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Magnitude of luminance modulation specifies amplitude of perceived movement

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A compelling impression of movement, which is perceptually indistinguishable from a real displacement, can be elicited by patterns containing no spatially displaced elements. An apparent oscillation, w-movement, was generated by a stationary pattern containing a large number of horizontal pairs of spatially adjacent dots modulated in brightness. The observer's task was to adjust the perceived amplitude of the w-motion to match the amplitude of a real oscillation. All of the data can be accounted for by a simple rule: If the relative change in the luminance, $W = \Delta L/L$, between two adjacent stationary dots is kept constant, the distance over which these dots appeared to travel in space comprises a fixed fraction of the total distance by which they are separated. The apparent amplitude of the w-motion increases strictly in proportion with luminance contrast, provided that the contrast is represented in the motion-encoding system by a rapidly saturating compressive Weibull transformation. These findings can be explained in terms of bilocal motion encoders comparing two luminance modulations occurring at two different locations.

It is somewhat astonishing that when Wertheimer's (1912) famous paper on ϕ-movement was published, the fact that a vivid impression of motion can be produced by a sequence of stationary stimuli was widely known. Simple toy stroboscopes were available in stores, and Wertheimer had no difficulty purchasing one after his sudden decision to leave a train in Frankfurt 2 years earlier. But he probably was the first to realize that ϕ-motion violates the layman's concept of motion. According to this concept, movement is an intrinsic property of an object, and encountering a situation in which a clear impression of motion is elicited without that property must come as a big surprise. For the physicist, however, motion appears to be a quality attributed to an object by an observer: The object can be decided to be in motion only if it is observed at two different instants and it is seen to be in two different positions at those two instants. Therefore, ϕ-motion may simply indicate that the movement experience requires a perceptible change in the position of one stimulus element with respect to another.

However, the displacement of some stimulus elements with respect to others cannot be regarded as a *necessary* condition for perception of movement. A distinct impression of movement can be elicited by patterns containing no spatially displaced elements. The perceived movement can be evoked by changes of light flux at different retinal locations. Johansson (1950, 1978) described the "wandering motion" seen between two or more spatially adjacent bright objects modulated in brightness (w-motion). What is particular to this and other analogous visual demonstrations (Anstis, 1967, 1986, 1990; Bülthoff & Götz, 1979; Gregory & Heard, 1983; Mastebroek & Zaagman, 1988; Mather, 1984) is that the perceived movement is generated by stimuli in which the elements do not change their relative spatial position and usually remain continuously visible. These findings are surprising only if the detection of motion is ultimately regarded as a matching process comparing two spatial luminance patterns at two instants in time. Most current theories of movement perception, on the contrary, regard motion as comparing two luminance modulations that occur at two different locations (Reichardt, 1957, 1987; van Santen & Sperling, 1984, 1985). Consequently, w-motion suggests that the appropriate stimulus for motion is a relative change in light flux at two spatial locations—not the spatial displacement tracking of some visual elements after they have been individually recognized.

It is impossible to distinguish an object moving in discrete jumps from a continuously moving object, provided that the time between jumps and their amplitude is not too great (Burr, Ross, & Morrone, 1986b; Morgan, 1979, 1980; Watson, Ahumada, & Farrell, 1986). The sequence of discrete jumps that occurs at rates greater than about 30 Hz is indistinguishable from smooth continuous motion because both provide the same effective stimulus to the visual system. In the present study, we present evidence that w-motion can be perceptually indistinguishable from real displacements. This means that despite their physical difference, w-motion and ϕ-motion are metameric, and they both rely on an identical underlying mechanism in the nervous system. Many

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current theories of motion perception assume that the visual system employs motion-encoding units with receptive fields extended over space and time that are tuned to movement along a particular trajectory (Adelson & Bergen, 1985; Burr, Ross, & Morrone, 1986a; van Santen & Sperling, 1984, 1985; Watson & Ahumada, 1985; Wilson, 1985). These units, measuring the amount of luminous energy in some spatiotemporal volume, are indifferent to whether this change in the luminance flux is produced by a moving object traveling from one location to another, or by the luminance modulation of two stationary objects at these two locations.

METHOD

Subjects. Two observers, M.R. (female) and A.P. (male; one of the authors), participated. One of the subjects was naive, having no knowledge of the way visual motion was generated in the experiment.

Procedure. The observer decided whether two display areas, the central part and its surround, showed identical movement. The impression of movement in the central part was generated by luminance modulation of stationary patterns (w-movement). The perceived movement of the surround was produced by spatial displacement of the elements—that is, by their stroboscopic displacement, or ϕ-movement. Thus, the observer's task was to adjust the *perceived amplitude* of periodic oscillation of a stationary

