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Transparency and coherence in human motion perception

G. R. Stoner, T. D. Albright & V. S. Ramachandran*†

The Salk Institute for Biological Studies, La Jolla, California 92037, USA
* Department of Psychology, C-009 University of California at San Diego, La Jolla, California 92093, USA

WHEN confronted with moving images, the visual system often must decide whether the motion signals arise from a single object or from multiple objects[1–5]. A special case of this problem arises when two independently moving gratings are superimposed. The gratings tend to cohere and move unambiguously in a single direction[2] (pattern motion) instead of moving independently (component motion). Here we report that the tendency to see pattern motion depends very strongly on the luminance of the intersections (that is, to regions where the gratings overlap) relative to that of the gratings in a way that closely parallels the physics of transparency. When the luminance of these regions is chosen appropriately, pattern motion is destroyed and replaced by the appearance of two transparent gratings moving independently. The observations imply that motion detecting mechanisms in the visual system must have access to tacit 'knowledge' of the physics of transparency and that this knowledge can be used to segment the scene into different objects. The same knowledge could, in principle, be used to avoid confusing shadows with real object boundaries.

A simple example of pattern motion can be seen in the complex plaid pattern shown in Fig. 1*c*. This pattern was created by superimposing two identical square wave gratings (Fig. 1*a* and *b*). The motion of each component grating is indicated by the arrows and this is what human observers always see when either grating is viewed separately. When viewing the plaid pattern, however, observers usually report seeing upward pattern motion that is (Fig. 1*c*) different from either of the two component directions of motion. Perhaps the visual system computes the loci of possible motion for the two gratings separately and then determines the single point where the loci intersect[2]. This point would uniquely specify both the direction and velocity of the coherently moving plaid pattern.

To explore the role of transparency in motion perception, we created a new class of moving stimuli that convey a striking impression of perceptual transparency (Fig. 2*b*). We found that this was best achieved by using asymmetrical square wave gratings instead of sine waves (see the legend of Fig. 2*a* for details). Although sine-wave gratings have been used in previous studies of motion coherence[2,5,6], we found that identical effects are obtainable with square-wave gratings. Also, it is far easier to manipulate luminance levels in square-wave gratings to achieve transparency effects. Asymmetric gratings (duty cycle is narrow bar width/(narrow bar + wide bar) and equals 0.286) were used to bias the figure-ground interpretation, which has, in turn, a strong effect on the interpretation of transparency. In these patterns a specific cycle portion (namely the narrow bars) was consistently seen as foreground. Trials consisted of brief presentations (1.5 s), after which the subject had to indicate (with a key press) whether he saw pattern motion. Subjects were instructed to fixate on a small cross in the centre of the aperture for the duration of each trial. Subjects under this type of instruction are capable of stable and reliable fixation[7].

On each trial the display consisted of three regions: (1) that formed by the intersection of the two gratings; (2) the narrow bars of both gratings (which were identical and held constant at 90 cd m^{-2}); and (3) the wide bars (which we term background) of both gratings (which were held constant at 231 cd m^{-2}). Perceptual transparency was manipulated by varying only the luminance of the intersections. Fifteen intersection luminance values were presented on a pseudo-random schedule. These varied from 4.90 to 125.3 cd m^{-2} in increments of ~8.50 cd m^{-2}.

The rules of perceptual transparency have been previously studied for stationary objects[8–10]. To understand these rules imagine two gratings superimposed on a background whose luminance is 100 cd m^{-2}. If the gratings are neutral density filters of 50% transmittance, then their luminances would be 50 cd m^{-2}, but the luminance of the intersections would be 50% of 50 cd m^{-2}, or 25 cd m^{-2}, so the relationship would be multiplicative rather than additive. Any intersection luminance above 25 cd m^{-2} but below 50 cd m^{-2} would still be compatible with the physics of transparency but the gratings would then be seen also to have some surface reflectance of their own, that is, they would both look like translucent or frosted glass plates. Values below 25 and above 50 cd, on the other hand, would be incompatible with physics. In our moving displays, these rules of transparency dictate that the optimal conditions for pure transparency (equivalent to the neutral density filter case) could be calculated by multiplying the narrow bar-to-background ratio (constant: 0.390) by the narrow bar luminance (90 cd m^{-2}): this would be 35 cd m^{-2}. Perceptual transparency should also be seen when the intersection luminance is increased beyond this point but remains less than the narrow bar luminance (Fig. 2*b*). Within this transparency zone, the foreground grating should be perceived to be transparent but also having some surface reflectance. When both gratings are of the same luminance (as in these experiments), an intersection luminance equal to the narrow bar luminance is the only condition compatible with occlusion. It follows that intersection luminances of <35 cd m^{-2} (Fig. 2*a*) or >90 cd m^{-2} (Fig. 2*c*) are totally incompatible with

