Motion transparency arises from perceptual grouping: evidence from luminance and contrast modulation motion displays

Peter W. McOwan and Alan Johnston

What circumstance lead to the perception of global motion transparency? It has been shown that, in paired random dot displays, motion transparency can be abolished if the separation of the dot pairs is sufficiently small [1]. Motion transparency has also been shown to be influenced by high level cognitive cues [2]. Here, we report that the combination of two moving dot stimuli, which separately invoke a percept of transparent motion, gives rise to a non-transparent percept of local rotation. These stimuli were constructed using various different pattern elements, including luminance defined elements and contrast modulations. The results extend and support the view that high-level grouping of local measures of the velocity field can determine whether a motion transparency is perceived or not.

Address: Department of Psychology, University College London, Gower Street, London WC1E 6BT, UK.

Received: **18 June 1996**
Revised: **29 July 1996**
Accepted: **15 August 1996**

Current Biology 1996, Vol 6 No 10:1343–1346

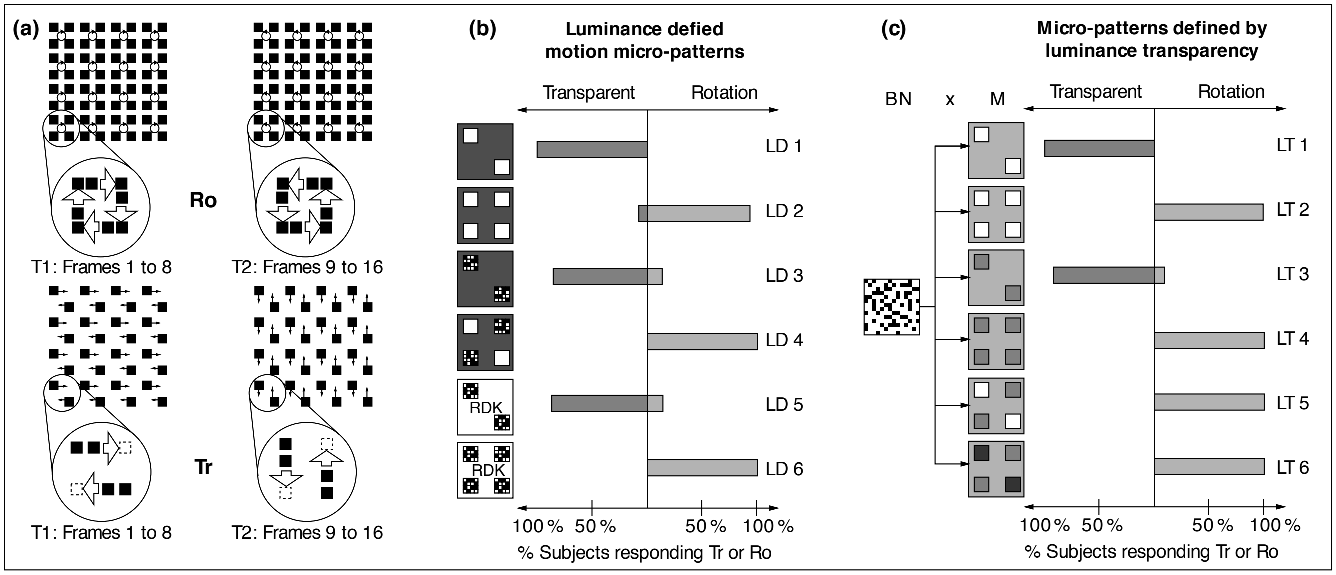
Results and discussion

The perception of motion transparency is often thought to depend upon a low-level segregation of the moving image. Early filters in the visual system process the motion signal and split it into independent spatial frequency, orientation [3,4] or direction selective channels [5,6]. These channels could allow the visual system to represent motion transparency by a function with multiple values at any spatial point in the visual field. Alternatively, the attribution of multiple surfaces reported in motion transparency could result from high-level grouping processes acting on local measures of velocity, generating a global consensus that there exist groups of elements moving in the same direction and establishing a transparency. How does the visual system represent and interpret the velocity field — the function describing how the speed and direction associated with motion sequences varies over space?

