What does the Ternus display tell us about motion processing in human vision?

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Abstract. The Ternus display is a moving visual stimulus which elicits two very different percepts, according to the length of the interstimulus interval (ISI) between each frame of the motion sequence. These two percepts, referred to as *element motion* and *group motion*, have previously been analysed in terms of the operation of a low-level, dedicated short-range motion process (in the case of element motion), and of a higher-level, attentional long-range motion process (in the case of group motion). We used a novel Ternus configuration to show that both element and group motion are, in fact, mediated solely by a process sensitive to changes in the spatial appearance of the Ternus elements. In light of this, it appears that Ternus displays tell us nothing about low-level motion processing, implying that previous studies using Ternus displays, for instance those dealing with dyslexia, require reinterpretation. Further manipulations of the Ternus display revealed that the orientation and spatial-frequency discrimination of the process underlying the analysis of Ternus displays is far worse than thresholds for spatial vision. We conclude that Ternus displays are analysed via a long-range motion, or feature-tracking, process, and that this process is distinct from spatial vision.

1 Introduction

A long-standing dichotomy in vision research is that between short-range and long-range processing of moving input. This distinction was introduced by Braddick (1974), via experiments involving the displacement of two-frame random-dot kinematograms. It transpired that for displacements beyond a certain critical spatial limit, $d_{\max}$, the perception of coherent motion broke down, and this was taken as evidence for a short-range motion process, which was contrasted with a long-range process which operated over larger displacements. Subsequent research has shown that, whilst the short-range process fails to operate if stimuli are presented dichoptically (Braddick 1974; Georgeson and Shackleton 1989), this is not the case for the long-range process (eg Pantle and Picciano 1976). Another difference between the two processes can be highlighted by introducing a temporal gap, or interstimulus interval (ISI), between successive image frames in an apparent-motion sequence—the short-range process operates at low or zero ISIs and the long-range process operates at higher ISIs, with a crossover value of around 40 – 50 ms (eg Pantle and Picciano 1976; Petersik 1989; Georgeson and Harris 1990; Hammett et al 1993) The two processes may be distinguished in several other ways: the short-range process appears to be preattentive (or passive), localised in the visual field, and operating over a limited spatial range; the long-range process seems to be attentional (or active), and able to operate over a wider area and greater spatial range (Anstis 1980; Braddick 1980). The long-range process has more recently been referred to as a feature-tracking system (eg Lu and Sperling 1995; Scott-Samuel and Georgeson 1999), the implication being that it relies upon the active, high-level observation of changes in position, in contrast to the passive, low-level dedicated motion processing of the short-range process.