† To whom correspondence should be addressed.

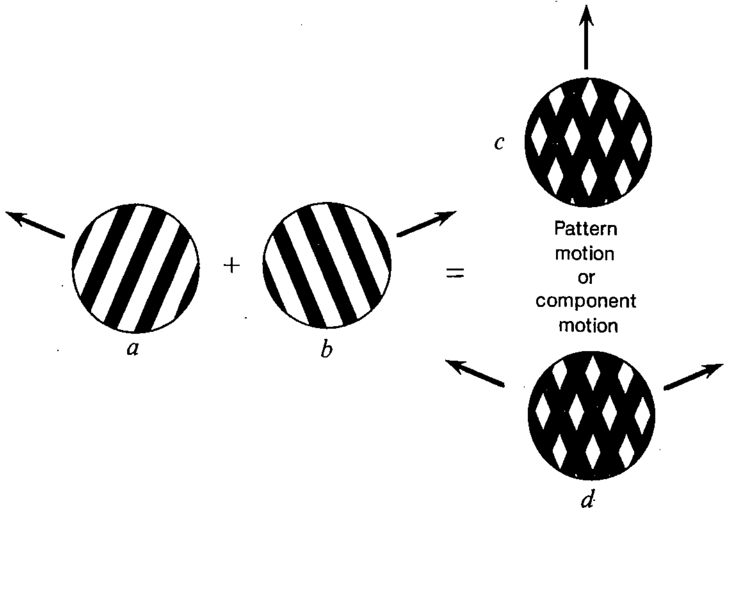

FIG. 1 *a* and *b*, Two square wave gratings. Each grating is moved orthogonally to its orientation and the velocities of the two gratings are identical. The perceived directions of motion are indicated by the arrows. *c*, Superimposition of *a* and *b*. Instead of seeing the two gratings move in separate directions, observers usually see a 'plaid' moving in a single direction (as shown by the arrow). *d*, Under some conditions, the gratings are seen to slide past each other, that is, component motion is seen instead of pattern motion.

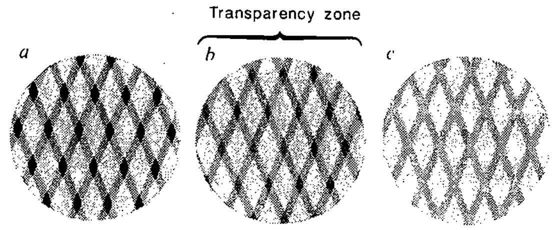

FIG. 2 *a*, Example of stimuli used in our experiment. The intersection luminance in this stimulus is too dark to be compatible with the physics of transparency. This leads to a decline in component motion (Fig. 3). Our stimuli were generated using a high-resolution graphics display controller (Pepper SGT, Number Nine Computer Corporation: 640 × 480 pixels, 8 bits per pixel; 60 Hz, non-interlaced) operating in an AT computer. Stimuli were displayed on a 14-inch analog RGB video monitor (Zenith ZCM-1490, flat technology CRT) and were viewed through a circular aperture subtending 11° at a distance of 57 cm. They were moved by updating their position in synchrony with the vertical refresh of the monitor on alternate cycles (that is, every 33.3 ms). *b*, Similar to *a*, except that the intersections between the two gratings are only slightly darker than other regions in the image and this conveys a vivid impression of transparency. When this pattern is moved, subjects usually see the two gratings sliding past each other, that is, they see component motion rather than coherent pattern motion in a single direction. *c*, Identical to *a*, except that the luminance of the intersections is brighter than that of either grating. This stimulus is physically incompatible with two transparent gratings and is usually seen as a single coherently moving plaid. It lies to the right of the 'transparency zone' in Fig. 3.

