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Speed Estimates from Grating Patches are not Contrast-normalized

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We have previously shown that the perceived speed of a moving grating depends upon its contrast, with lower-contrast patterns appearing to move more slowly than otherwise identical higher-contrast patterns. To explain this finding while remaining consistent with the findings of McKee, Silverman and Nakayama [(1986) *Vision Research, 26*, 609–619], we proposed that this misperception might arise from a modified version of the contrast-normalization procedure, envisaged by Adelson and Bergen [(1986) *The extraction of spatio-temporal energy in human and machine vision* (pp. 135–139). Charleston, S.C.: IEEE Computer Society] as a necessary second stage of motion-energy models of human motion processing. Specifically, our previous results might be explained if the two gratings to be compared interfered with each other's normalization. To test this hypothesis we performed two experiments. Experiment 1 demonstrates that the contrast effects persist even when two grating patches to be compared are presented up to 5 sec apart so that they would not be expected to bias each other's normalization. Experiment 2 shows that the contrast effects are unchanged when the two grating patches are surrounded by a range of patterns whose contrast would be expected to interfere with any normalization process. These two results allow the rejection of the contrast-normalized motion-energy hypothesis as an explanation of human speed perception. We discuss the consequences of these results on models of speed processing in the human visual system.

Motion perception Speed discrimination Contrast Motion energy Area V1 Area MT

INTRODUCTION

The most biologically plausible models of human motion perception have a first stage comprising linear spatio-temporal filters (Watson & Ahumada, 1983), consistent with the physiological responses of V1 neurones (e.g. Hamilton, Albrecht & Geisler, 1989; Reid, Soodak & Shapley, 1991; Emerson, Adelson & Bergen, 1992; McLean & Palmer, 1994). Although there are many advantages to this approach, one problem is that the response amplitude of such filters (and neurones) depends not only on the spatio-temporal properties of the stimulus but on their contrast as well. Thus, if speed estimation were done using the raw output of such filters, it would be confounded with stimulus contrast. Recognizing this fact, Watson and Ahumada (1985) designed a model of motion perception in which speed estimation was made independent of contrast by computing speed from the temporal frequency of the response of the linear spatio-temporal filters, a quantity which is independent of contrast. This model predicts that speed estimation would be largely independent of contrast. A different solution was put forth by Adelson and Bergen (1985) who proposed a 'motion-energy' model whose initial energy measurements (the sum of the squares of the outputs of odd and even phase spatio-temporal filters) are indeed contrast dependent. Adelson and Bergen (1986) subsequently added a second stage in which the estimates are normalized to correct for this problem. This model also generates robust speed estimates.

Using the method of single stimuli, with foveal presentation, McKee, Silverman and Nakayama (1986) indeed found support for accurate human speed estimation by showing that randomizing contrast has no effect on speed discrimination. However, when the speeds of two moving perifoveal stimuli are matched, the human visual system appears less capable of disambiguating speed and contrast: lower-contrast patterns consistently appear to move more slowly. This was first described by Thompson (1976) and has been confirmed by a number of authors, e.g. Campbell and Maffei (1981), Thompson (1982), Stone and Thompson (1992), Müller and Greenlee (1994), Hawken, Gegenfurtner and Tang (1994), and Ledgeway and Smith (1994, 1995). In an attempt to reconcile these apparently conflicting results, Stone and

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Thompson (1992) suggested that a modified contrast-normalized motion energy scheme might underlie both the observed speed misperception when two stimuli of different contrasts are matched and the lack of a contrast effect on speed discrimination observed by McKee *et al.* In this paper we test this hypothesis directly and find it wanting. Furthermore, we examine alternative mechanisms of speed coding consistent with our new findings.

There are several ways in which motion-energy models might implement contrast normalization. Adelson and Bergen (1986) proposed to apply it to motion-energy mediated speed estimation. They showed that by taking the difference in response between motion detectors tuned for opposite directions and dividing ('normalizing') this differential motion-energy response (*E*) by the output of some putative 'stationary' (*S*) channel (a non-directional channel tuned to low temporal frequency), they could derive a signal proportional to speed and independent of contrast. Later, Heeger (1987, 1990) suggested that the normalization might use some 'average-contrast' signal that pools the output of cells responding over a range of orientations and spatiotemporal frequencies. To avoid division by zero, he included a small constant (ε) in the normalizing factor. The details notwithstanding (i.e. how S is derived and whether ε is included), the normalized difference between rightward and leftward motion energy is a contrast-independent measure of speed (*V*). Because the contrast dependencies of the numerator and denominators are assumed equal (i.e. they are both proportional to contrast squared), they should cancel each other out

