Vision Res. Vol. 26, No. 4, pp. 599–607, 1986
Printed in Great Britain.

0042-6989/86 $3.00 + 0.00

WHAT DETERMINES CORRESPONDENCE STRENGTH IN APPARENT MOTION?*

MARC GREEN
Psychology Department, York University, 4700 Keele St., Downsview, Ontario, Canada M3J 1P3

(*Received* 19 *August* 1985; *in revised form* 4 *December* 1985)

Abstract—A sequence of static frames may produce the perception of coherent motion. The experiments described below investigated the psychophysical basis of this correspondence matching. Observers judged the direction of motion for "Gabor functions" which varied in spatial frequency, orientation or phase. The strongest determinant of correspondence was similarity of spatial frequency: objects tend to move toward neighbors of the same spatial frequency content. Orientation similarities also produced correspondence, although the effect was somewhat weaker than for spatial frequency. Phase played no role in determining correspondence.

Motion Correspondence Token Spatial frequency

INTRODUCTION

Correspondence is the process by which an object maintains its identity when seen in different places at different times. This phenomenon underlies the ability to perceive coherent motion when a series of static pictures, or "frames", is sequentially viewed. Each object in one frame appears to move to the location of the corresponding object in the subsequent frame. Correspondence implies a selection procedure by which each object in frame n sorts through the objects in frame $n + 1$ to find the appropriate match. This "correspondence problem" is solved through the affinity of critical attributes ("tokens") between objects in different frames.

Correspondence tokens presumably represent values along some dimension of form. However, it has proved surprisingly difficult to identify correspondence tokens since apparent motion tends to be independent of form similarity. Early studies (e.g. Wertheimer, 1912) found that when there was only one object in each frame, apparent motion was equally strong whether the objects in successive frames were identical or very different. More recently, Kolers and Pomerantz (1971) compared the strength of apparent motion with identical or different geometric shapes, circles, squares, etc. and found that only 1% of their data could be accounted for by form similarity. Navon (1976) used a variety of displays, each containing many alphabetic characters per frame. In one situation, letters were arranged in a circle. Successive frames contained the same circle of letters, except for clockwise or counter-clockwise rotation of each letter's position. If some aspect of letter shape were a correspondence token, then a coherent rotational motion would seem perceived. In fact, coherent motion never occurred, leading Navon to state that form similarity is irrelevant in apparent motion. Burt and Sperling (1981) drew the same conclusion based on experiments which tested the effects of similarity in a number of dimensions such as brightness, size and orientation.

In reviewing the previous studies, I noted two factors which might have caused a failure to identify correspondence tokens. First, stimuli were geometric forms, circles, squares, letters, etc. which differ in high spatial frequency content, but are similar in low spatial frequencies. Since so many studies (e.g. Blakemore and Campbell, 1969; Stromeyer and Julesz, 1972) have suggested that the visual system contains analyzing mechanisms narrowly tuned to different spatial frequencies, it might be supposed that spatial frequency similarity would be a token in apparent motion. Previous failures could be explained by correspondence between low frequency components shared by all objects. High spatial frequency differences may not be strong enough to override the correspondence of low frequencies, or perhaps high spatial frequencies are not tokens at all (Ramachandran *et al.*, 1983). Second, previous investigators

*Supported by NEI Grant EY05849 to M.G.

have used a flash technique, so that a luminance change accompanied the presentation of form. If luminance change *per se* is a token, then an effect of form similarity might be overshadowed. Alternately, it might be said that the luminance change represents a common zero order spatial frequency component, again suggesting that the problem has been common low spatial frequencies.

The experiments described below were designed to determine tokens which produce correspondence. My display avoided the pitfalls which possibly snared previous investigators. To eliminate the problem of common low frequency components, I used Gaussian modulated sinusoids or "Gabor functions". The spatial frequency content of Gabor functions is narrow and easily controlled by varying the period of the sinusoid. Luminance changes were eliminated by insuring that the space-averaged luminance of the Gabors was equal to that of the background. By taking these precautions, I discovered that spatial frequency similarity is, in fact, a powerful token in the correspondence process. Orientation similarity also proved to be a token, although weaker than spatial frequency. On the other hand, phase similarity seemed to have no effect on correspondence strength.