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The Ternus display (Ternus 1926; Pantle and Picciano 1976) is an apparent-motion sequence which produces very different percepts according to the size of the ISI between each image frame, and it has been used extensively to probe the short-range and long-range processes. The first frame of the Ternus display (see figure 1a) contains three collinear elements which are equally spaced horizontally, and 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. When the first and second frames are alternated an impression of motion is produced. The Ternus display has a bistable appearance when the ISI is around 40–50 ms, and gives different motion percepts above and below this figure (Pantle and Picciano 1976). At short ISIs, *element motion* is seen—the endmost element of the display appears to hop from one end to the other [figure 1b(i)]. At long ISIs, *group motion* prevails—all the elements in the display appear to move together from side to side [figure 1b(ii)]. These two types of motion have been associated with short-range (element motion) and long-range (group motion) processes (Pantle and Picciano 1976; Petersik 1989). It has been suggested that, when element motion is seen, the short-range process is signalling the non-motion of the central elements, leaving the long-range process to signal the hopping motion of the outermost element (Braddick and Adlard 1978). This signalling of non-motion by the short-range motion process is assumed to be different from the absence of any signal when long-range conditions prevail.
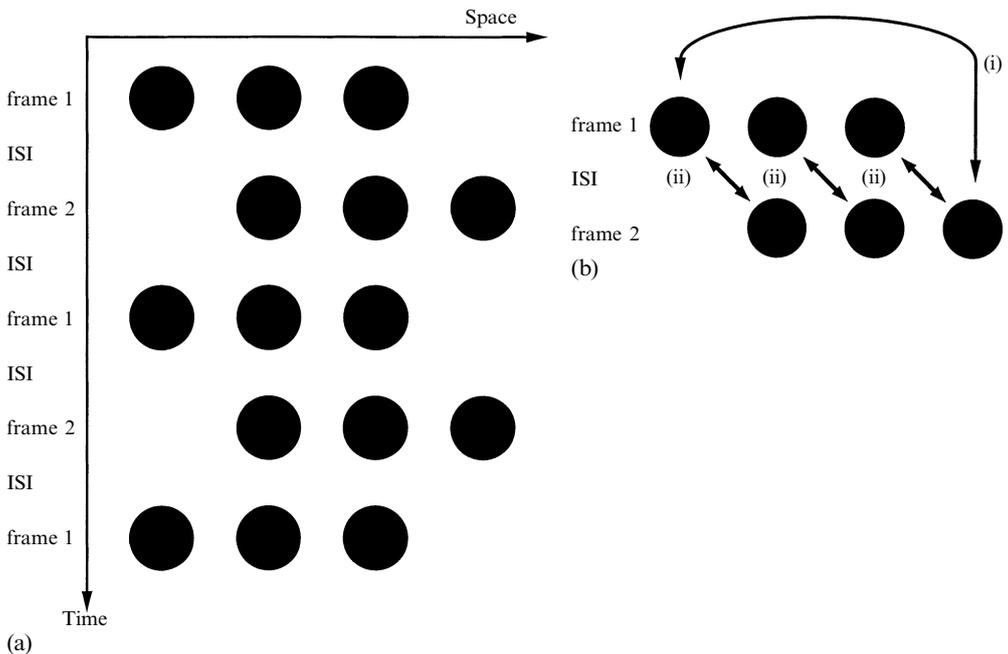

Figure 1. The Ternus display. (a) Space–time representation of the Ternus display used here. The equally spaced collinear elements in frame 1 are shifted by the element separation to give frame 2. The two frames are alternated, with or without a temporal gap (an interstimulus interval, or ISI) between them. (b) The length of the ISI determines the type of motion seen: element motion at short ISIs (i), group motion at longer ISIs (ii). The display is bistable for ISIs around 40–50 ms.

In experiment 1 we used a Ternus display with each element defined by a static noise field to establish baseline measurements, and changed this noise field from static to dynamic in order to test Braddick and Adlard's (1978) hypothesis that a non-motion signal from the short-range motion process leads to the perception of element motion at short ISIs. In experiment 2 we elaborate on the results from experiment 1 by addressing the question of what signals the non-motion of the central elements at short ISIs, and hence provide a new explanation of how the Ternus display is analysed. In experiment 3 we further characterise the process which signals the motion or not of the central elements by investigating the orientation and spatial-frequency tuning of this process.

2 Experiment 1: static and dynamic noise
The identity of element motion with the short-range motion process is, on the face of it, paradoxical—if the short-range process operates over a limited spatial range, then how can it signal the large displacement of the outermost element as it moves from end to end of the display when the ISI is short? Braddick and Adlard (1978) suggested that when element motion is seen the short-range motion process is, in fact, signalling an absence of motion or change in the central elements of the Ternus display. This 'non-motion signal' then leaves the long-range process to track the movement of the outer element, hence we see element motion. For longer ISIs, the central elements are no longer analysed as stationary, which allows a group-motion interpretation of the display by the long-range process. Thus motion in the Ternus display is always signalled by the long-range process; the short-range process acts only to signal lack of motion of the central elements at short ISIs. In experiment 1, we established baseline measurements for a Ternus display defined by static noise, and then attempted to discourage a stationary percept of the two middle elements in the display by making the noise dynamic.