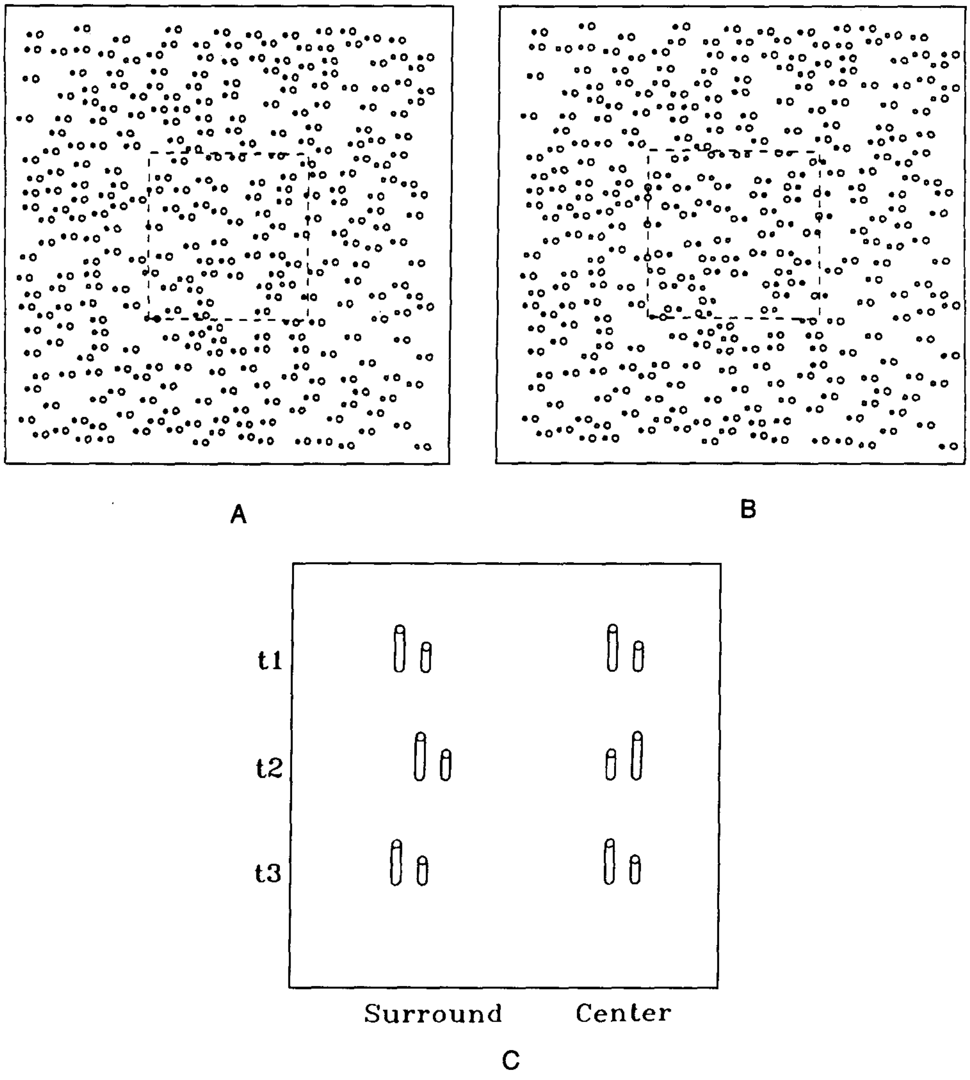

Figure 1. An illustration of one stimulus composed of two patterns—the original (A) and its slightly modified replica (B)—exposed in an alternation rate of 3.3 Hz. Each pattern consisted of a large number of horizontal pairs of dots (dipoles); one was dark with a fixed luminance L (small circles), and the second one was light with adjusted luminance $L + \Delta L$ (large circles). In the central area (dashed rectangles), movement was produced by luminance modulation; all the dark dots became light, and, in turn, all the light dots became dark. Surround movement was elicited by a real displacement of all dipoles without exchange of position between light and dark members within a dipole. (C) A magnified picture of two dipoles in the surround and central area from three subsequent frames—t1, t2, and t3. The height of the cylinders represents luminance.

pattern to the amplitude of *real* oscillation. In this experiment, stimuli were composed of 1,500 micropatterns distributed randomly within a rectangular area that, viewed from 250 cm, had a size of about 5.3° × 3.5° (see Figure 1). The central area (indicated by a dashed rectangle), within which the movement was produced by luminance modulation, was approximately 2.75° wide and 2.07° high. Each micropattern consisted of a horizontal pair of dots (dipoles), separated from each other by a spatial distance, *d*. The dot size was 1 pixel, or about 0.0084° of arc (about half of a minute). Special care was taken to avoid overlap between micropatterns by applying a rule prohibiting any two micropatterns from being closer to each other than 5′. One of the two dots in each dipole had a fixed luminance, *L* (dark dots), and the second one had a variable contrast, $L + \Delta L$ (light dots), which could be adjusted by the observer. The dark dots served as a standard, and the light ones served as a test. The motion stimulus was generated by endless cycling of a given stimulus pattern and its slightly modified replica. These two patterns, the original one and its slightly modified duplicate, were presented in alternation at the rate of 3.3 Hz on the screen of an Amstrad color monitor. Thus, each pattern remained visible for 300 msec and was thereafter instantaneously replaced between two frames with the second pattern.

In the central part of the display, all the dipoles remained stationary; only dark (with a fixed luminance, *L*) and light (with a variable luminance, $L + \Delta L$) dots exchanged their spatial positions. In the first and every subsequent odd frame, all the left members of the dipoles were dark, and all the right members were light. In the second and every subsequent even frame, the left element became light and the right element became dark. If the luminance difference ΔL between the two types of dots was small, no motion of the central area could be seen. Above a certain luminance increase, however, the coherent horizontal oscillation of the whole central area began. Shortly, a luminance increment, ΔL, was alternatively added to the left and the right dots, which produced cyclical w-motion of the central portion of the display. With the increase of the luminance modulation, ΔL, the perceived amplitude of oscillation increases. In the surround area, there was no exchange of positions between dark and light elements of dipoles; their relative spatial positions remained the same. Instead, all the dipoles were uniformly displaced by a distance, *s*, to the right in the second and every subsequent even frame, and back to the left on the third and every subsequent odd frame. This displacement produced a coherent to and fro ϕ-motion of the surround area. In most cases, it was phenomenologically difficult, if not impossible, to tell whether the motion was induced by luminance modulation or by real displacement, provided that the perceived amplitudes of both movements were equalized.

