. All other conditions were the same as the main experiment. Discrimination of motion direction was almost perfect at all ISIs (range 0–100 ms) for both observers (mean for N.S.S. 98% and mean for M.A.G. 99.6% correct).

(c) Discussion: feature binding leads to a feature mismatch

In the aligned strips sequence (figure 1*a*) there are long, vertical bars (a grating) in every other frame. It is evidently this alternation between the long (5°) and short
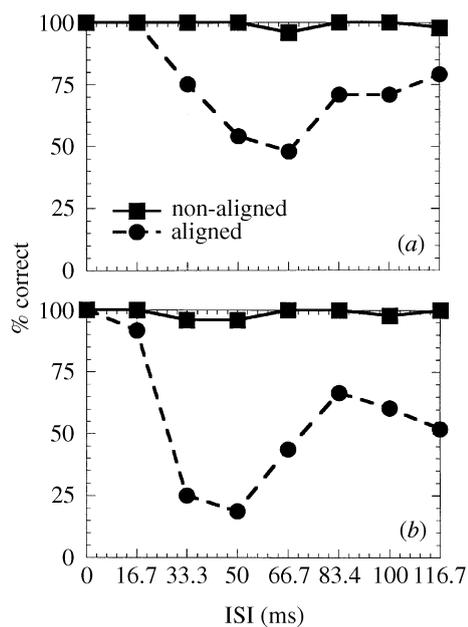
Figure 2. Experiment 1: results. The results for two subjects ((*a*) N.S.S. and (*b*) M.A.G.) at eight ISIs for the aligned and non-aligned strips sequences (figure 1*a*,*b*). The performance in direction discrimination (% correct) is plotted against the ISI in milliseconds.
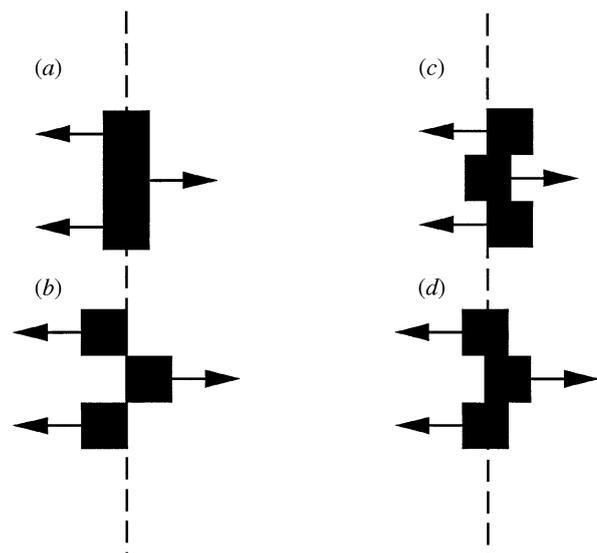

Figure 3. Feature binding? The first two frames of the aligned and non-aligned sequences are represented schematically. For the aligned sequence, the elements in each strip may be bound together into an extended vertical feature (*a*) which must be broken up in the transition from (*a*) to (*b*) to yield motion. For the non-aligned sequence, the elements in each strip are no longer collinear and so no new segmentation is required in the transition from (*c*) to (*d*).

(0.5°) bars that degrades motion perception at ISIs greater than 20 ms, since when every frame contained long bars (with unidirectional motion) or short bars (with interleaved strips of motion) performance was at or near 100%. We suggest that, at ISIs over 20–40 ms, the time-gap is too long to support the direction selectivity of first-order motion mechanisms and that feature tracking becomes the dominant process at longer ISIs (Georgeson & Harris 1990). Experiments by Ullman (1980) suggested that there is a greater 'affinity' in motion correspondence (Ullman 1979) between spatial features that are similar in length or orientation than between dissimilar features. To achieve a correspondence of similar features in our aligned condition, the long vertical bars would have to be segmented into a representation consisting of multiple short bars in order that separate bars could be seen to move in opposite directions (see figure 3*a*,*b*). This account presupposes that the different parts of a long bar are by default bound together to represent a single, long structure and that this binding would have to be undone before apparent motion of the parts could be perceived. Such segmentation might be difficult and time-consuming compared with the case where all features are equal in length and misaligned, and require no more segmentation (figure 3*c*,*d*). Thus, the ability to perceive direction of motion in the central strip would be more difficult in the aligned condition than the non-aligned condition.

3. EXPERIMENT 2: BREAKING UP THE VERTICAL FEATURES

If poor performance in the aligned sequence can be explained in terms of feature binding, then it follows that encouraging the break-up of these vertical features could lead to improved motion perception at longer ISIs. The non-aligned condition of the last experiment can be seen

as one example, where the quarter-cycle offset between adjacent strips in the sequence may prevent the features in different strips from being bound together into an extended vertical structure.

We tested this account by using a second way of breaking up the vertical features of the aligned sequence. Stationary horizontal lines were drawn across the junctions of the strips of grating in every frame (figure 1*c*) and we predicted that direction discrimination performance should improve at longer ISIs for this sequence, even though the stationary lines provided no cue to the direction of motion.