2.1 Methods
Stimuli were generated on a Macintosh G3 running custom-written software, and displayed on a gamma-corrected Sony 520 GS monitor with a refresh rate of 75 Hz and a mean luminance of 47.5 cd m^{-2}. The motion sequence was a Ternus display (see figure 1), consisting of two image frames which were alternated with an ISI in between each frame shown. Image frames were displayed for 200 ms, and the ISI varied between 0 and 120 ms in 13.3 ms intervals. The Ternus elements were circular disks filled with binary noise (1 min of arc × 1 min of arc square noise elements) on a mean luminance background; the noise was either static or dynamic across the image frames of the motion display. The noise was 50% Michelson contrast with a mean luminance which was the same as the background.

The starting position of the Ternus elements was randomised from trial to trial. At the viewing distance of 115 cm, the diameter of each element subtended 80 min of arc, and the centre-to-centre separation of the elements was 120 min of arc. A central fixation spot was provided, viewing was binocular, and observers indicated the type of motion perceived (element or group) in a single interval, binary choice task. Data were collected from one of the authors and an experienced psychophysical observer, with 50 trials per observer per condition.

2.2 Results: the effect of dynamic noise
Both observers produced typical Ternus data for the static-noise condition (figure 2, open symbols)—at short ISIs, element motion was seen, and this percept changed to one of group motion at longer ISIs. When the Ternus elements were defined by dynamic noise (figure 2, solid symbols) group motion was always seen, except with a 0 ms ISI, when the display appeared bistable.
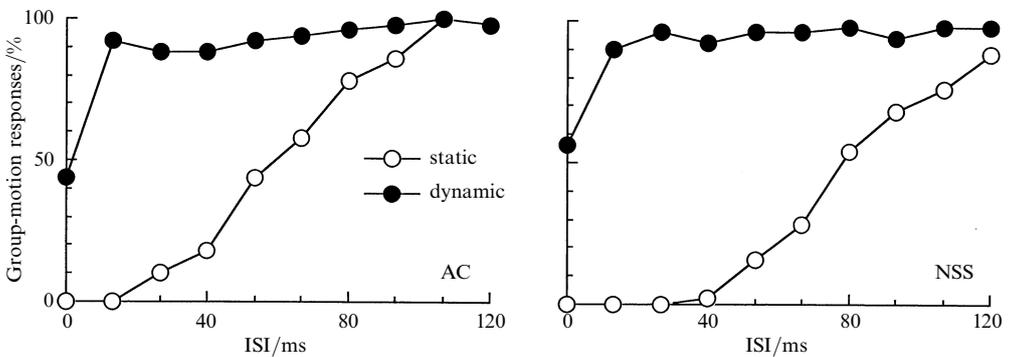
Figure 2. Experiment 1 results. Percentages of group-motion responses are plotted against ISI for two observers. The binary noise pattern defining each Ternus element was either static (open symbols) or dynamic (solid symbols).

2.3 Discussion: central elements have a key role

The results confirm an earlier report that elements defined by dynamic texture tend to give rise to increased group-motion responses (Petersik et al 1978). It appears that the use of dynamic instead of static noise to define the Ternus elements decreases the chance of identifying the central elements as remaining stationary from frame to frame, and hence leads to an increased group-motion percept at shorter ISIs. Similarly, a group-motion percept has also been encouraged by moving the central elements laterally from frame to frame (Petersik and Pantle 1979). The increased group-motion responses reported here are consistent with Braddick and Adlard's (1978) hypothesis that the motion signal, or rather lack of it, given by the central elements is the critical factor at short ISIs (where element motion usually dominates).