The observer was instructed to adjust the luminance increment ΔL until the movement of the central part of the display appeared to be identical to that of the surround area. The adjustment procedure was as follows. The luminance of the two types of dots, dark and light, were tuned to be equal, and the observer started to increase, by revolving a multirevolution knob, luminance increment ΔL, added to all the light dots. After reaching the luminance value that was necessary for equalizing apparent movement in the central and surround areas, the trial was stopped, and the ΔL value

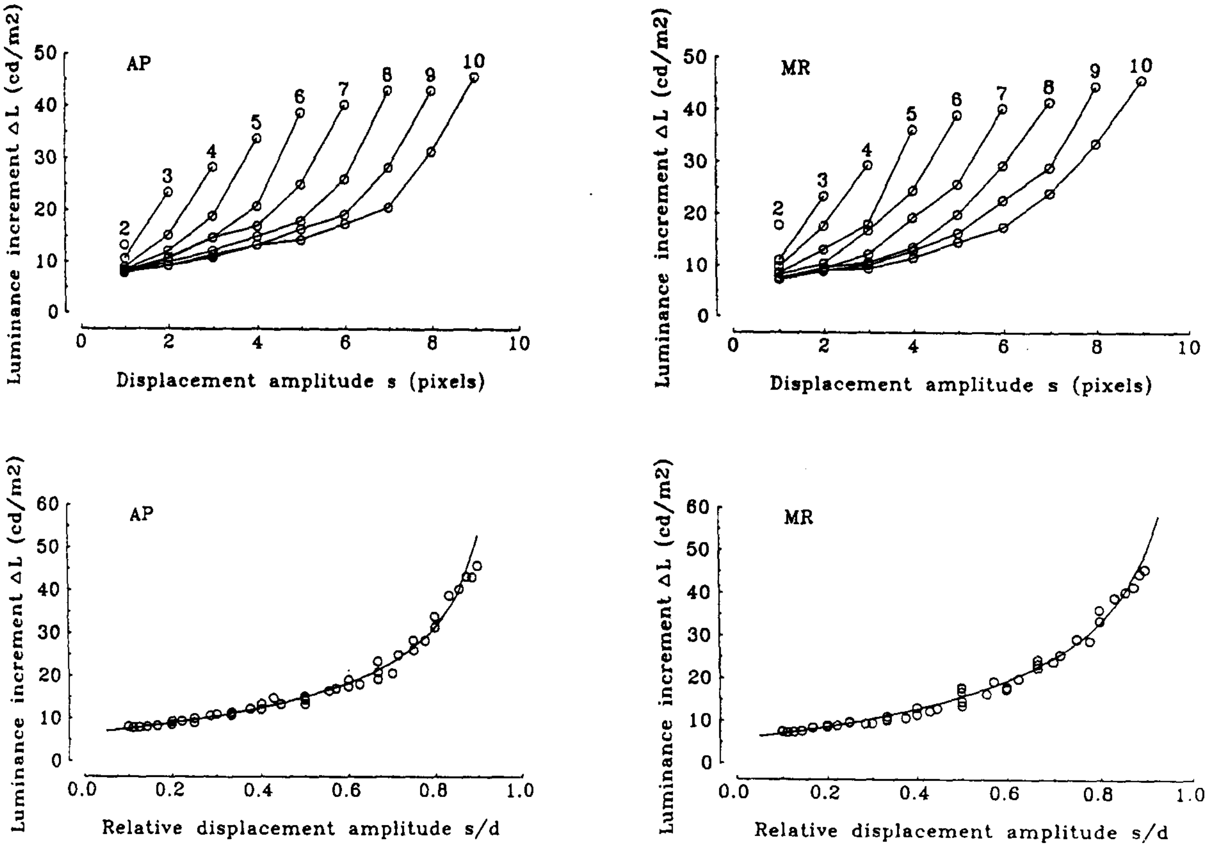

Figure 2. Upper panels: The luminance increment ΔL (cd/m^2) required to make the apparent oscillation of the central part perceptually indistinguishable from the surround oscillation with the displacement amplitude *s* (in pixels), for Subjects A.P. (left panel) and M.R. (right panel), for nine different interdot separations (2, 3, . . . , 10), *d*. Lower panels: The same data replotted as the function of the relative displacement amplitude *s*/*d* (in proportion to interdot separation).

was stored. Although the adjustment time was not limited, usually it took only 5–6 sec to reach a satisfactory ΔL value.

There were two different experiments. In each experimental session, one of the fixed reference luminance values, L, was selected. There were one ($L = 6$ cd/m^2) and three ($L = 3$, 6, 12 cd/m^2) different referent luminance values in the first and second experiments, respectively. Before each trial in the first experiment, one of the interelement separations, d, was selected from nine interelement separations ($d = 2, 3, \ldots, 10$ pixels). In the second experiment, the interdot separation was $d = 6$. Before each trial in both experiments, one of the displacement values (s) was randomly selected. Since the perceived amplitude of w-motion never exceeded interelement separation d, the amplitude of ϕ-motion s was always smaller than d.

In both experiments viewing was binocular, without head fixation, in a semidarkened room. The adjustment was repeated at various combinations of L, d, and s for 5 (M.R.) or 10 (A.P.) times.