(a) *Method*

The experimental conditions were similar to those used in experiment 1, differing only in the stimulus sequences used. Instead of a comparison between aligned and non-aligned sequences, an aligned sequence of the type used previously (figure 1*a*) was compared with a modified aligned sequence which had narrow, horizontal, black bars (2 minarc high, covering the full width of the display) placed across the boundaries between the oppositely moving strips of the motion sequence (figure 1*c*).

(b) *Results: broken features restore motion*

The results for the aligned condition were very similar to those in experiment 1: there was 100% correct performance at zero ISI, but not at longer ISI durations (filled circles in figure 4). The effect of the added horizontal bars on motion perception was striking: at the longer ISIs, direction discrimination performance was markedly improved to around 80–90% correct for both subjects (squares in figure 4), as predicted. This was true even at ISIs of *ca.* 50 ms where motion was at chance, or reversed, when the horizontal bars were absent.
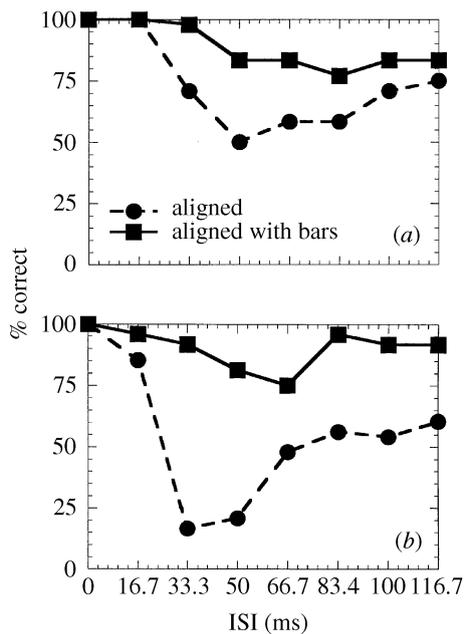
Figure 4. Experiment 2: breaking up the features. The results for two subjects ((*a*) N.S.S. and (*b*) M.A.G.) at eight ISIs for the aligned strips sequences with and without overlaid bars (figure 1*a,c*). The performance in direction discrimination (% correct) is plotted against the ISI in milliseconds.

(c) Discussion: parsing before motion correspondence

Recently, Tse *et al.* (1998) defined a new mode of apparent motion—transformational apparent motion—in which the parsing or segmentation of figures is the essential precursor to correspondence matching. Unlike standard apparent motion, transformational apparent motion is 'sensitive to geometrical constraints of contiguity, smooth contour continuity and occlusion, and is influenced by more ecological constraints as well...' (Tse *et al.* 1998, p. 253). Our results at the longer ISIs show that apparent motion of this kind can fail when incompatible parsings (long and short features) are derived from alternate frames of the motion sequence, but can be restored by static form cues that induce an alternative segmentation that has good correspondence across time.

4. GENERAL DISCUSSION

Perception of interleaved strips of motion was improved when the long bars of the aligned sequence were segmented by the addition of horizontal black bars to the stimulus sequence. This result supports the idea that the mismatch between long and short features in alternate frames of the strips sequence was responsible for poor direction discrimination performance at long ISIs. When the lengths were physically matched, performance was good at all ISIs. The fact that the horizontal bars did not improve performance to 100% suggests that the addition of bars to the aligned strips sequence segmented the vertical features only partially, thus reducing (but not eliminating) feature mismatch between alternate frames of the sequence.

Introducing an ISI greater than 40 ms has previously been shown to be a good way of recruiting the long-range

mechanism for motion perception (e.g. Braddick 1974; Pantle & Picciano 1976; Georgeson & Harris 1990; Smith 1994), perhaps because it disrupts the operation of the short-range mechanism (Boulton & Baker 1993). The differences in performance between low and high ISI values revealed here are therefore taken to highlight differences in the short-range and long-range processes. At short ISIs performance was always good, with or without alignment. This suggests that the short-range process is not sensitive to the spatial relations between features, but is driven by local phase shifts in the space–time image.

Intriguingly, a similar disrupting effect of feature alignment has been reported for the motion after-effect (Harris & Sullivan 1996): if a vertical test grating is surrounded by a grating of the same spatial frequency, then the strength of the motion after-effect is weaker when the test and surrounding gratings are spatially aligned. Given that the effect of alignment of adjacent strips described in this paper occurred over a wide range of ISIs and, therefore, might be attributed to a high-level, feature-tracking mechanism, it may be that Harris & Sullivan's (1996) findings can be attributed to feedback from a high-level process to a low-level process (Watanabe & Miyauchi 1998); the signalling of aligned features in the former might attenuate the motion signal in the latter.

The influence of alignment and grouping of features at long ISIs indicates that, in addition to the well-established, low-level motion mechanisms, a comprehensive view of motion processing must include a long-range mechanism which tracks the location of corresponding features over time.

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