3 Experiment 2: a role for short-range motion?

What could be signalling the non-motion of the central elements of a Ternus display at short ISIs? It appears that this non-motion might be analysed either via the lack of a signal from the short-range motion process, as proposed by Braddick and Adlard (1978), or through the presence of a static signal derived from a process sensitive to features. The latter could be characterised either as a long-range motion process (or feature-tracking process), or simply as spatial vision.

For either account—one based upon low-level motion processing, one based upon features—the process in question is providing the visual system with a 'no motion' signal. If the individual Ternus elements each contained a short-range motion signal, then one would expect this to have some influence on the perception of element and group motion; by adding sinusoidal modulation to each Ternus element and changing its phase from frame to frame, it should be possible to influence the balance of group and element motion reports by observers at short ISIs (see figure 3).

Consider the effects of various phase shifts from frame to frame within each Ternus element on either a short-range motion process or a feature-based process. For no phase shift, both possibilities will signal no motion, and therefore on Braddick and Adlard's (1978) account element motion will dominate as the central elements will not be seen as moving or changing. For a phase shift of 180° (as illustrated in figure 3), a feature-based process will register a maximum difference with light bars becoming dark, and vice versa, from frame to frame, and thus group motion would be seen. The short-range motion process, on the other hand, decomposes a counterphasing grating into two oppositely drifting gratings of equal amplitude (Levinson and Sekuler 1975), and will therefore signal no net directional motion: it will signal no difference for the central elements, and so element motion would be perceived. A 90° phase shift (ie a quarter of the spatial
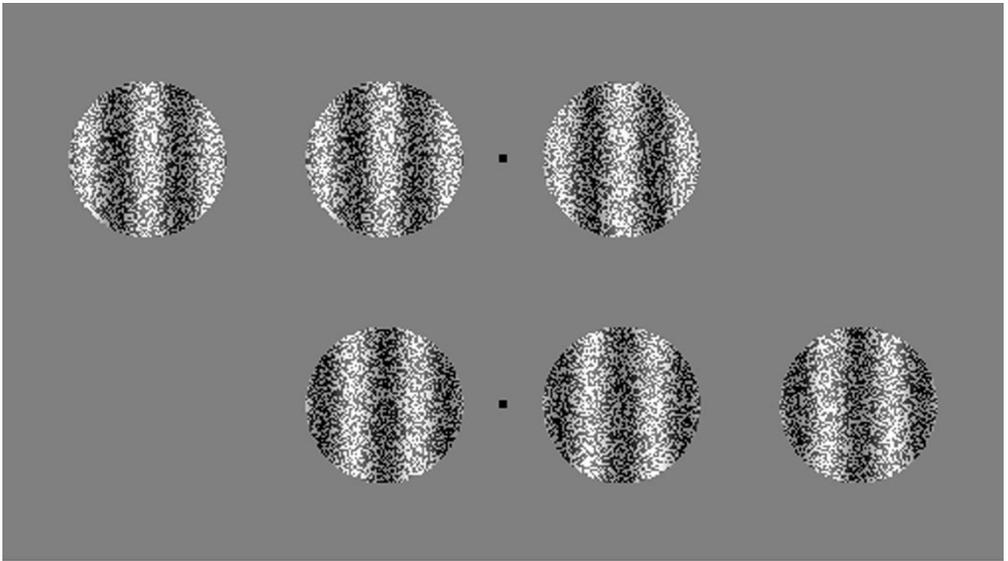
Figure 3. Experiment 2 stimuli. Two frames from the stimulus sequence are shown, one above the other. The noise carrier is dynamic, and the vertical luminance modulation shifts in phase by 180° from frame to frame.

period of the grating), however, will give a near optimal response for the low-level short-range motion sensors if one assumes that they are based on a quadrature model (eg Adelson and Bergen 1985); this would encourage group motion. For a feature-based process, this 90° shift indicates change, but not as strongly as a 180° phase shift.

In experiment 2, we attempted to determine which of the two explanations of element motion is correct by using a stimulus designed to yield different responses according to which system underpins the non-motion signal attached to the central Ternus elements under conditions where element motion is usually seen.