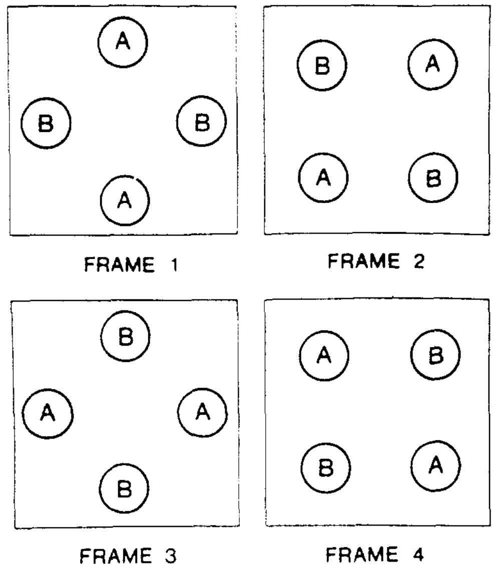

Fig. 1. Schematic representation of the 4 frames used to produce apparent motion. The circles with the same letter show the position of identical Gabors.

METHODS

Observers

The experiments described below were performed on a number of observers, M. O., D. S., J. T. and D. L. All subjects had normal vision with the aid of corrective spectacles. M. O. had partial knowledge of the rationale for the experiments while D. S., J. T. and D. L. were experimentally naive.

Display

Stimuli were displayed on a Hitachi high resolution monitor driven by a Grinnell graphics system. The viewing area was 14 by 12 deg and had a mean luminance of 65 cd/m^2. When no stimuli were being displayed, the screen was uniform in luminance with the exception of a central cross-hair provided for fixation. Each observer sat with his/her head positioned by a chin rest, and binocularly viewed the screen at a distance of 100 cm.

Targets in all experiments were Gaussian modulated sinusoids, or "Gabor functions". These were created by calculating a sine-wave function, which varied around the mean luminance, and then multiplying the sinusoid by a circular Gaussian. The final product appeared as a circular patch of sine-wave about 1.7 deg in diameter in which contrast was maximum at the center and decreased radially. Unless otherwise stated, phase of the sinusoid was 0 deg with respect to the Gaussian function. This was necessary to insure that the space-averaged luminance of the Gabor would always be the same as that of the background. Contrast of the Gabor functions was determined by a matching procedure. The Gabor containing the highest central frequency, 10 c/deg, was set to 85% contrast. Physical contrast of all other Gabors was set to the same apparent contrast.

Experiments consisted of a series of trials in which the observer viewed a sequence of 4 frames. As shown in Fig. 1, the frames contained four Gabors drawn at corners of an imaginary square. Frames consisted of two pairs of identical Gabors ("A" and "B"). In the experiments, A and B represented different values along the dimensions spatial frequency, orientation or phase. Frames 2–4 consisted of the same stimuli rotated by 45 deg to new positions. Note that the rotation changed only position, not orientation of the Gabors. That is, if the "A" Gabor were vertical, it would be vertical at all positions.

The rationale for this display is illustrated in Fig. 2, where Gabors from frame 1 are shown

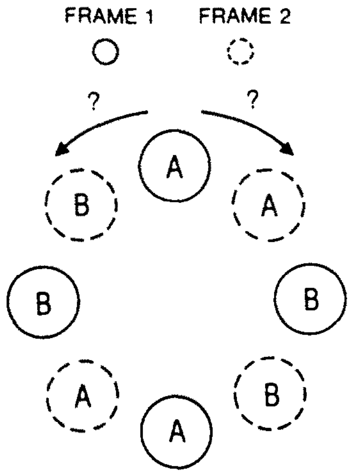

Fig. 2. Schematic representation of two successive frames. Solid lines show location of Gabors in frame *n*, broken lines locations in frame *n* + 1.