The idea that transparency in motion is based on multiple measures at a point has been challenged by Qian *et al.* [1,7]. They constructed paired random dot displays in which pairs of dots move over each other in opposite directions. Transparent planes are not seen in these displays, although transparency can be induced by a slight spatial displacement of one of the paired dots in the direction orthogonal to its motion. This result may be accounted for by postulating that detectors at different locations with different preferred directions of motion are activated maximally by the paired moving dots and that the resultant signals from similar preferred directions are then grouped over space to give transparency. When the dots are not separated, transparency is extinguished due to local opponent motion mechanisms [7]. Similar results exist for spatially dense stimuli: two identical, superimposed sine gratings moving in opposite directions appear as a static contrast reversing grating, not a transparency. Transparency can be observed in plaids, patterns made by adding together two sinusoidal gratings, provided that the components used to construct the pattern are sufficiently different in terms of orientation, speed, contrast or spatial frequency [8]. The perception of transparency in these displays is often labile [4] and can be switched on and off by an effort of will, evidence which supports the grouping hypothesis. Transparent motion in plaids composed of two identical square wave gratings can be manipulated by altering the luminance value at the grating intersections [2]. When the luminance in the area of overlap of the two gratings is in agreement with the value one would expect from the physics of transparency, the gratings appear to move transparently — strong evidence for a high-level mechanism. Introducing a suitable stereo disparity has also been shown to influence the perception of transparency in plaids [9].

Here, we investigate the operation of mechanisms involved in the grouping of low-level motion signals for a range of different motion stimuli, and extend the examination of how high-level cues may influence the perception of transparency. To examine the grouping hypothesis, the method should allow local motions to be kept essentially the same, but the global percept to be transformed from a transparent to a non-transparent motion. Here, we use a novel manipulation of the underlying pattern of motions in the display, which does not involve a change in the spatial separation of the moving components [1] or high-level luminance cues [2]. This display has a grid of moving micro-patterns in which dots oscillate around the perimeter of a square — like runners on a baseball diamond (Fig. 1a, Ro). Half of the dots moved in opposite directions horizontally and half the dots moved in opposite directions vertically in sequential frames. We refer to these as 4-element displays. All the results were collected using a two alternative forced choice paradigm. If we removed the dots at opposing corners of the squares (Fig. 1a, Tr), so that on the first 8 frames only pairs of dots moving horizontally were drawn and on the second 8 frames only dots moving vertically were drawn (2-element displays), subjects reported a clear transparency with two sheets of dots first moving across one another horizontally and then vertically (Fig. 1b,