3.1 Methods

The methods were as reported in section 2.1, except that the 50% contrast binary noise (either static or dynamic) used to define the Ternus elements was sinusoidally modulated by a vertical luminance grating with a spatial frequency of 2.0 cycles deg^{-1} and a contrast of 50%. In alternate frames of the Ternus sequence, the phase of the modulation was jumped back and forth through a fixed amount, which was randomly selected from the range 0° to 270° sampled at 45° intervals. The ISI was fixed at 0 ms, a value that greatly favours element motion.

3.2 Results: local phase affects the motion percept

Changing the carrier (ie whether the binary noise was static or dynamic) had no effect on the type of motion perceived. This was not the case in a separate control condition (data not shown), where it was found that when the modulation contrast was reduced to 10%, observers' responses were mediated by carrier type, not modulation phase. Thus it seems that the type of motion (element or group) seen in the Ternus display is determined by the most visible component within each Ternus element.

The results reported here (for static and dynamic noise carriers with a modulation contrast of 50%) were collapsed, as there was no difference between them. These data, for two observers, are shown in figure 4, along with the predictions of the two explanations of how the motion (or non-motion) of the central Ternus elements might be signalled. The prediction made by an explanation based on a feature-based process is a good fit to both sets of data, whereas that made by the short-range motion process is not.
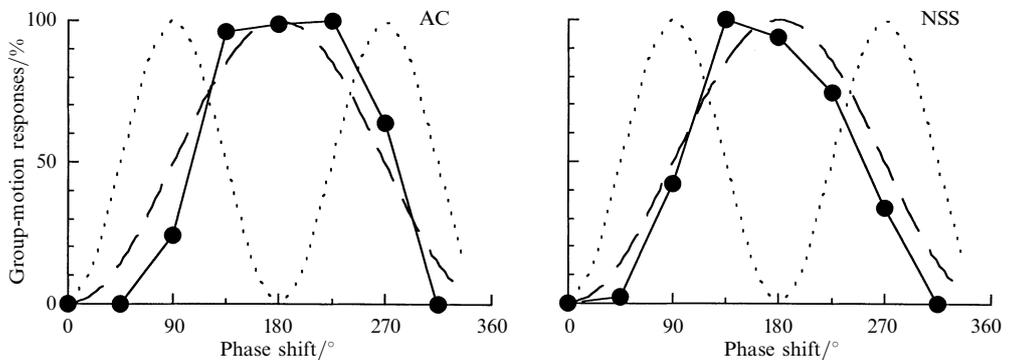
Figure 4. Experiment 2 results. Percentages of group-motion responses are plotted against phase difference for vertical modulation from frame to frame for two observers. Predictions of two possible explanations for the non-motion signal elicited by the central elements are shown as dashed lines (feature-based process) and dotted lines (short-range motion process).

3.3 Discussion: no short-range processing in Ternus displays

It appears that the motion or non-motion of the central elements of a Ternus display is signalled by a feature-based process, not by a low-level motion mechanism (ie the short-range motion process). The difference between element and group motion is whether this feature-based process indicates that the central elements are unchanged and stationary, or that they are different and moving.