in solid circles while Gabors from frame 2 are represented by broken circles. The correspondence problem asks how the Gabors in frame 1 decide which Gabor in frame 2 is a proper match. Since the distance from A to B or another A is equal, there is no *a priori* reason for motion to be clockwise or counter-clockwise. If the difference between A and B is not helpful in resolving the uncertainty, then direction of motion will be ambiguous because A is just as likely to match B as another A. However, if the difference between A and B can be used to determine correspondence, then A moves to A and B to B. This will produce a coherent clockwise motion of the Gabors and suggest that values along the dimension by which A and B vary represents tokens in the correspondence domain. In the actual experiment, of course, direction of coherent motion was randomly selected to be clockwise or counter-clockwise.

Procedure

The observers' task in all experiments was to discriminate clockwise from counter-clockwise motion. On each trial, the sequence of 4 frames was shown twice in succession to produce rotation through 315 deg. Frame duration was 84 msec (5 sweeps of the raster) and the interstimulus interval (ISI) between frames, during which only the uniform field was visible, was 17 or 50 msec. The only reason for chosing these time intervals was that they produced clear motion. However, I tested other durations and ISI's, and the pattern of results described below was always obtained. After viewing the series of frames, the observer made a forced-choice response by pushing a joystick to indicated clockwise or counter-clockwise motion. In each session, the A Gabor was fixed and the value of the B varied randomly among 5 possibilities. Forty trials at each of 5 B values and 2 ISI's produced a run of 400 trials. This was generally sufficient to produce stable data. In a few cases, when the data were noisy, the condition was run a second time to produce 80 trials per data point.

RESULTS

Spatial frequency

In the first set of experiments, A and B represented different spatial frequencies. Values of the first four Gabors, 1.0, 1.7, 3.0, 5.0 c/deg, were nominally 3/4 octave steps. The last step, to 10 c/deg, was a full octave in order to avoid serious aliasing in the display. The left panel of Figure 3 shows the results obtained when A was fixed at 1.7 c/deg and the distance between the centers of similar Gabors was 3.6 deg. Translated into step size, this means that each Gabor shifted a linear distance of 1.4 deg between frames. For both ISI's, ability to perceive direction of motion was at chance levels when A and B had the same value. As spatial frequency of B increased, ability to discriminate between clockwise or counter-clockwise directions improved until performance was perfect. Observers reported that their ability to judge direction resulted from a coherent motion of the Gabors in a circular path. The B of 1.0 c/deg, showed chance performance at the short ISI but some evidence of discrimination at the longer ISI. Data in the right panel show results obtained when spatial frequency of A was fixed at 3.0 or 5.0 c/deg. Clear spatial frequency tuning of the correspondence process is again evident for both observers. Sharpness of the tuning was surprisingly narrow. Performance moved from chance to near perfect discrimination in 1.0–1.5 octaves.

I repeated the experiment, except that spacing between Gabors was varied. Figure 4 shows results obtained when distances between similar Gabors were 5.4 deg (step size 2.1) while Fig. 5 shows data for an experiment in which separation was 2.3 deg (step size 1.0). Spatial frequency tuning of correspondence is not greatly affected by spatial separation, although the narrow spacing appears to somewhat sharpen the tuning between 1.7 and 1.0 c/deg. Again ISI had no major effect.

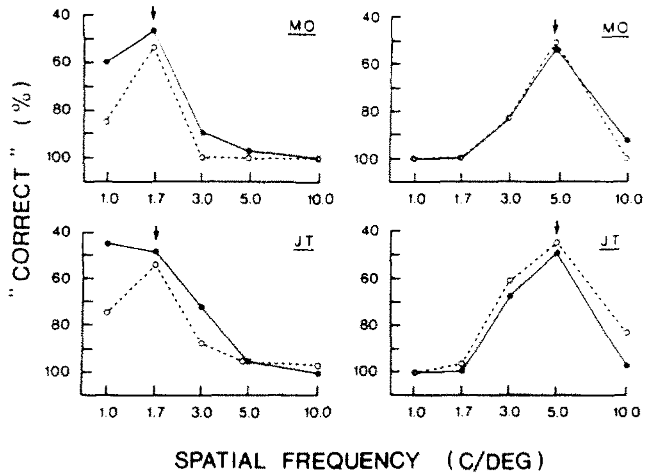

Fig. 3. Percent "correct" as a function of spatial frequency of the B Gabor. Solid dots show data for an ISI of 17 msec while open symbols represent results obtained with a 50 msec ISI. Arrows indicate the spatial frequency of the A Garbor. Step size between frames was 1.4 deg.