$$V = \frac{E_{\mathrm{r}} - E_{\mathrm{l}}}{S + \varepsilon}. \tag{1}$$

Equation (1) is merely a specific implementation of the general principle of taking the ratio of the output of two (transient and sustained) channels to derive an estimate of speed, as proposed by Tolhurst, Sharpe and Hart (1973) and Harris (1980), and will work well as long as the average contrast is not too small (i.e. $S >> \varepsilon$). At very low contrast (i.e. $S < \varepsilon$), because the denominator of equation (1) is inappropriately high, the resulting speed estimates would be low. Therefore, even with contrast normalization, one might expect an underestimate of speed at low contrast. However, our previous results (Stone & Thompson, 1992) and recent results of others (Hawken *et al.*, 1994; Ledgeway & Smith, 1994, 1995) show no evidence of diminution of the contrast effect on perceived speed even at contrasts as high as 50%. Even more surprisingly, we have shown the effect to be a quasi-linear function of the log contrast ratio of the two grating patches compared, i.e. independent of absolute contrast. These findings are inconsistent with the standard view of contrast normalization which predicts veridical speed estimates, except possibly at low contrast. However, abandoning this approach altogether seemed premature given the results of McKee *et al.* (1986). Therefore we proposed a modified contrast-normalization scheme to explain speed perception within the context of a motion-energy model.

Clearly, our previous data indicate that, if a motion-energy model is to describe human speed estimation, its contrast-normalization stage must fail at least under some circumstances, even at high contrast. Within the normalized motion-energy scheme, one way by which contrast-induced errors could be a function of the contrast ratio would be if the spatial extent over which the normalization signal (*S*) is derived were larger than the extent over which the energy signal (*E*) is derived, thus allowing the two gratings to interfere with each other's normalization.* Suppose that a subject simultaneously views two patches of grating identical in all respects except contrast, and suppose that the average contrast signal that provides the normalization is derived over an area sufficiently large as to encompass both patches while the energy signal is derived over an extent equal to or less than the extent of a single patch. Then the high-contrast moving stimulus would be normalized by a contrast that includes a contribution from the low-contrast stimulus and vice versa. Hence the normalizing contrast would be inappropriately high for the low-contrast stimulus and inappropriately low for the high-contrast stimulus, plausibly producing the effect of contrast we reported previously. Furthermore, in the method of single stimuli, because only one grating is present at a given time, normalization would be correct. Therefore speed perception would be unaffected by contrast. This is an attractive idea as it is consistent with both our previous findings and those of McKee *et al.* (1986). It generates several predictions and this study focuses on two of them.

Firstly, one would expect the normalization process to be temporally tuned. That is, when normalizing the speed signal of a particular pattern, we would expect the normalizing signal to be determined primarily by the contrast of recently-presented patterns. In this paper, we report experiments that investigate the effect of speed matches made sequentially across a range of temporal intervals. We find that this interval can be up to at least 5 sec without diminishing the size of the effect of contrast upon speed. Secondly, we would expect the normalization to be affected by the contrast of the immediately surrounding background. A second set of experiments investigates the consequences of presenting the two moving patches within a patterned background. Several manipulations that should influence the speed estimates of the patches are investigated yet none shows any effect on the basic finding. These results are incompatible with the spatially normalized motion-energy model described above. Preliminary results have been presented elsewhere

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*If E itself were taken over an extent that included both patches, then speed discrimination Weber fractions would be increased. However, under the simultaneous perifoveal viewing condition (Stone & Thompson, 1992), we showed that speed discrimination is often near the 5% optimal value found by McKee *et al.* (1986).

(Thompson, Stone & Stone, 1992; Thompson, Stone, Swash & Stone, 1994).

GENERAL METHODS

The same basic paradigm was used in all the experiments reported here. Subjects were presented with a pair of upwardly drifting, horizontal, 2 c/deg grating patches, one centred 1 deg above and one centred 1 deg below the fixation point (Fig. 1). The task was to report whether the upper or lower patch appeared faster. The dimensions of the elliptical patches were 2 deg horizontally × 1 deg vertically. Both the spatial and temporal windowing of the stimuli were sharp. We have previously shown that stimuli that were vignetted with a spatial Gaussian and smoothly ramped on and off with Gaussian time–course produced largely similar results to those produced with sharp spatial and temporal windows (Stone & Thompson, 1992).