RESULTS

Figure 2 (upper panels) shows the luminance increment ΔL required to make the luminance-modulated w-motion perceptually equivalent to the surround movement produced by a given displacement s, for Subjects A.P. (left panel) and M.R. (right panel), for nine different interdot separations, d. The reference luminance was $L = 6$ cd/m^2. Each set of data, corresponding to a given interdot separation d, formed a function clearly distinct from other functions. Two empirical rules can be noticed in these data:

1. The luminance increment ΔL that was required to equalize w-motion in the central area with a real displacement in the surround area increased monotonically with the increase of the stroboscopic displacement amplitude s. This means, in particular, that even when the spatial separation between the luminance-modulated dots remained the same, the perceived amplitude of w-motion increased with the luminance modulation amplitude ΔL.

2. The luminance increment ΔL that was required to match a given stroboscopic jump s of the surround area was smaller for small interdot separations and became progressively larger with the increase of the interdot separations, d. As the separation between the dots increased, less incremental energy flux was needed to produce w-motion that had the same perceived displacement amplitude. This means that the same amount of the luminance modulation ΔL over a larger spatial separation conveys more evidence for the presence of motion than those over a smaller spatial separation.

Figure 2 (lower panels) shows the same data, but normalized with respect to the displacement distance. In the lower panels, the luminance increment ΔL is plotted against the relative rather than the absolute displacement

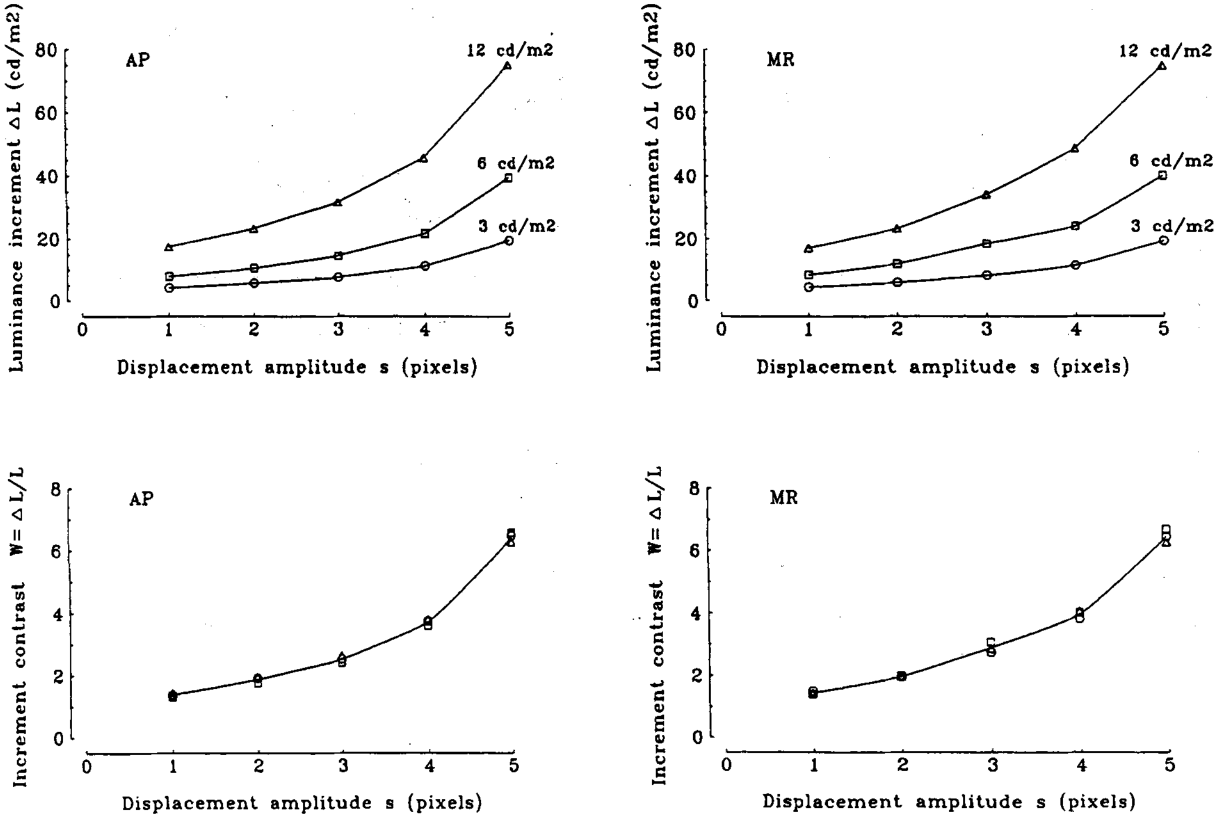

Figure 3. Upper panels: The required luminance increase ΔL (cd/m^2) as a function of the displacement amplitude, s (in pixels), for three different reference luminances, $L = 3$ (circles), 6 (squares), and 12 (triangles) cd/m^2, for 2 observers—A.P. (left panel) and M.R. (right panel). Lower panels: The same data expressed in terms of the relative contrast $W = \Delta L/L$. Symbols are the same as those in the upper panels.

distance. The displacement amplitude is expressed in terms of the proportion to the interdot separation, or simply *s*/*d*. After this transformation, all nine, clearly separate data sets come together to form one single functional relation. This makes it clear that almost the same pattern of results holds for all interdot separations, provided that the amplitude of the adjusted stroboscopic jump is appropriately scaled. Thus, any given luminance difference ΔL between two dots produces an apparent movement whose amplitude is a fixed fraction of spatial separation. This result means, in particular, that the perceived movement is not scaled in terms of velocity; there could be two completely different velocities corresponding to one *s*/*d* value, provided that the transition time remains constant.