During the introduction, I speculated that previous studies may have failed to find correspondence tokens because of the luminance flux which accompanied form presentation. To test this possibility, I repeated the basic experiment except that the background luminance was dark (actually 0.5 cd/m^2) or half that of the Gabors (32.5 cd/m^2). Gabor separation in this and all subsequent experiments was set at the intermediate 3.6 deg value. Figure 6 shows the results for this experiment. Observers failed to perceive strong coherent motion under any conditions. Performance was uniformly poor, although the trusting reader might see some hint of a tuning. In any event, it is clear that a difference in luminance between target and backround almost eliminates coherent motion.

I performed one addition test as a control procedure. As noted above, physical contrast of Gabors was set to produce equal apparent contrast. I wondered whether the precision of the matches was critical. Suppose that correspondence could be based on different apparent contrasts. Errors in the contrast matching might produce correspondence which was based, not on spatial frequency differences, but rather on variations in apparent contrast. I checked this possibility by performing an experiment which A was 1.7 c/deg with a contrast fixed at the usual level. The B Gabors were all 5.0 c/deg, but of different contrast. The results of contrast manipulation are shown in Fig. 7. It is clear that, within the range used, contrast variations produce little effect. This strengths the conclu-

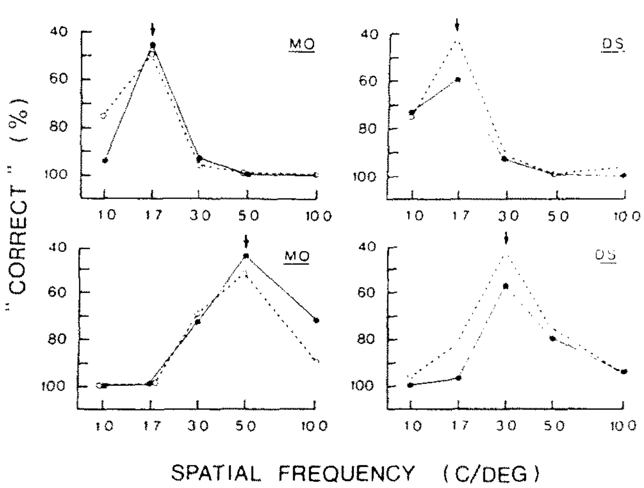

Fig. 4. Percent "correct" as a function of spatial frequency of the B Gabor. Details are the same as in Fig. 1, except that step size was 2.1 deg.

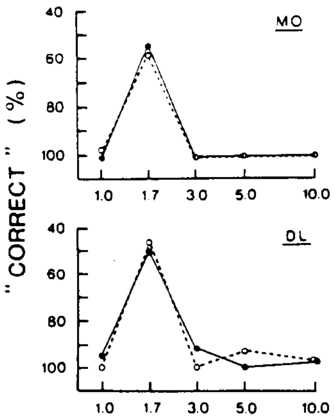

Fig. 5. Percent "correct" as a function of spatial freqency of the B Gabor. Details are the same as in Fig. 1, except that step size was 1.0 deg.

sion that spatial frequency *per se* is a correspondence token.