Figure 1



The structure and results for the micro-pattern displays. **(a)** The Ro and Tr stimuli consisted of a 4 × 4 array of micropatterns. The first experiment compared 4-element displays (Ro) in which four dots rotated around a square, first clockwise then counter-clockwise, with 2-element displays (Tr) in which opposite corner elements were removed to leave only horizontal motion or vertical motion at any one time. The dots took 8 frames to traverse from one corner to another. Subjects report transparency in Tr and rotations in Ro. The moving display subtended 7.24 degrees of visual angle in total. The elements of the micro-pattern, square dots in this case of width 0.5 degrees, were separated by 0.5 degrees. A motion cycle involved two phases; T1, a clockwise rotation and T2, an anticlockwise rotation, each involving 8 single pixel linear displacements presented with a 60 Hz non-interlaced frame rate. Subjects saw three cycles on each trial. The display programme included a look-up table to ensure that the intensity of the displayed image was linear. **(b)** Luminance defined (LD) motion micro-pattern displays. The key on the left shows the type of micro-pattern defining the stimulus. The numbers of subjects reporting transparency or rotation in a two alternative forced choice (2AFC) task are shown on the right as percentages of subjects tested ($n = 14$). Subjects could repeat the trial until they until sure of their response. Subjects consistently reported transparency for the 2-element patterns and rotation for the 4-element patterns. The dots had a luminance of 52.2 cd m^{-2} and were presented on a grey background of 39.0 cd m^{-2}. Subsequently, the 4 × 4 pixel dots were replaced by binary noise which either translated over a grey background with the same mean luminance (rows LD 3, LD 4) or a static binary noise indicated by RDK (rows LD 5, LD 6). The rotation seen with mixed binary noise and luminance dots (row LD 4) demonstrates subjects were grouping elements on the basis of the motion of the dots not on the basis of identity. That subjects are grouping on the basis of the velocity field is confirmed by the similar pattern of results (rows LD 5, LD 6) for random dot kinematograms (RDKs). In RDKs, the moving elements are presented on a field of static binary noise and are therefore invisible on any single frame. The structure of the micro-patterns only becomes apparent through motion. **(c)** Micro-pattern displays defined by luminance transparency (LT). The key on the left shows the type of micro-pattern M defining the pattern of spotlights and shadow falling on the background. The numbers of subjects reporting transparency or rotation are shown on the right as percentages of subjects tested ($n = 8$). The key shows the luminance pattern, M, used to multiply a random binary noise field background (BN). This field took the values 0.5 and 1.5 which fixed the Michelson contrast at 0.5 throughout the entire display. In rows LT 1, LT 2 results are presented for the simulation of moving spotlights over a uniformly illuminated static random texture. Rows LT 3, LT 4 provide equivalent data for shadows or film transparencies. Row LT 5 shows a micropattern in which spotlights and shadows are mixed and row LT 6 has data for the simulation of different depths of shadow or layered film transparencies. In all cases 2-element displays appear transparent and 4-element displays appear to rotate. For this experiment the background mean luminance was 34.4 cd m^{-2}. For shadows and spotlights the mean luminance was 19.1 and 45.5 cd m^{-2} respectively. In row LT 6, the two dark regions had mean luminances of 19.1 cd m^{-2} and 9.1 cd m^{-2}.

row LD 1). When the two transparent patterns were added (Fig. 1a, Ro), subjects reported seeing local rotations of the dots around the perimeter of the square (Fig. 1b, row LD 2), although a structural model based on separate direction tuned channels might be expected to predict a four-way transparency. Even if there are structural constraints on the number of available channels [10], one could still anticipate the presence of transparent motions as all the previous motion components remain unchanged in the display. We have to conclude that the lack of transparency in the Ro display motion is due to the perceptual reorganization of the component Tr motion sequences to form this new representation, and that the presence of coherent motion in opposite directions is not sufficient for transparency. To ensure that the transparent percept was not simply due to the reduced number of elements in the display, we confirmed that equating the total number of elements present in a 4-element display to match that in a 2-element display did not induce transparency.