If the conclusion drawn here is correct, then it should be the case that the orientation of the modulation is not important, only the fact that it changes phase. A control experiment was run on two observers to test this idea. The orientation of the first-order sinusoidal modulation was horizontal, rather than vertical, but otherwise the conditions were the same as before. The results (figure 5) were similar to those recorded for vertical modulation, confirming the result reported above.
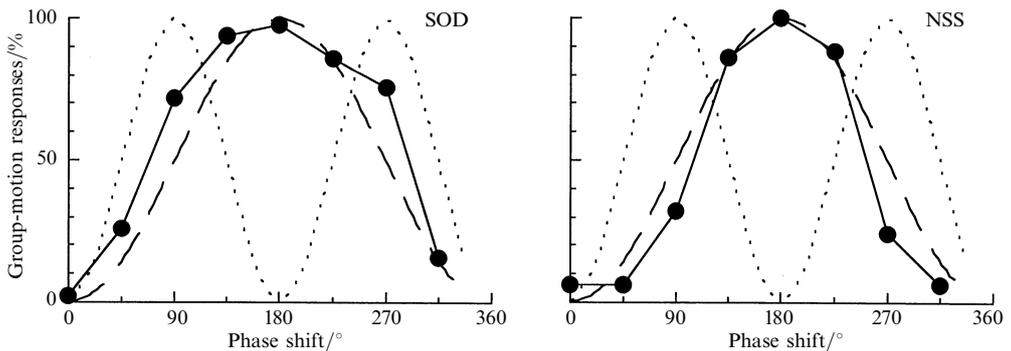

Figure 5. Control experiment results. Percentages of group-motion responses are plotted against phase difference for horizontal modulation from frame to frame for two observers. Predictions of two possible explanations for the non-motion signal elicited by the central elements are shown as dashed lines (feature-based process) and dotted lines (short-range motion process).

4 Experiment 3: how different is different?

The similarity of the central elements in successive frames of the Ternus display plays a crucial role in observers' perception of the type of motion seen. In experiment 1, changing the type of binary noise used to define each element from static to dynamic resulted in an increased perception of group motion for both types of stimulus. In experiment 2, it was shown that this signalling of the motion (or not) of the central elements was mediated not by a short-range motion process but by a feature-based process.

An outstanding question is the nature of this feature-based process. There appear to be two possibilities: it is either long-range motion processing (feature tracking), or spatial vision. In experiment 3, we looked at the effect of changing orientation and spatial frequency within elements from frame to frame of the Ternus display. For spatial vision, orientation discrimination thresholds are around $1°$ and Weber fractions for spatial-frequency discrimination are around 5%. By manipulating the orientation or spatial-frequency content of the elements in a Ternus display from frame to frame we aimed to test the discriminability of these properties, and hence determine what underpins the feature-based process.

4.1 Methods

The methods were as reported in section 2.1, except that the binary noise used to define the Ternus elements was sinusoidally modulated by a luminance grating with a contrast of 50%. Two conditions were used: in the first, the spatial frequency of the luminance grating was fixed at 2.0 cycles deg^{-1} and its orientation was jumped back and forth through a fixed angle from frame to frame, centred on the vertical, which was randomly selected from the range $0°$ to $40°$ sampled at $10°$ intervals; in the second, the orientation of the luminance grating was fixed at the vertical, and in alternate frames of the Ternus sequence the spatial frequency of the modulation was jumped back and forth between the base spatial frequency (2.0 cycles deg^{-1}) and a randomly selected spatial frequency from the range 0 to 50.0% smaller and larger than the base spatial frequency sampled in 12.5% steps. These two stimuli are illustrated in figure 6. The ISI was fixed at 0 ms for both conditions, as in experiment 2.

4.2 Results: higher thresholds

As with experiment 2, the results obtained with static and dynamic carriers were the same, and therefore the data were collapsed across this parameter. The results for the manipulations of orientation and spatial frequency are shown in figures 7a and 7b respectively. The points at which the display appears to be bistable (ie where observers' responses are evenly divided between 'group' and 'element') is around $15°$ for the orientation condition (figure 7a); ie the modulation in successive frames was approximately $\pm 7.5°$ from the vertical. For the spatial-frequency condition (figure 7b) the Weber fraction is around 20%.

4.3 Discussion: perception does not reflect acuity

The thresholds measured here for the crossover between element and group motion percepts at a 0 ms ISI are both well above threshold for static stimuli, which is around $1°$ for orientation discrimination (eg Regan and Beverley 1985; Dakin et al 1999) and 5% for spatial-frequency discrimination (eg Regan et al 1982).