Multiple components

As noted in the introduction, the geometric forms used by previous investigators, although differing in high spatial frequencies, shared low spatial frequency components. I postulated that this might be one reaons why they failed to uncover correspondence tokens. In the next experiment, I examined this possibility by investigating what would happen if Gabors shared a spatial frequency component. To accomplish this, I used compound Gabors, i.e. Gabors containing two sinusoidal components. Figure 8, left panel, shows result obtained when A was fixed at 1.2 c/deg and B was a compound of 1.2 + a 2nd, 3rd, 4th or 8th harmonic. The A and B Gabors therefore shared the low spatial frequency but differed in the presence of a high spatial frequency. The results show that differences in high spatial frequency content were able to support only a modest degree of correspondence.

The right side of Fig. 8 shows the results for the inverse experiment, in which a subharmonic was added. A was 5.0 c/deg while B was a compound of 5.0 plus a second component. Differences in low spatial frequencies were sufficient to produce perfect performance. The difference between the presence of high and low frequency harmonics support the view (Hochberg and Brooks, 1978; Ramachandran *et al.*, 1983) that low spatial frequency differences are the major determinant of correspondence.

Orientation

I also investigated the possibility that orientation may be a token for correspondence. For this experiment spatial frequency was set at 3.0 c/deg and orientation difference between A and B varied. As shown in Fig. 9, correspondence exhibits a clear tuning for orientation. Differences of 22.5 deg from the A value were sufficient to produce almost perfect performance in most cases. Although performance was excellent with orientation as the correspondence token, observers agreed that the coherence of the motion produced by orientation, although clear enough to make a correct judgment, was never as smooth as for spatial frequency. This view was supported by an additional demonstration. The array of Gabors was rotated 55 deg instead of 45 deg between frames. By doing this, the distance between Gabors of

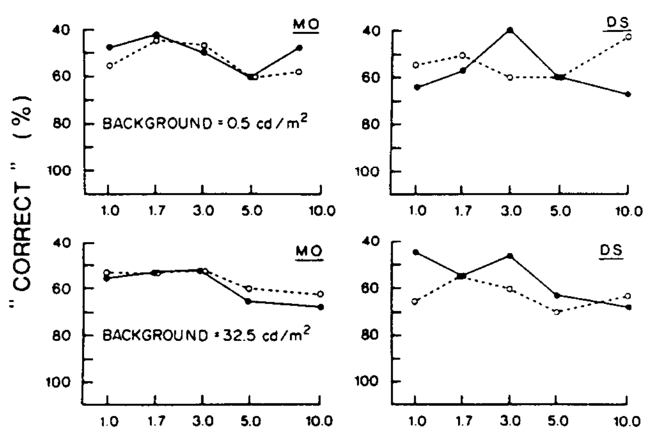

Fig. 6. Percent "correct" as a function of spatial frequency of the B Gabor. Luminance of the background was 0.5 cd/m^2 (top panels) or 32.5 cd/m^2 (bottom panels). Otherwise, details are the same as in Fig. 1.

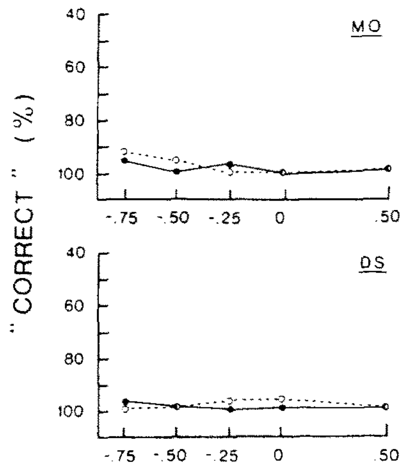

Fig. 7. Percent "correct" as a function of relative amplitude of the B. Gabor. The A and B Gabors had spatial frequencies of 1.7 and 5.0 c/deg, respectively.

different orientation was shorter than that for identical Gabors. (Referring to Fig. 2 will make this clearer.) If proximity, which is a powerful token, determines correspondence, the observers should perceive a "backward" motion, just as in the wagon wheel effect. The affinity created by orientation similarity should conflict and promote correct "forward" motion as previously seen. I found that even when the orientations were orthogonal, the resulting percept was highly ambiguous with some element of backward motion. When different spatial frequencies were used with a 55 deg rotation, however, direction of motion was still in the forward direction. Using ability to overcome the proximity factor as a yardstick, it is clear that spatial frequency is a more potent token than is orientation.