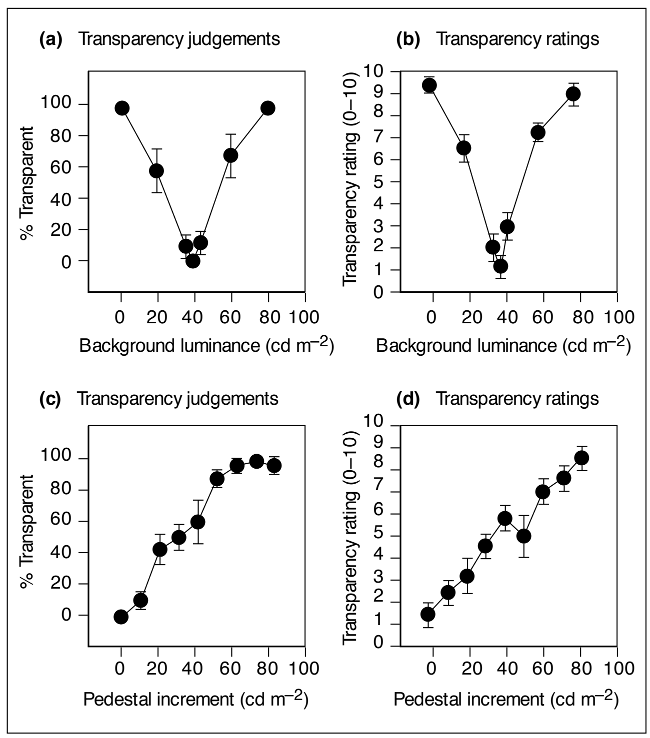
It may be argued that, in the combined 4-element display, subjects had no physical basis on which to group elements into two separate transparent patterns. To test this, we substituted elements comprising binary random dot patterns at opposite corners in the 4-element displays. All subjects reported local rotations, even though the moving elements could be grouped into two sets on the basis of element identity (Fig. 1b, row LD 4). It would appear that transparency in these sequences involves the operation of grouping processes acting on the velocity field rather than on the elemental spatial patterns. To confirm this, we constructed 2-element displays with random dot kinematograms (RDKs) as the elements [11]. In this display, binary random dot patterns translate over a static binary random dot background — the elements are defined solely by motion and are not visible in any single frame of the display. Any grouping effects must be dependent upon the motion signal. The transparency seen in the 2-element RDK (Fig. 1b, row LD 5) allows us to discount an image feature tracking mechanism as the basis for this percept. There are, in effect, no features to be tracked in this stimulus.

The micro-patterns used above allowed a shift between the perception of transparency and local rotations. It is possible that rotation is especially effective in blocking transparency. To test this hypothesis, we constructed a luminance-defined display where the 4-element micro-patterns now move to produce a more complex pattern of local oscillations. Two of the elements move out orthogonally from one corner of the micro-pattern as the two remaining elements move orthogonally into the opposite corner. This pattern of motion reverses in alternate micro-patterns producing a checker-board-like pattern of local oscillations which should not selectively activate rotation detection mechanisms. In this experiment, the display was rotated through 45°. When observed, 100 % of subjects ($n = 8$) reported local oscillations. By removing all the display elements moving vertically (or alternatively horizontally), we reinstated a transparent percept for 100 % of subjects. Even when the 4-element displays could be grouped by colour identity, by using black and white dot elements on a grey background, 87 % of subjects reported local oscillation.

We next examined whether the introduction of an explicit luminance transparency to the rotation displays could effect the perception of motion transparency as has been reported for plaids by Stoner *et al.* [2]. We constructed displays where the motion elements were formed by areas of altered luminance moving over a textured background. The luminance values of a binary random dot static field were multiplied by the micro-pattern values to simulate the appearance of sets of moving spotlights or shadows playing on a uniformly illuminated background. Subjects saw transparent translation in 2-element displays and rotations in 4-element displays, as before (Fig. 1c), even when the four-element displays involved pairs of spotlights and shadows (Fig. 1c, row LT 5) which should have been attributed to different physical causes. Using a micro-pattern comprising two shadows of different value to simulate the luminance attenuation produced by two overlapping films, did not reinstate transparency (Fig. 1c, row LT 6). In these micro-pattern displays, transparency results solely from grouping by common fate and is not influenced by a tacit knowledge of the physics underlying luminance transparency [2].

Finally, we examined a micro-pattern where the moving elements were second-order — the movement of contrast modulation or texture modulation, with a requirement that the average luminance over the entire image is zero [12]. For the second-order micro-pattern elements we used moving patches of dynamic binary noise which have the same mean luminance as a grey background. It has been suggested that there exists two separate motion pathways in the visual system, a linear system for first-order motions and a non-linear system for second-order [12,13]. It is possible to transform our selected micropattern between first-order and second-order by keeping the mean luminance of the dynamic noise constant and varying the background luminance level. When the background luminance is different from the mean luminance of the noise there is a variation in the average luminance over the display, hence the motion is first-order. Figure 2a shows the subject transparency judgements for 2-element dynamic noise micro-patterns as a function of the uniform background luminance. Subjects were also asked to rate the level of transparency on a scale of 0–10 (0, no transparency, to 10,