One referee pointed out that the difference between the thresholds reported here and those quoted from the literature could be due to the presence of a texture mask (ie the binary noise carrier) in the stimuli used here. We accept that this is a possible explanation of the discrepancy between our results and the lower thresholds quoted from earlier studies, but would argue that the similarity of our results for stimuli with static and dynamic noise implies that masking is not the explanation here; one would expect any masking effect of the noise carrier to vary with the temporal properties of the mask (ie whether the carrier were static or dynamic). Furthermore, Badcock and Hutchison (1998) showed that orientation discrimination thresholds for luminance modulations of dynamic noise were in the region $1°-2°$ which is very similar to the thresholds reported for stimuli with no carrier (eg Regan and Beverley 1985; Dakin et al 1999).
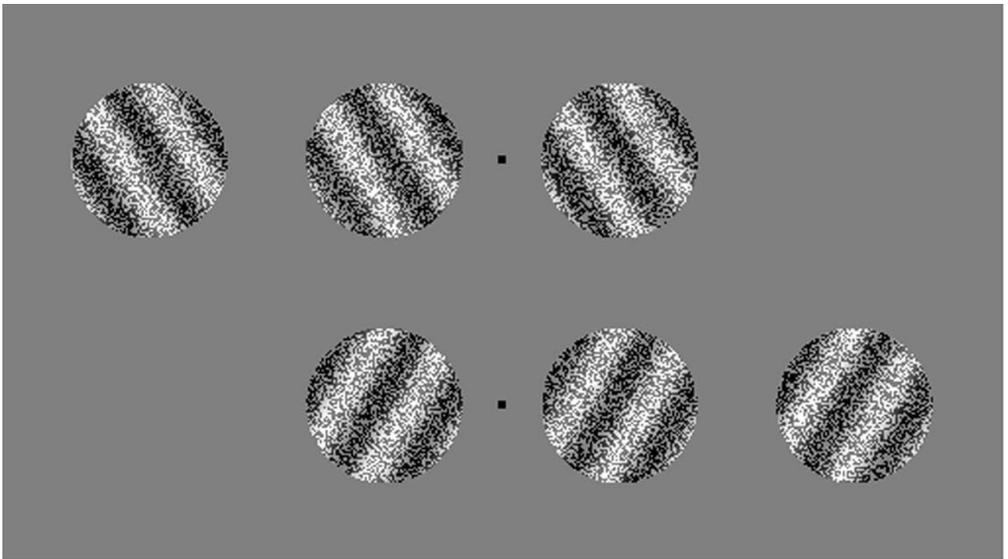
(a)
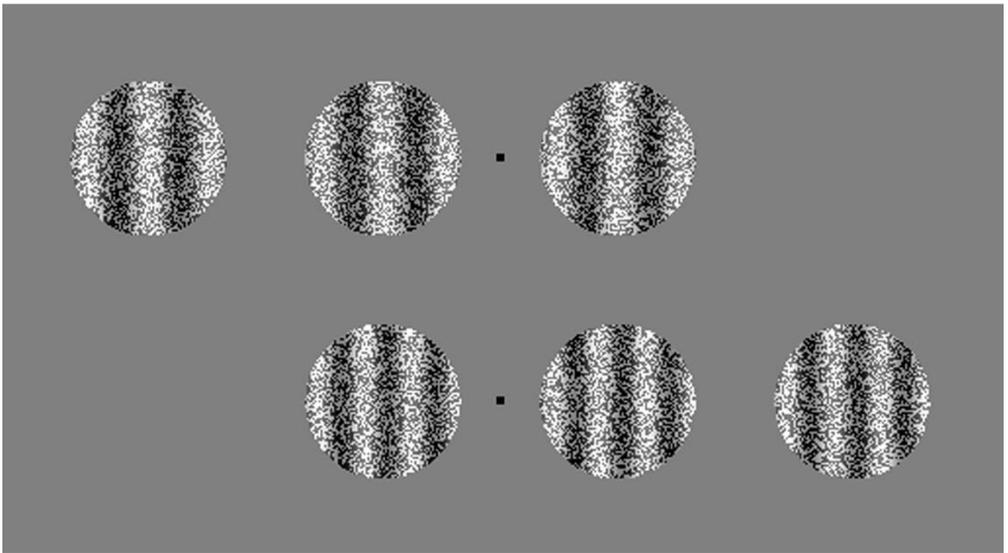
(b)