Phase

In the next experment, Gabor phase was the independent variable. Phase of the A Gabors was always 0 deg, while B varied between 45 and 180 deg. Gabor spatial frequency was 1.7 c/deg. The results (Fig. 10) show that there is little correspondence when phase is the only token. Note that phases other than 0 deg produce small luminance increments over the background. It may be supposed that correspondence did not occur, as above, because of variation in mean luminance. However, this seems unlikely because a 180 deg Gabor, which produced no luminance change, also failed to create correspondence.

Having found that absolute phase was not a correspondence token, I next checked whether relative phase between the components of a compound Gabor would produce coherent motion. In the first test, the stimuli were Gaussian modulated sawtooth gratings (essentially $f + 2f$) with a fundamental frequency of 1.5 c/deg. The A target faced left while the B target faced right. Sessions consisted of 150 trials at an ISI of 17 msec. Discrimination accuracy for the sawtooths was only 53 and 50% correct for two observers (D. S. and M. O.). In a similar test, the targets were compounds of 1.5 and 4.5 c/deg in 0 deg, peaks-add phase and 180 deg, peaks-subtract phase. Discrimination for the two observers was 53 and 51% correct. These

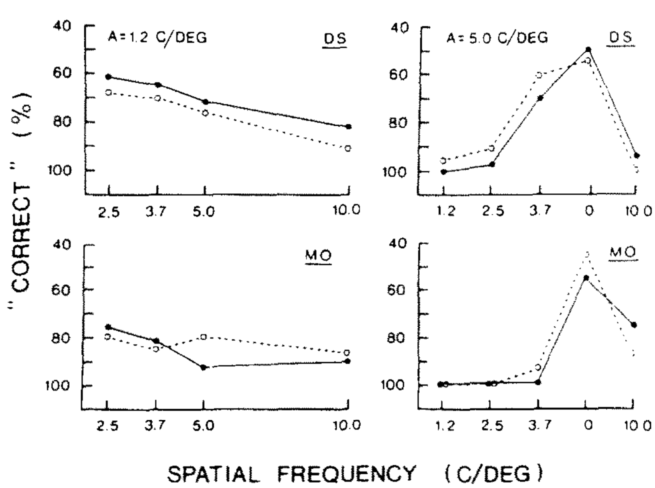

Fig. 8. Percent "correct" as a function of the spatial frequency of a harmonic component added to the A Gabor. The left panels show results obtained when the A Gabor was 1.2 c/deg while right panels show data from an experiment in which the A Gabor was 5.0 c/deg.

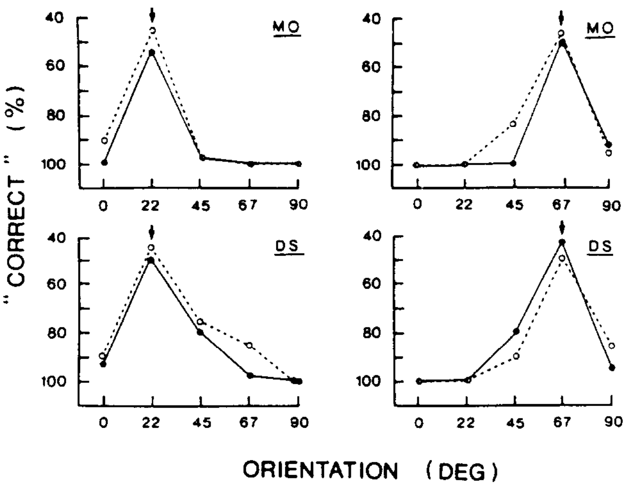

Fig. 9. Percent "correct" as a function of orientation of the B Gabor. All Gabors had a spatial frequency of 3.0 c/deg. Details are the same as in Fig. 1.

data extend the conclusion that phase is not a correspondence token.