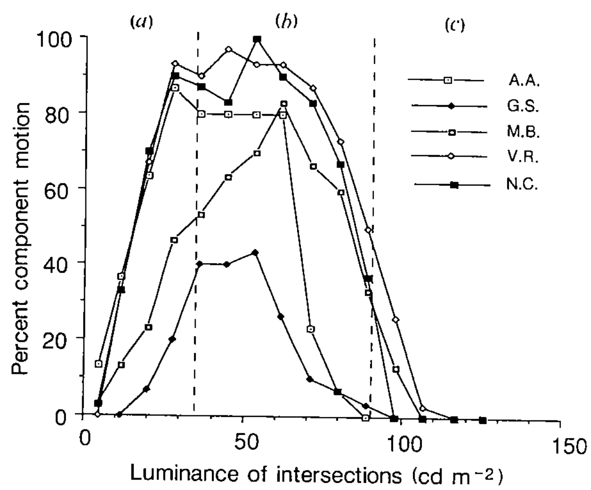

FIG. 3 Probability of component motion percept as a function of plaid pattern intersection luminance. Both gratings were of the same spatial frequency (1.75 cycles per deg). On each trial the individual gratings were moved at an angle of 135° relative to one another at a speed of 3° s^{-1}, resulting in a pattern speed of 8° s^{-1}. Pattern direction was either up or down, and varied on a random schedule. Each datum point represents the mean of 30 trials at each intersection value (in three series of 10 trials per intersection value). Data are shown from three naive (A.A., M.B., N.C.) and two experienced subjects (G.S., V.R.). The intersection/luminance was varied in roughly equal steps. The 'transparency zone' extends from pure transparency (35 cd m^{-2}) up to the point of 'occlusion' (90 cd m^{-2}). Component motion is most likely within a region roughly centred on the transparency zone.

physical transparency or occlusion. They are unlikely to lead an observer to interpret the display as two independently moving gratings and we therefore predict a decline in component motion judgements under these conditions.

Figure 3 shows the results: notice that for each subject there is a range of intersection luminances for which there is a high probability of seeing component motion. The midpoint of this range coincides with the centre of the transparency zone (the region in which the gratings both filter and reflect light). This implies that the tendency to see component motion depends strongly on whether or not the gratings look transparent. If the luminance of the intersections is adjusted so that the gratings look transparent, component motion is usually seen instead of pattern motion. On the other hand, if the luminance ratios are incompatible with two physically transparent gratings, subjects are much less likely to see component motion. For example, Fig. 2*c* is physically incompatible with transparency; there are no two gratings that can overlap to produce intersections that are actually brighter than either grating alone and consequently, the visual system rejects this percept.

Another interpretation of our findings might be that adding luminance to the intersections would introduce new horizontally oriented Fourier components, whose unambiguous upward motion might capture the two gratings[4,5] and result in pattern motion. This model would predict that maximal component motion should occur when the two gratings are simply added together, but our findings contradict this. In fact, our data (Fig. 3) demonstate that component motion is much greater when the interaction between the grating luminances is multiplicative (as in two overlapping neutral density filters; corresponding to the left-most dotted line in Fig. 3) rather than additive. In Fig. 3 the intersection luminance value closest to the linear (additive) superimposition is 4.90 cd m^{-2} (leftmost data points). Horizontally oriented Fourier components are at a minimum here and increase in power as the intersection luminance increases. Thus, we might expect component motion to decrease monotonically as we move towards the right in the graph, but instead it increases until the value becomes incompatible with transparency and then declines again. These findings are more consistent with a transparency model than with an interpretation in terms of Fourier components.

Our results have two interesting implications. First, if computational models of motion perception are to provide more than "mere caricatures"[11] of human visual processes, they have to take into account the effects of multiple sources of information[12,13], such as those implied by the transparency illusion reported here. Second, a certain proportion of cells in the middle temporal area of primates[14-16] exhibit direction-selective responses to pattern motion[17-19], rather than component motion, when confronted with Fig 1*c*. Would this response to pattern motion be reduced if the gratings were made to look transparent? □

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