A trial consisted of two stimulus intervals in which a grating patch was presented for either 280 msec (for Expt 1A, Fig. 2) or 380 msec (all other experiments) separated by a blank period in which only the mean luminance was present. The onset of the second stimulus interval relative to that of the first [stimulus onset asynchrony (SOA)] ranged from 0 (simultaneous) to 5000 msec in Expt 1 and was fixed at 500 msec for Expt 2. One of the pair, the 'standard', always moved at 2 deg/sec (4 Hz), the speed of the other, the 'test', was determined by a staircase procedure based on that of Findlay (1978). Each staircase terminated after a total of 12 reversals (about 30 trials). We define the 'speed match' as the ratio of the test speed at the point of subjective equality (determined by taking the mean of the last eight reversals) to the standard speed. As shown previously (Thompson, 1982; Stone & Thompson, 1992), the speed of the test was generally increased to match a standard of higher contrast and decreased to match a standard of lower contrast. In most experiments, four pairs of grating contrasts were investigated with interleaved independent staircases. All figures in this paper use the following conventions. The two baseline conditions consisted of standard and test gratings of equal contrast, either 10% (○) or 70% contrast (●). Two mixed-contrast conditions were run: one with standard 10% and test 70% contrast (□), the other with standard 70% and test 10% contrast (■). In Expt 1B (Fig. 3), the baseline conditions were not tested. Veridical matches would yield speed matches of 1.0 and would fall on the dashed line.

For Expt 1A [Fig. 2(B)], three naive observers and one of the authors (PT) served as subjects. For Expt 1B [Fig. 3(B)], five naive subjects and one of the authors (PT) served as subjects. For Expt 2A (Fig. 4), six naive observers were used. For Expt 2B (Fig. 5), four naive observers were used. All conditions were run three times in Expts 1A and 1B and twice in Expts 2A and 2B. Stimuli were generated on a Barco Calibrator 7651 screen using a Cambridge Research Systems VSG 2.1 graphics display card housed in a Compaq Deskpro 386/20 computer. Subjects sat 114 cm from the screen at which distance the screen subtended 18 × 14 deg of visual angle. The gamma nonlinearity of the monitor was