DISCUSSION

The present results show that, contrary to conclusions of several previous authors (e.g. Kolers and Pomerantz, 1971; Navon, 1976; Burt and Sperling 1981) there are aspects of form which serve as tokens in the correspondence process. The most powerful token appears to be spatial frequency. Differences in spatial frequency produced clear, coherent motion, with each Gabor moving to the position of the neighbor of the same spatial frequency. Orientation also proved to be a correspondence token, although anecdotal observer reports suggest that it is not as powerful a token as spatial frequency. While coherent motion was seen, it was never quite as clear or unambiguous as that obtained with differences in spatial frequency. Lastly, phase differences failed to produce coherent motion. Neither absolute phase, nor the relative phase of two components resulted in motion.

These results were highly robust over variations in temporal intervals and spatial separation of the Gabors. Tuning curves were similar whether Gabor locations in successive frames overlapped (the 1.0 and 1.4 deg steps) or were separated (the 2.1 deg step). There was no evidence of the separate short and long range process postulated by other authors (Braddick, 1974; Anstis, 1978). Moreover, most of the experiments reported above were also performed with the type of display used by Burt and Sperling (1981). They also used alternating A and B stimuli, but the placement was along a single horizontal row. Successive frames showed the same row shifted downward and to the left or right. Correspondence would have been revealed by a tendency for objects to move to like neighbors, resulting in a sideways component to the motion. Burt and Sperling found that direction of motion was solely determined by distance: objects moved to the closest neighbor. Form similarity, including line orientation, never affected the motion path. When I used Gabors in a similar paradigm, motion path

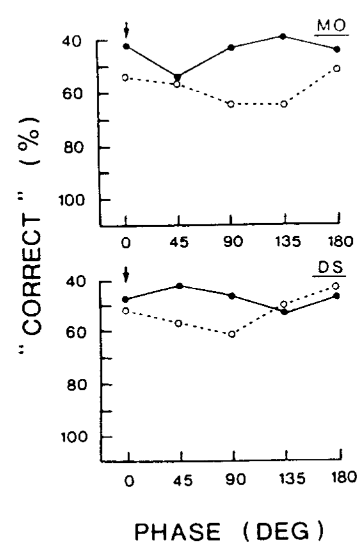

Fig. 10. Percent "correct" as a function of the phase of the B Gabor. Arrows indicate the phase of the A Gabors.

depended on spatial frequency and orientation. However, I preferred the circular display because it was less affected by eye movements.

My experiments further demonstrate that previous difficulty in identifying correspondence tokens was due to luminance artifacts as well as to the presence of shared low spatial frequency components. The transients caused by reducing the background luminance completely disrupted correspondence. Evidently, luminance *per se* is a strong correspondence token. This conclusion is supported by other data (Green, 1985) showing that when the A stimulus is a luminance increment and the B is a luminance decrement, there is clear rotational motion.

I also found that correspondence is weaker when stimuli share some spatial frequency components and differ. This result is consistent with the view (Ullman, 1980) that correspondence is determined by computation of a "preference metric". The metric is calculated by determining the number of token matches between an objects in frame n and those in frame $n + 1$. Clearest motion is seen when only one object in frame $n + 1$ matches tokens with the object in frame n. If several objects in frame $n + 1$ produce some token matches, then the strongest motion will be toward the one with the highest preference metric. However, the resulting motion is somewhat ambiguous. Presumably, this is what occurs when compound Gabors have one of their spatial frequency components in common: magnitude of the preference metric for competing objects is similar. When the common components were low in frequency, correspondence was greatly reduced. On the other hand, Gabors with similar high frequencies and different low frequencies exhibited strong coherent motion. This suggests that the low frequencies have greater weighting in computation of the preference metric (e.g. Hochberg and Brooks, 1978; Ramachandran *et al.*, 1983).