Figure 3 shows the results of the second experiment, in which the luminance increment ΔL, required to equalize w- and ϕ-motions, was measured as a function of the reference dot luminance *L*. Three different reference luminance values (L = 3, 6, and 12 cd/m^2) at one fixed interdot separation (d = 6 pixels; equivalent to 0.05° of arc) were used. As the reference luminance *L* increased, more luminance modulation ΔL was needed to produce w-motion with the same perceived amplitude. In the lower panels of Figure 3 the same data are replotted, but they are normalized with respect to the luminance modulation. The luminance modulation is expressed in terms of the Weber fraction $W = \Delta L/L$. As a result of this normalization, all the data became almost exactly superimposed. Thus, at a fixed distance between two dots, any given luminance contrast modulation $\Delta L/L$ between these dots produces an apparent displacement of the same amplitude.

The almost perfect constancy of $\Delta L/L$ is a little bit surprising. Usually, photopic luminance discrimination thresholds are measured in conditions in which two spatially separate objects, typically two squares, appear on a large uniform background. The observer's task in the luminance discrimination experiments is to indicate which of these two objects is darker or lighter. Spatially separate stimuli are used to make it more likely that the results will be related to the responses, both subjective and neural, that each stimulus would produce on its own. In these conditions, the luminance difference between two separate objects is noticed as soon as their relative contrast—the ratio between increment or decrement and the standard luminance—reaches a constant threshold value (Whittle, 1986). Unlike in the luminance discrimination task, in the present study, two stimulus dots were always adjacent. They were so close to each other that it was impossible to compare their separate appearances. Instead of telling which of the two dots was darker or lighter, the observer estimated the apparent amplitude of displacement, not of a single micropattern, but of the whole stimulus area. Despite these essential differences between the two psychophysical tasks, all the data obey the same Weber's law: $\Delta L/L$ = constant perceptual outcome.

Many independent psychophysical researchers have indicated that the response of the human motion encoders saturates at low contrast (Campbell & Maffei, 1981; Derrington & Goddard, 1989; Derrington & Henning, 1987; Keck, Palella, & Pantle, 1976; Nakayama & Silverman, 1985; Stone, Watson, & Mulligan, 1990; Thompson, 1982). It has been proposed that the input signals undergo an amplitude-distorting nonlinearity before the motion information is determined. One function that saturates rapidly to a constant value as the signal amplitude increases is the Weibull function:

$$f(w) = 1 - e^{-\left(\frac{w}{k_1}\right)^{k_2}}, \qquad (1)$$

where $W = \Delta L/L$ (Weber's fraction) and k_1 and k_2 are two free parameters of the contrast compression function. We searched for such a function, *f*, which would allow us to present the adjusted luminance contrast *W* as a linear function of the relative distance between the two dipole elements. The optimal-fit values were $k_1 = 1.11$ and $k_2 = 0.68$ for A.P., and $k_1 = 1.56$ and $k_2 = 0.68$ for M.R. These estimates are close to $k_1 = 1.99$ and $k_2 = 0.76$ obtained by Stone et al. (1990) in a completely different psychophysical setting. Figure 4 shows the transformed luminance contrast $f(W)$ as a function of the adjusted displacement amplitude, expressed as a fraction of the interdot separation. The correlation coefficients for the

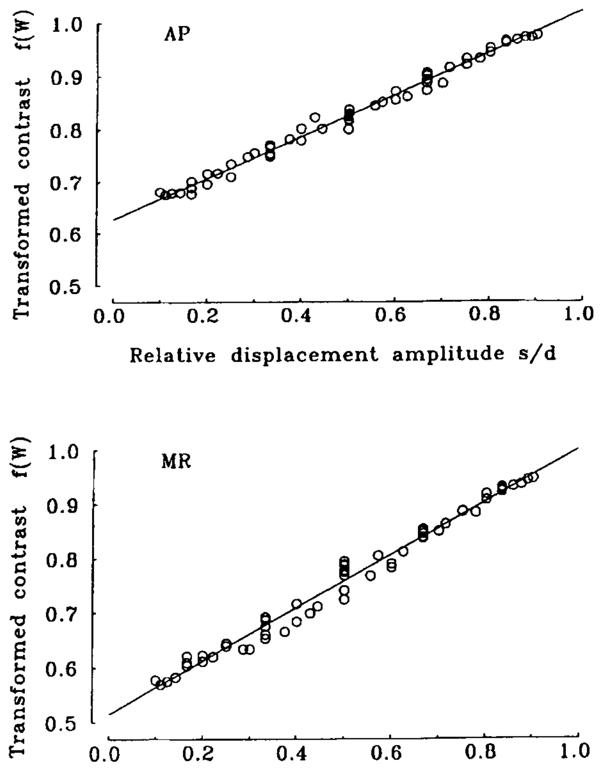

Figure 4. Compressively transformed contrast $f(W)$ as a function of the relative displacement amplitude *s/d*, for 2 observers—A.P. (upper panel) and M.R. (lower panel). The data are from the two experiments shown in Figures 2 and 3.

best-fitting functions were highly significant in both cases ($r = .995$ and $r = .991$, respectively). Thus, the proposed linearization function accounts for approximately 98%–99% of the variance in data.