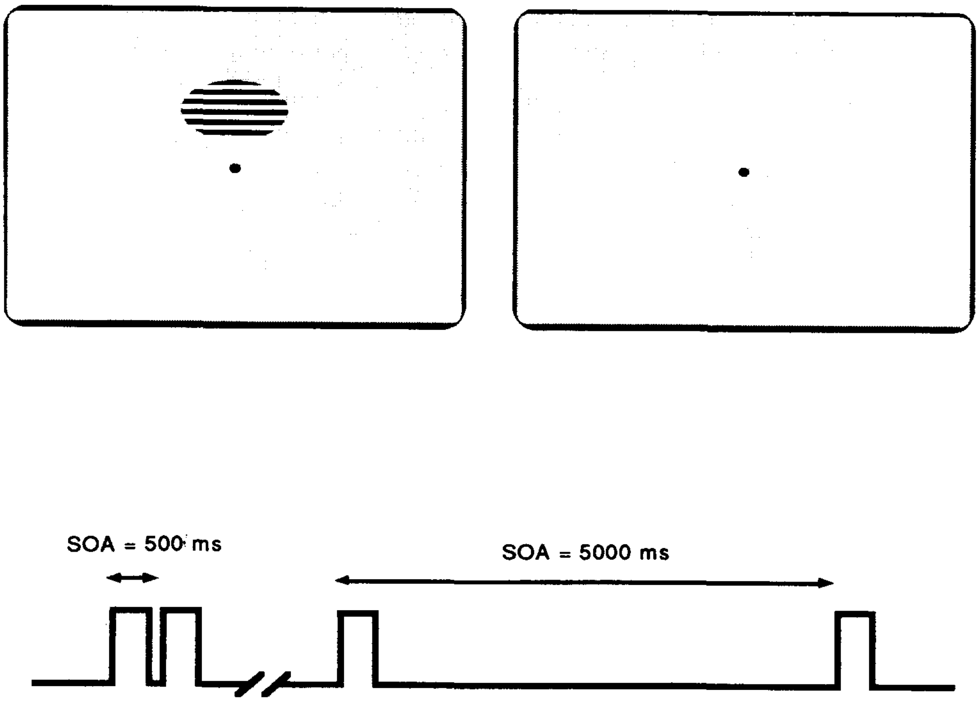

FIGURE 1. Stimulus configuration. The spatial configuration is shown in the upper part of the figure. A grating patch centred 2 deg above (or below) the fixation point was followed by a second grating centred symmetrically below (or above) the fixation point. The 'test' grating was randomly shown above or below fixation and in the first or the second temporal interval. Each trial comprised the presentation of a pair of gratings with a SOA. Each grating was presented with rapid onset and offset. The sequence of events is shown in the lower part of the figure.

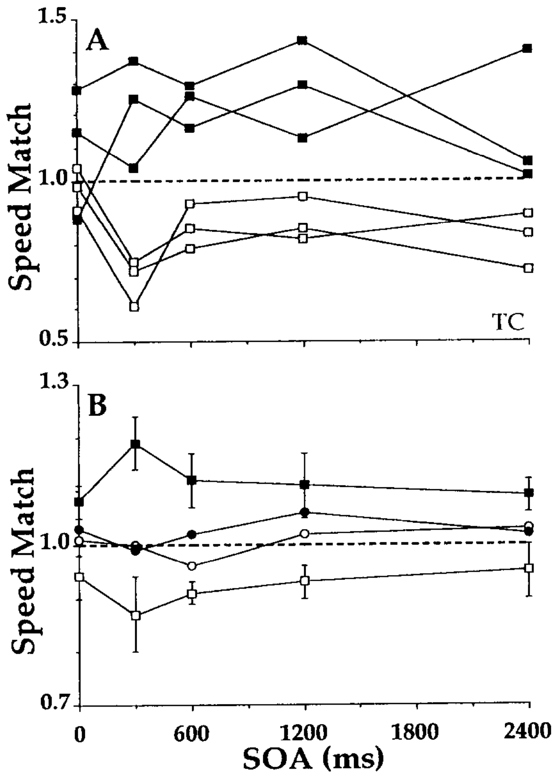

FIGURE 2. Results of Expt 1A. (A) Raw data for subject TC. The 'speed match', the speed at which the test stimulus appeared to the subject to be moving at the same speed as the standard stimulus, is plotted over a range of SOAs from 0 (both stimuli presented simultaneously) to 2.4 sec. ■ The matches for the condition in which the standard has a contrast of 0.7 and the test a contrast of 0.1. □ The matches for a 0.1 contrast standard and a 0.7 contrast test. Three experimental runs are shown. (B) Mean data for four subjects. This graph includes the conditions in which both standard and test gratings are of equal contrast, either 0.1 (○) or 0.7 (●). The error bars here and in all other figures represent ±1 SD across subjects. For clarity, error bars here and in all other figures were omitted for the equal contrast conditions.

corrected using a look-up table. The mean luminance of the screen was ~20 cd/m^2 for Expt 1 and ~80 cd/m^2 [close to the 75 cd/m^2 used in Stone and Thompson (1992)] for Expt 2. This may be the reason why the contrast effect documented previously and in Expt 2 is larger than that seen in Expt 1.

RESULTS

Experiment 1: effect of temporal asynchrony

In Expt 1 we measured the effect of various SOAs on the speed discrimination of unequal contrast gratings. In Expt 1A (Fig. 2), SOAs of 0 (simultaneous presentation), 300, 600, 1200 and 2400 msec were used. Figure 2(A) shows the raw data from three separate runs for a single naive subject (TC) for the two conditions using unequal contrast. Note that the speed match was <1.0 in all but one case when the test was 10% contrast and the standard 70% contrast (□), and >1.0 in all but one case when the test was 70% and the standard 10% (■). For clarity, the equal contrast conditions are not shown.

Three of the four subjects showed this pattern of results. Figure 2(B) shows the data averaged over all four subjects tested. Again, the speed match was <1.0 when the test was 10% contrast and the standard 70% contrast (□), and >1.0 when the test was 70% and the standard 10% (■). When both contrasts were 10% (○) or 70% (●), the speed matches were largely veridical. The main finding is that, on average, the mismatch in perceived speeds is still apparent at longer SOAs. These results extend our previous finding to stimulus pairs presented up to 2.4 sec apart. However, the data show a possible trend of decreasing effects at longer SOA which deserves further attention.