Comparison with previous experiments

While most previous studies have failed to find correspondence tokens, there have been a few successes. Some studies (Orlansky, 1940; Ullman, 1980) have found some corresponence based on orientation differences. However, these studies must be interpreted cautiously because single lines were used. Distance between two lines of identical orientation was easily specified. When lines were not parallel, however, spatial separation had to be computed by an arbitrary distance metric. Since distance is a powerful correspondence token, interpretation of these studies rests on the validity of the distance metric. Ullman (1980) further limited his conclusions by suggesting that orientation correspondence may be limited to the short range system. Although the d_{max} for the short-range system is probably not fixed but depends on spatial frequency (Green and Blake, 1981), the step sizes used here were larger than the most liberal d_{max} estimates possible. Assuming that the short-long range dichotomy is valid, orientation should be considered token for both systems. However, others (e.g. Burt and Sperling, 1981) failed to obtain any effect of orientation. After reviewing these studies, I can find no obvious reason for the differences in data.

Ramachandran *et al.* (1983) performed a study in which a centrally viewed square was followed by two flanking figures. They found that motion was toward a flanking figure regardless of orientation differences as long as the flanking figure had similar low spatial frequencies. Their conclusion was that low spatial frequencies dominate in apparent motion and that orientation is "relatively unimportant" (p. 460). This result is generally consistent with the present data. The reason for failure to find an orientation effect was that they pitted spatial frequency against orientation. As my observers commented, spatial frequency seemed a much stronger token than orientation. It is therefore not surprising that the affinity produced by orientation was not obvious. Their failure to find that high spatial frequencies affect correspondence may have been due to the greater weighting of low spatial frequencies in the similarity metric. Another interpretation, suggested by the authors, is based on the relative amplitude of the high frequency and low frequency components. In squares, amplitudes of high spatial frequencies are reduced relative to the magnitude of low frequency components. Moreover, visibility of high frequencies is reduced by the contrast sensitivity function of the visual system. To remove this possibility, I equated the stimuli for apparent contrast. Even so, low frequencies seemed to have a heavier weighting.

Lastly, van Santen and Sperling (1984, 1985; see also Sperling, van Santen and Burt, 1985) described an elegant model of motion perception based on temporal covariance, and criticized the frame-by-frame approach of analyzing motion. Since their work is concerned only with short-range motion, I doubt its relevance in my experiments. As mentioned above, the step sizes employed here were likely too great for the short-range system. Moreover, the short-range system is restricted to monocular stimulation (Braddick, 1974). I have found (Green, 1985) that when frames are presented alternately to the two eyes, coherent circular motion is still readily seen. In contrast, observers who dichoptically view overlapping gratings perceive no coherent motion (Green and Blake, 1981).

Channel bandwidths

It is possible to make a rough comparison between the channel bandwidths for correspondence and those obtained by other techniques such as selective adaptation and masking. However, any comparison must be taken with caution since there is no reason to assume that the scale properties of "per cent correct" in motion judgments and "contrast elevation" in adaptation and masking are similar. Moreover, my study was not thoroughly parametric, so that precise estimates of bandwidth are not possible. None the less, it is interesting that examination of Figs 3–5 reveals the spatial frequency channels, estimated by the standard half-height at half-width criterion, were roughly 0.50–1.0 octave wide. The bandwidth similar to that found by adaptation (Blakemore and Campbell, 1969) and masking (Stromeyer and Julesz, 1971). The steps in my orientation curves were too coarse to make a close comparison with other studies. The correspondence channels are certainly narrower than the 22.5 deg steps in the present experiment. This is at least consistent with fact that other techniques find bandwidths of about 7–12 deg (e.g. Blakemore and Nachmias, 1971; Campbell and Kulikowski, 1966). The consistency of my data with results of previous studies is particularly noteworthy because I used highly suprathreshold patterns while adaptation and masking studies measure threshold phenomena. Therefore, the present experiments provide clear evidence that spatial channels in suprathreshold vision are similar to those found near threshold.

CONCLUSIONS

In the present experiment I have found that the matching of objects in different places at different times is performed, at least in part, by an affinity between similar spatial frequencies and orientations. Adding distance to the list procedures three well established correspondence tokens. However, there are undoubtedly other display attributes which play a role in determining correspondence. For example, elsewhere we have shown that correspondence is also based on disparity (Green and Odom, 1985) and luminance polarity (Green, 1985).

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