DISCUSSION

The results of the present study demonstrated that spatial displacement of individual elements is not a necessary condition for motion perception. A distinct movement impression can be elicited by a relative change in the light flux at two spatial locations. It was demonstrated that alternating the modulation of luminance of two adjacent dots produced perceived oscillatory w-motion that could not be perceptually distinguished from that produced by a real oscillation. Due to luminance modulation, two stationary dots appeared to oscillate with an amplitude that was easy to match to the amplitude of a real displacement. All of the data can be accounted for by a simple rule: If the relative change in the luminance $W = \Delta L/L$ of two adjacent stationary dots is kept constant, the distance over which these dots appeared to travel in space comprises a fixed fraction of the total distance by which these dots are separated. This result appears to be at variance with the fine-grain movement illusion on human periphery, in which two very closely spaced subsequent flashes produce the impression of movement over a path whose extent considerably exceeds the spatial separation between flashes (Foster, Gravano, & Tomoszek, 1989; Foster, Thorson, McIlwain, & Biederman-Thorson, 1981). Assuming a rapidly saturating luminance contrast compression, it was possible to present the luminance modulation amplitude as a linear function of the relative distance between dots. This may mean, in particular, that exactly the same amount of increase in effective luminance contrast causes exactly the same proportion of the apparent displacement. The established equivalence between the effective relative luminance increment W and the perceived amplitude of displacement suggests that models that posit motion encoding based on the matching of two spatial patterns are not suitable for this particular situation (Dawson, 1991; Lappin & Bell, 1976; Ullman, 1979). The appropriate stimulus for motion is a relative change in light flux at two spatial locations.

Reichardt's (1957) elegant work on the insect movement analyzing system made clear that the simplest operation to detect motion involves the comparison of a signal registered from one spatial location with a delayed signal from another adjacent spatial location. The most general property of any motion-discrimination system is that the comparison process must be nonlinear; multiplication is the minimal operation required to accomplish this comparison (Buchner, 1976; Poggio & Reichardt, 1973; Reichardt, 1987). As a consequence of the multiplication, motion-detection systems based on correlation cannot reliably measure velocity, since their output depends on the contrast and spatial structure of moving patterns. Like insects, the human observer is not able to estimate the perceived velocity of a moving pattern independently of its spatial frequency (Diener, Wist, Dichgans, & Brandt, 1976) and contrast. Thompson (1982) found, for example, that low-contrast gratings appear to move more slowly than a high-contrast reference moving at the same speed. This contrast dependence also implies that the perceived motion direction of a composite pattern can be considerably changed by selectively increasing the luminance of some components of this composite pattern (Allik, 1992; Stone et al., 1990). The results of the present experiment appear to reveal the same property of the underlying motion-encoding operation: The perceived amplitude of w-motion increases monotonically with relative contrast W. Many previous studies have proposed that the correspondence strength between two elements involved in motion increases with luminance flux (Burt & Sperling, 1981; Nishida & Takeuchi, 1990; Shechter & Hochstein, 1989; van Santen & Sperling, 1984; Werkhoven, Snippe, & Koenderink, 1990b). These studies, however, were mainly concerned with the problem of estimating the likelihood that two separate spatial elements form an elementary motion path, rather than with the perceived properties of that path. Correspondence strength, by itself, is ambiguous concerning the output velocity or displacement amplitude. The main advantage of the method equalizing w- and ϕ-motion is that this approach allows the expression of motion strength not only in terms of dimensionless probability of discrimination of direction of motion, but also in metrical units of spatial displacement.

Another consequence of the correlation-type movement-encoding systems concerns the perception of motion without spatial displacement. A motion-encoding system does not need to establish correspondence between similar individual spatial features in a motion sequence. Bilocal motion encoders can ignore the correspondence problem by measuring the asymmetry in the change of the luminance flux at two sampled locations. The bilocal encoding model is indifferent to whether this change in the luminance flux is produced by a moving object traveling from one sample point to another, or by the luminance modulation of two stationary objects at these sample points. Despite obvious physical differences, the motion-encoding system is not able to distinguish these two cases. This explains why w-motion caused by luminance modulation is perceptually indistinguishable from motion evoked by a real displacement. Many current theories of motion perception, which have been shown to be formally equivalent to the elaborated Reichardt model (van Santen & Sperling, 1985), assume that the visual system employs motion-encoding units with receptive fields extended over space and time that are tuned to movement along a particular trajectory (Adelson & Bergen, 1985; Burr et al., 1986a; Watson & Ahumada, 1985; Wilson, 1985). These units measure the amount of luminous energy in some spatiotemporal volume irrespective of the distribution of the luminous energy in that volume. That is why the luminance increment ΔL added alternatively to two stationary objects evokes the perceived motion that is indistinguishable from the impression of motion caused by an object moving from one location to another.

The extended-in-space-time receptive fields means, in particular, that during motion encoding some part of the stimulus information is discarded. For example, when different local motions are spatially superimposed or given within a sufficiently small region, information about individual motion components will be lost and the region is perceived to move in the direction representing a resultant combination of these individual components (Mather & Moulden, 1980; Williams & Sekuler, 1984; Williams, Tweten, & Sekuler, 1991). Similarly, motion encoders seem to ignore the absolute luminance values and respond to the ratio of luminance fluxes, $W = \Delta L/L$, at two sampled locations: Two different pairs of dots with different absolute distance but the same luminance ratio W produce exactly the same magnitude of w-motion.