We therefore performed Expt 1B, a repetition of Expt 1A with SOAs of 0,500 and 5000 msec. The data for Expt 1B are shown in Fig. 3. As the 5-sec SOAs made the experiment very long, we omitted the equal contrast conditions. Figure 3(A) shows the raw data for three runs for subject PT.

Note that when the test contrast was lower than the standard (■), the speed match was always >1.0 and that, when the test contrast was higher than the standard (□) the speed match was always <1.0. Furthermore, note that the effect does not disappear at the long SOAs. Five of the subjects showed this same basic pattern of results; the sixth showed an effect that appeared to diminish at the longest SOA. Figure 3(B) shows the data averaged over all six subjects. Again, the increase in speed with higher contrast is readily apparent at all SOAs. There is no

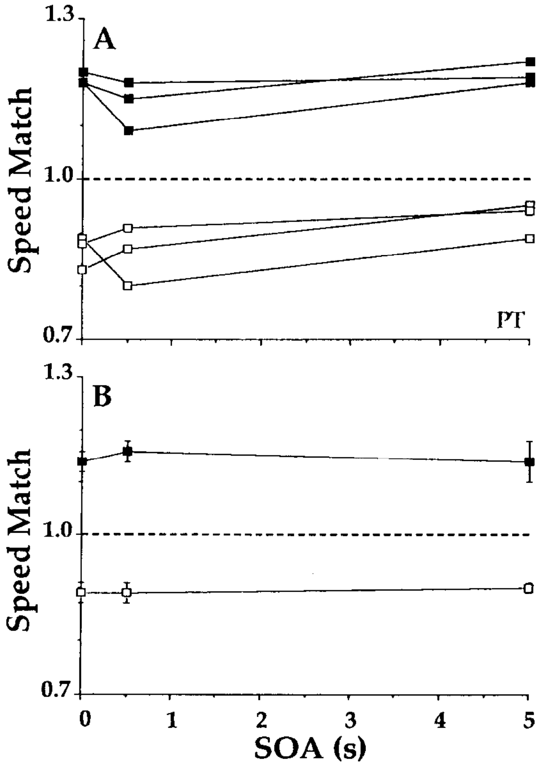

FIGURE 3. Results of Expt 1B. (A) The raw data for subject PT. As in Fig. 2(A) except that different SOAs were investigated (0, 500 and 5000 msec). (B) Mean data for six subjects. In this experiment the equal contrast conditions were not run; other conditions as Fig. 2(B).

indication of diminution of the contrast effect even with an SOA of 5 sec.

Because we were investigating the possibility that a contrast-normalization mechanism might be operating over very long intervals of time, there is a potential problem with our experimental procedure. The subject's response was always followed by a 1 sec delay before the presentation of the next stimulus. This meant that the time between the end of the second stimulus presentation of one trial and the first presentation on the following trial was often shorter than the SOA. Thus, there could be contamination from one trial into the next. However, we repeated the 5 sec SOA condition on two of the subjects with a 10 sec inter-trial interval and found that the contrast effect was largely unchanged. The mean speed matches for these two subjects were 0.88 and 1.11 for the high and low test contrast conditions respectively, vs 0.89 and 1.20 in Expt 1B.

Experiment 2: effect of surrounding contrast

For the normalization mechanism described by equation (1) to explain the contrast effect observed previously (Thompson, 1982; Stone & Thompson, 1992) and in Expt 1 the motion energy from each patch would have to be normalized using a signal pooled over an area that includes both patches. If the normalization area is spread over this wide spatial extent, it is clear that speed judgements should depend on contrast signals present within the local background contiguous with the two patches. In our previous studies and in Expt 1, the local background was always maintained at the mean luminance level of the whole display. In Expt 2 we now introduce contrast into this local background.

Experiment 2 was identical in all respects to Expt 1 except that the SOA was fixed at 500 msec and the local background contrast was manipulated over the extent of the 18 × 14 deg screen. In Expt 2A three different surround conditions were run: (1) mean luminance, (2) horizontal stationary grating with a spatial frequency of 2 c/deg and a contrast of 20% and (3) horizontal counterphase grating of 2 c/deg modulated at 4 Hz and a contrast of 40%. The first condition is merely a replication of the 500 msec SOA condition of Expt 1. Conditions 2 and 3 examined the effects of stationary and flickering backgrounds respectively. The contrast of the counterphase-modulated grating (defined as the sum of two spatially identical gratings drifting in opposite directions) was set at 40% to equate the contrast of each of its drifting components with that of the stationary background grating condition (see Levinson & Sekuler, 1975).