Figure 6. Experiment 3 stimuli. (a) Two frames from the stimulus sequence are shown, one above the other. The noise carrier is dynamic, and the luminance modulation changes orientation from $-30°$ to $+30°$ from frame to frame. (b) Two frames from the stimulus sequence are shown, one above the other. The noise carrier is dynamic, and the vertical luminance modulation changes in spatial frequency by 50% from the first frame to the second.

The results of experiment 3 suggest that the way the central Ternus elements are perceived is not simply a question of whether spatial vision is capable of registering a change in the static image. Rather, there is some higher threshold which must be exceeded before this occurs. It seems reasonable to conclude that this higher threshold is a reflection of the long-range process, ie the attentional tracking of spatial features over time.
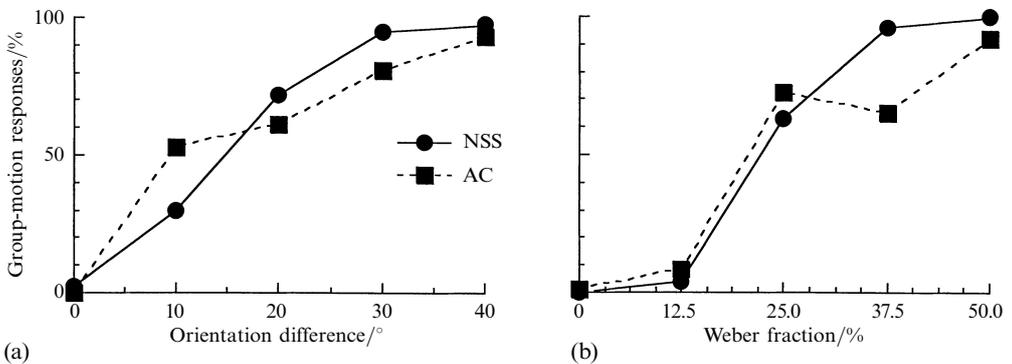
Figure 7. Experiment 3 results. Percentages of group-motion responses are plotted against (a) the orientation difference and (b) the Weber fraction of the spatial-frequency difference from frame to frame for two observers.

5 General discussion

We have confirmed that Ternus elements defined by dynamic noise are more likely to give a group-motion percept than those defined by static noise (experiment 1). Manipulation of the short-range motion signal within each element in the Ternus display revealed that the lack of motion of the central elements, which allows element motion to occur, is signalled not by the short-range motion process but by some feature-based process (experiment 2). Changing the orientation and spatial-frequency content of the Ternus elements from frame to frame only resulted in group motion at 0 ms ISIs when the differences were large compared with typical spatial thresholds for discrimination of these properties, suggesting that the measured thresholds characterised a long-range motion, or feature-tracking, process (experiment 3).

It appears that Ternus displays are not, after all, a good stimulus for distinguishing short-range and long-range motion processing. On the contrary, they appear to tap into only the long-range motion process. In the light of this, some of the conclusions drawn from previous Ternus studies investigating motion processing would perhaps merit another look. For example, the use of Ternus displays to highlight magnocellular/parvocellular processing differences with reference to dyslexia (eg Slaghuis et al 1996; Cestnick and Coltheart 1999) may have to be revised; if only one process is involved in analysing Ternus displays, then appealing to differential processing for element and group motion is no longer valid.

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