The results of our experiment suggest that it is easier to elicit motion between two elements with larger spatial separation than between those with smaller spatial separation. As is shown in Figure 2 (upper panels), less modulation in the luminance flux is needed to evoke motion with a required displacement amplitude for a larger interdot separation compared with a smaller one. This finding contradicts the traditional viewpoint that the strongest apparent motion occurs over short interelement distances (Burt & Sperling, 1981; Miller & Shepard, 1993; Shechter & Hochstein, 1989; Shechter, Hochstein, & Hillman, 1988; Ullman, 1979; Werkhoven, Snippe, & Koenderink, 1990a, 1990b). It is more natural, however, to assume that larger displacements convey more information for the presence of object motion than small displacements, which are, for example, difficult to separate from displacements caused by involuntary eye movements. Many other psychophysical data, including kinematic thresholds and the detection of motion onset or instantaneous displacement, also require for their proper explanation an assumption that the motion-weighting function increases with the displacement magnitude (Allik, 1992; Allik & Dzhafarov, 1984; Dzhafarov, 1992; Dzhafarov & Allik, 1984; Dzhafarov, Sekuler, & Allik, 1993). In order to avoid dependence on a variable motion-weighting function, we analyzed s/d as a fraction of interdot separation. After this normalization, all the curves converged to a single functional relationship, specifying exactly the perceived amplitude of w-motion. For any two values, the luminance modulation increment ΔL and the interdot separation d, there is only one amplitude of the perceived oscillation.

Finally, the idea that the motion-encoding system subjects the input signal to a nonlinear compression is not a new one. The existence of such a compressive operation has been suggested in various contexts (e.g., Bülthoff & Götz, 1979; Chubb & Sperling, 1988, 1991; Egelhaaf & Borst, 1989; Stone et al., 1990; Thorson, 1966). The rapid contrast saturation seems to be an inevitable consequence of a motion-encoding scheme based on the computation of correlation between two input signals. As already noted, this scheme has an intrinsic difficulty with estimating the velocity of a moving object. A simple solution, for a system based on correlation but at the same time not very dependent on stimulus contrast, is to apply the input signal to a rapidly saturating compressive transformation. In that case, only near-threshold low-contrast stimuli are vulnerable to luminance-dependent changes in perceived velocity.

REFERENCES

Adelson, E. H., & Bergen, J. R. (1985). Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America A*, **2**, 284-299.

Allik, J. (1992). Competing motion paths in sequence of random dot patterns. *Vision Research*, **32**, 157-165.

Allik, J., & Dzhafarov, E. N. (1984). Reaction time to motion onset: Local dispersion model analysis. *Vision Research*, **24**, 99-101.

Anstis, S. M. (1967). Visual adaptation to gradual change of intensity. *Science*, **155**, 710-712.

Anstis, S. [M.] (1986). Recovering motion information from luminance. *Vision Research*, **26**, 147-159.

Anstis, S. [M.] (1990). Motion aftereffects from a motionless stimulus. *Perception*, **19**, 301-306.

Buchner, E. (1976). Elementary movement detectors in an insect visual system. *Biological Cybernetics*, **24**, 85-101.

Bülthoff, H., & Götz, K. G. (1979). Analogous motion illusion in man and fly. *Nature*, **278**, 636-637.

Burr, D. C., Ross, J., & Morrone, M. C. (1986a). Seeing objects in motion. *Proceedings of the Royal Society of London: Series B*, **227**, 249-265.

Burr, D. C., Ross, J., & Morrone, M. C. (1986b). Smooth and sampled motion. *Vision Research*, **26**, 643-652.

Burt, P., & Sperling, G. (1981). Time, distance, and feature tradeoffs in visual apparent motion. *Psychological Review*, **88**, 171-195.

Campbell, F. W., & Maffei, L. (1981). The influence of spatial frequency and contrast on the perception of moving pattern. *Vision Research*, **21**, 713-721.

Chubb, C., & Sperling, G. (1988). Drift-balanced random stimuli: A general basis for studying non-Fourier motion perception. *Journal of the Optical Society of America A*, **5**, 1986-2007.

Chubb, C., & Sperling, G. (1991). Texture quilts: Basic tools for studying motion-from-texture. *Journal of Mathematical Psychology*, **35**, 411-442.

Dawson, M. R. W. (1991). The how and why of what went where in apparent motion: Modeling solutions to the motion correspondence problem. *Psychological Review*, **98**, 569-603.

Derrington, A. M., & Goddard, P. A. (1989). Failure of motion discrimination at high contrasts: Evidence for saturation. *Vision Research*, **29**, 1767-1776.

Derrington, A. M., & Henning, G. B. (1987). Errors in direction-of-motion discrimination with complex stimuli. *Vision Research*, **27**, 61-75.

Diener, H. C., Wist, E. R., Dichgans, J., & Brandt, T. (1976). The spatial frequency effect on perceived velocity. *Vision Research*, **16**, 169-176.

Dzhafarov, E. N. (1992). The structure of simple reaction time to step-function signals. *Journal of Mathematical Psychology*, **36**, 235-268.

Dzhafarov, E. N., & Allik, J. (1984). A general theory of motion detection. In M. Rauk (Ed.), *Computational models of hearing and vision* (pp. 77-84). Tallinn: Estonian Academy of Sciences.

Dzhafarov, E. N., Sekuler, R., & Allik, J. (1993). Detection of changes in speed and direction of motion: Reaction time analysis. *Perception & Psychophysics*, **54**, 733-750.

Egelhaaf, M., & Borst, A. (1989). Transient and steady-state response properties of movement detectors. *Journal of the Optical Society of America A*, **6**, 116-127.

Foster, D. H., Gravano, S., & Tomoszek, A. (1989). Acuity for fine-grain motion and for two-dot spacing as a function of retinal eccentricity: Differences in specialization of the central and peripheral retina. *Vision Research*, **29**, 1017-1031.