The results for Expt 2A are illustrated as speed matches averaged across all six subjects (Fig. 4). When the test was of higher contrast than the standard (□), the speed matches for all subjects were always <1.0; when the test was of lower contrast than the standard (■), the speed matches were always >1.0; and the equal contrast conditions (○) and (●) yielded largely veridical speed matches. The mean data show that neither a stationary nor a counterphase background makes any difference. That is, neither background condition is significantly different from the no-background condition (paired t-tests for both the 10% and 70% test contrast cases, $P >> 0.05$). Therefore, regardless of whether the background is processed by a motion or a stationary channel, local background contrast appears to have little or no effect on the perceived relative speed of the two patches. These results appear incompatible with the contrast-normalization hypothesis because it would be fortuitous indeed for the 'average' or 'stationary' contrast used in the normalization [S in equation (1)] to have been exactly the same in all three disparate background conditions.

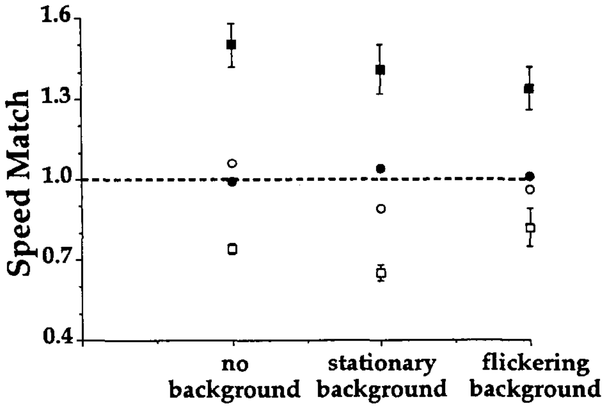

FIGURE 4. Results of Expt 2A. Mean speed match for all six subjects is plotted for three different background conditions as described in the text. Symbols as in Fig. 2.

In order to test the hypothesis more directly, we performed Expt 2B. Instead of using the same background for both patches, we used a different background for each of the two grating patches. We again compared two background conditions. In the first (enhancing background), the 10% contrast patches were surrounded by stationary gratings of 100% contrast and the 70% contrast patches were surrounded by stationary gratings of 5% contrast. This condition should result in an increase in the contrast-induced speed mismatch for two reasons. Firstly, because the 10% contrast patch's motion energy will be normalized by a signal dominated by the 100% contrast surround, the perceived velocity of this patch should be reduced. Secondly, because the 70% contrast patch's motion energy will be normalized by a signal dominated by the 5% contrast surround, the perceived velocity of this patch should be increased. In the second condition (reducing background), the backgrounds were simply reversed. This should, by the logic espoused above, reduce the contrast-induced speed mismatch. Thus, a comparison of these two conditions should show a large difference: the first having a larger misperception of speed and the second having a reduced misperception of speed. The results of this experiment are illustrated in Fig. 5.

The data shown are the average of four subjects. As in Expt 2B, when the test was of higher contrast than the standard (□), the speed matches for all subjects were always <1.0; when the test was lower contrast than the

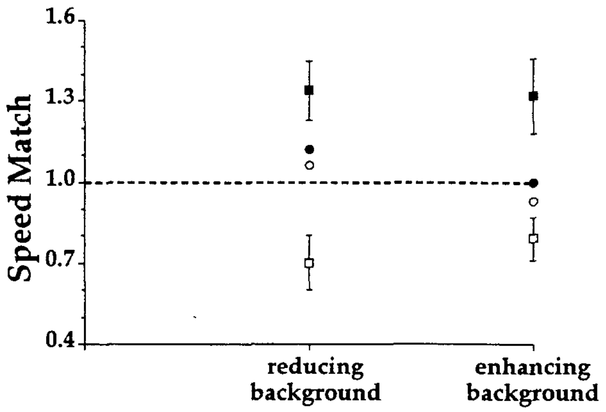

FIGURE 5. Results of Expt 2B. Mean speed match for four subjects is plotted for two different background conditions as described in the text. Symbols as in Fig. 2.

standard (■), the speed matches were always >1.0; and the equal contrast conditions (○) and (●) yielded largely veridical speed matches. Clearly, there is no difference in the two experimental conditions (paired *t*-tests for both the 10% and 70% test contrast cases, $P >> 0.05$).