Figure 2



The effect of noise in micro-pattern displays. **(a,c)** The mean percentage of transparent responses in a 2AFC task averaged over 8 subjects. Each subject's data is the average of 5 observations. In all graphs, the bars indicate ±1 standard error of the mean taken over subjects. **(b,d)** Subjects were also asked to rate the degree of transparency in the display on a 10 point scale. (a) Subjects were asked to report if dynamic noise 2-element displays, presented on a uniform luminance background, showed transparency or local rotations. The mean luminance of the dynamic noise was 39.0 cd m^{-2}. When the background luminance was equal to this value, the motion is second-order, and subjects reported no transparency; (b) the rating data gave the same pattern of results. (c) To investigate whether the lack of transparency in second-order displays was due to noise, we added a dynamic noise background, mean luminance 31.5 cd m^{-2}, to a luminance defined 2-element RDK display. Subjects were asked whether the dots appeared transparent or rotating. The percentage of transparent responses is plotted as a function of the amplitude of the luminance signal, the pedestal, added to the luminance defined RDK signal. The rating data are shown in (d) and gives the same pattern of results.

fully transparent) for each of the displays (Fig. 2b). When the mean luminance of the noise was equal to the background — when the motion signal was solely second-order — subjects did not report transparency in the 2-element displays; instead, 'twinkling' pairs of dots seemed to orbit around each other, like a binary star system. We investigated a range of second-order motion sequences, but were unable to generate transparency for 2-element displays. Why then do we find only rotations for second-order, 2-element displays, when in all the previous 2-element displays examined we find transparency? One possible answer is that, in second-order displays, transparency is absent because the 'twinkling' dynamic noise elements have a noisy local velocity field, exciting motion detectors in all directions and providing no consistent direction of motion on which the grouping process may operate. Alternatively, the low-level mechanisms supporting transparency may not be present in a 'second-order motion channel'.

To resolve this question, we introduced a dynamic noise background to the 2-element luminance defined RDK display. It is shown in Figure 1, row LD 5 that the analogous first-order RDK 2-element display with a static background supports a transparent percept. With dynamic noise forming the background, transparency was eliminated. When the mean luminance of the RDK 2-element display random dot patches was raised above the mean luminance of the dynamic background noise by a prescribed luminance pedestal increment, the transparency was reinstated (Fig. 2c). This pattern of results is also reflected in the subjects' transparency rating measurements (Fig. 2d). Hence, the first-order motion of the elements only gives rise to transparency when the level of noise associated with the velocity field at the boundaries is sufficiently low to allow grouping. We conclude that the loss of transparency in second-order patterns may be attributed to the noise in the local velocity field, and there is no need to appeal to the properties of an additional motion system to explain the results.

Conclusions

The experiments of Qian *et al.* [1,7] showed that motion transparency may be eliminated by overlapping dots moving in opposite directions. This can be explained by interactions at an early stage of motion computation. Here, we demonstrate that transparency may also be eliminated for spatially separate dot patterns by imposing an alternative organization of the velocity field. This may be explained by high-level grouping processes. From a computational perspective, it has been assumed previously that models for motion transparency must support multiple motion measures at a point [4,6]. The results presented here indicate that models of motion computation which provide only one measure of image velocity at a point [14–20] may also be able to account for motion transparency. The RDK data and the evidence supporting the grouping process points to a late rather than early site for the mechanisms serving motion transparency. A suitable neural basis for this process may be found in the human analogue of monkey MSTd. In primates, neurons in the area MSTd have been shown to have large receptive fields which are selectively tuned to local rotations, spiral motion and translations [21–23]. It is at this level of processing that neural systems could distinguish effectively between the local rotations and transparent translations found in the experiments reported here.

Acknowledgements

We would like to thank O. Braddick for commenting on an earlier draft of the paper. The work is supported by a grant from the Wellcome Trust. P.W. McOwan is supported by a Wellcome Fellowship in Mathematical Biology.