Foster, D. H., Thorson, J., McIlwain, J. T., & Biederman-Thorson, M. (1981). The fine-grain movement illusion: A perceptual probe of neuronal connectivity in the human visual system. *Vision Research*, **21**, 1123-1128.

Gregory, R. L., & Heard, P. F. (1983). Visual dissociations of movement, position and stereo depth: Some phenomenal phenomena. *Quarterly Journal of Experimental Psychology*, **35A**, 217-237.

Johansson, G. (1950). *Configurations in event perception*. Uppsala: Almquist & Wiksell.

Johansson, G. (1978). Visual event perception. In R. Held, H. W. Leibowitz, & H. L. Teuber (Eds.), *Handbook of sensory physiology: Vol. VIII. Perception* (pp. 675-711). Berlin: Springer-Verlag.

Keck, M. J., Palella, T. D., & Pantle, A. (1976). Motion aftereffect as a function of the contrast of sinusoidal gratings. *Vision Research*, **16**, 187-191.

Lappin, J. S., & Bell, H. H. (1976). The detection of coherence in moving random-dot patterns. *Vision Research*, **16**, 161-168.

Mastebroek, H. A. K., & Zaagman, W. H. (1988). Apparent movement induced by luminance modulation: A model study. *Perception*, **17**, 667-679.

Mather, G. (1984). Luminance change generates apparent movement: Implications for models of directional specificity in the human visual system. *Vision Research*, **24**, 1399-1405.

Mather, G., & Moulden, B. (1980). A simultaneous shift in apparent direction: Further evidence for a "distribution shift" model of direction coding. *Quarterly Journal of Experimental Psychology*, **32**, 325-333.

Miller, G. F., & Shepard, R. N. (1993). An objective criterion for apparent motion based on phase discrimination. *Journal of Experimental Psychology: Human Perception & Performance*, **19**, 48-62.

Morgan, M. J. (1979). Perception of continuity in stroboscopic motion: A temporal frequency analysis. *Vision Research*, **19**, 491-500.

Morgan, M. J. (1980). Spatiotemporal filtering and the interpolation effect in apparent motion. *Perception*, **9**, 161-174.

Nakayama, K., & Silverman, G. H. (1985). Detection and discrimination of sinusoidal grating displacements. *Journal of the Optical Society of America A*, **2**, 267-274.

Nishida, S., & Takeuchi, T. (1990). The effect of luminance on affinity of apparent motion. *Vision Research*, **30**, 709-721.

Poggio, T., & Reichardt, W. (1973). Considerations on models of movement detection. *Kybernetik*, **13**, 223-227.

Reichardt, W. (1957). Autokorrelations-Auswertung als Funktionsprinzip des Zentralnervensystem. *Zeitschrift für Naturforschung*, **12B**, 448-457.

Reichardt, W. (1987). Evaluation of optical motion information by movement detectors. *Journal of Comparative Physiology*, **B211**, 533-547.

Shechter, S., & Hochstein, S. (1989). Size, flux and luminance effects in the apparent motion correspondence process. *Vision Research*, **29**, 579-591.

Shechter, S., Hochstein, S., & Hillman, P. (1988). Shape similarity and distance disparity as apparent motion correspondence cues. *Vision Research*, **28**, 1013-1021.

Stone, L. S., Watson, A. B., & Mulligan, J. B. (1990). Effect of contrast on the perceived direction of a moving plaid. *Vision Research*, **30**, 1049-1067.

Thompson, P. (1982). Perceived rate of movement depends on contrast. *Vision Research*, **22**, 377-380.

Thorson, J. (1966). Small-signal analysis of a reflex in the locust: I. Input parameters. *Kybernetik*, **3**, 41-53.

Ullman, S. (1979). *The interpretation of visual motion*. Cambridge, MA: MIT Press.

van Santen, J. P. H., & Sperling, G. (1984). Temporal covariance model of human motion perception. *Journal of the Optical Society of America A*, **1**, 451-473.

van Santen, J. P. H., & Sperling, G. (1985). Elaborated Reichardt detectors. *Journal of the Optical Society of America A*, **2**, 300-321.

Watson, A. B., & Ahumada, A. J., Jr. (1985). Model of human visual-motion sensing. *Journal of the Optical Society of America A*, **2**, 322-342.

Watson, A. B., Ahumada, A. J., Jr., & Farrell, J. E. (1986). Windows of visibility: A psychophysical theory of fidelity in time-sampled visual motion display. *Journal of the Optical Society of America A*, **3**, 300-307.

Werkhoven, P., Snippe, H. P., & Koenderink, J. J. (1990a). Effects of element orientation on apparent motion perception. *Perception & Psychophysics*, **47**, 509-525.

Werkhoven, P., Snippe, H. P., & Koenderink, J. J. (1990b). Metrics for the strength of low-level motion perception. *Journal of Visual Communication & Image Representation*, **1**, 176-188.

Wertheimer, M. (1912). Experimentelle Studien über das Sehen von Bewegung. *Zeitschrift für Psychologie*, **61**, 161-265.

Whittle, P. (1986). Increments and decrements: Luminance discrimination. *Vision Research*, **26**, 1677-1691.

Williams, D., Tweten, S., & Sekuler, R. (1991). Using metamers to explore motion perception. *Vision Research*, **31**, 275-286.

Williams, D. W., & Sekuler, R. (1984). Coherent global motion from stochastic local motions. *Vision Research*, **24**, 275-286.

Wilson, H. R. (1985). A model for direction selectivity in threshold motion perception. *Biological Cybernetics*, **51**, 213-222.

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