References

1. Qian N, Andersen RA, Adelson EH: **Transparent motion perception as detection of unbalanced motion signal. 1. Psychophysics.** *J Neurosci* 1994, **14**:7357–7366.
2. Stoner GR, Albright TD, Ramachandran VS: **Transparency and coherence in human motion perception.** *Nature* 1990, **344**:153–155.
3. Movshon JA, Adelson EH, Gizzi EH, Newsome WT: **The analysis of moving visual patterns.** In *Pattern Recognition Mechanisms.* Edited by Chagass C, Gattas R and Gross C. New York: Springe; 1985.
4. Noest AJ, van den Berg AV: **The role of early mechanisms in motion transparency and coherence.** *Spat Vis* 1993, **7**:125–147.
5. van Doorn AJ, Koenderink JJ: **Detectability of velocity gradients in moving random–dot patterns.** *Vision Res* 1983, **23**:799–804.
6. Andersen RA, Sowden RJ, Treue S, Graziano M: **Hierarchical processing of motion in the visual cortex of monkey.** *Cold Spring Harb Symp Quant Biol* 1990, **55**:741–748.
7. Qian N, Andersen RA, Adelson EH: **Transparent motion perception as detection of unbalanced motion signal. 3. Modelling.** *J Neurosci* 1994, **14**:7381–7392.
8. Adelson EH, Movshon JT: **Phenomenal coherence of moving visual patterns.** *Nature* 1982, **300**:523–525.
9. Trueswell JC, Hayhoe MA: **Surface segmentation mechanisms and motion perception.** *Vision Res* 1993, **33**:313328.
10. Mulligan JB: **Motion transparency is restricted to two planes.** *Invest Ophthal Vis Sci* 1992, **33**:1049.
11. Braddick O: **A short-range process in apparent motion.** *Vision Res* 1974, **14**:519–527.
12. Chubb C, Sperling G: **Drift-balanced random dot stimuli: a general basis for studying non-Fourier motion perception.** *J Opt Soc Am A* 1988, **5**:1986–2007.
13. Wilson HR, Ferrera VP, Yo C: **A psychophysically motivated model for two-dimensional motion perception.** *Vis Neurosci* 1992, **9**:79–97.
14. Horn BKP, Schunck BG: **Determining optical flow.** *Artif Intel* 1981, **17**:185–203.
15. Lucas BD, Kanade T: **An iterative image registration technique with an application to stereo vision.** *Proceedings of the 7th International Joint Conference on Artificial Intelligence.* Vancouver, BC; 1981:674–679.
16. Grzywacz NM, Yuille AL: **A model for the estimate of local image velocity by cells in visual cortex.** *Proc Roy Soc Lond B* 1990, **239**:129–161.
17. Heeger DJ, Simoncelli EP: **A model of visual motion sensing.** In *Spatial Vision in Humans and Robots.* Edited by Harris L. Cambridge: Cambridge University Press; 1995.
18. Johnston A, McOwan PW, Buxton H: **A computational model of the analysis of some first-order and second–order motion patterns by simple and complex cells.** *Proc R Soc Lond B* 1992, **250**:297–306.
19. Johnston A, Clifford CWG: **A unified account of three apparent motion illusions.** *Vision Res* 1995, **35**: 1109–1123.
20. Sobey P, Srinivasan MV: **Measurement of optical flow by a generalized gradient scheme.** *J Opt Soc Am A* 1991, **8**:1488–498.
21. Tanaka K, Saito H: **Analysis of motion of the visual field by direction, expansion/ contraction, and rotation cells clustered in the dorsal part of the medial superior temporal area of the macaque monkey.** *J Neuropysio.* 1989, **62**:626–641.
22. Duffy CJ, Wurtz RH: **Sensitivity of MST neurons to optic flow stimuli. I. A continuum of response selectivity to large field stimuli.** *J Neurophysiol* 1991, **65**:1329–1345.
23. Graziano MSA, Andersen RA, Snowden RJ: **Tuning of MST to spiral motions.** *J Neurosci* 1994, **14**:54–67.