DISCUSSION

In previous studies (Thompson, 1982; Stone & Thompson, 1992), we have shown that when two unequal-contrast gratings, which are otherwise identical, are presented simultaneously, the lower contrast grating is perceived to move more slowly. Here we have extended this finding to gratings presented sequentially up to 5 sec apart. This result is not compatible with mechanisms that use the pooled responses of a group of V1 neurones over a wider area to divide or to 'normalize' the output of the subset of neurones signalling the motion of the smaller patch. Such pooled responses would presumably act only over a short period of time. Therefore, in the long SOA conditions, the pooled response would only reflect the contrast of a single patch. Contrast normalization therefore predicts that speed perception would be veridical at long SOA. This however is not the case. We also tested the spatial contrast-normalization hypothesis more directly by manipulating the local background areas surrounding the patches to be compared. We found that background manipulations, that would be expected to increase or decrease the contrast-induced speed mismatches, had little or no impact on the effect. We conclude that our present results rule out our previously proposed explanation of the contrast effect on perceived speed.

These results also show that, in our paradigm, speed discrimination does not depend greatly on spatial or temporal interactions. This fact suggests that speed discrimination involves the comparison of two local measures of speed, one from each patch, rather than a single measure of relative speed, with each speed estimate largely independent (i.e. unaffected by surrounding contrast or the presence of another patch). Our data are not consistent with speed discrimination being supported by a single global mechanism which responds to both gratings and provides an estimate of their relative speed. Furthermore, given that speed is persistently mismatched even when patches are presented in relative temporal and spatial isolation, the local mechanisms that generate the speed estimate for each patch appear fundamentally unable to disambiguate speed from contrast.

Relationship to models of speed perception

These experiments have investigated a number of conditions under which the perceived relative speed of two grating patches is dependent upon their relative contrasts. In all cases, the results are not accounted for by some contrast-normalization process gone awry as postulated by Stone and Thompson (1992) and described in the Introduction. The motion model espoused by Adelson and Bergen (1986) and Heeger (1987) circumvents the fact that motion energy confounds speed and contrast by 'normalizing' motion energy with respect to some estimate of 'average' or 'stationary' contrast. If applied locally and effectively, it would therefore predict accurate speed estimates that are independent of contrast. This is inconsistent with our previous results. However, we noted that a normalizing procedure that operates more globally over a large spatial extent would fail to operate accurately when presented with the particular stimulus configuration used in our previous experiments. Nevertheless, given our present results, this explanation of the effects of contrast on speed estimation must be abandoned also. We conclude that no straightforward local or more global process of motion-energy normalization can explain the effects of contrast on human speed perception.

Motion models that either use temporal frequency (Watson & Ahumada, 1983, 1985) or are based on cross-correlation (e.g. Bulthoff, Little & Poggio, 1989) may escape the normalization problem altogether, but must be able to provide some other account of the contrast-dependence of speed perception. The temporal frequency of the modulating output of V1 neurones and cross-correlations are both largely independent of contrast. This in fact is one of the strengths of these two approaches. However, given that the algorithm used by the human brain appears less robust to variations in contrast, these non-motion-energy models also cannot explain human speed perception either.

Our results however do not rule out the possibility of a partially normalized motion-energy scheme in which the contrast dependence of S is weaker than that of E. In particular, if both are power functions of contrast and the exponent for S is smaller than that for E, then equation (1) will yield a measure of speed which is a power function of contrast. This would generate contrast effects that are linear in log contrast ratio, as we found previously (Stone & Thompson, 1992). However, the purpose of such a partial contrast-normalization scheme in speed perception is unclear as it would be largely ineffective.

Relation to contrast–response functions of cortical neurones

If the models of speed perception that successfully disambiguate speed and contrast described above are not appropriate models of human perception, how then can we explain our results? Motion-energy-like signals have indeed been found in V1 (e.g. Emerson *et al.*, 1992) and although there is physiological evidence for contrast normalization within striate cortex (Heeger, 1990; Carandini, Heeger, O'Keefe, Tang & Movshon, 1994), perhaps non-normalized motion energy is used directly as a crude measure of speed. In our previous study (Stone & Thompson, 1992), we found a non-saturating, quasi-linear relationship between perceived speed and log contrast. This relationship has been confirmed by others (Hawken *et al.*, 1994; Ledgeway & Smith, 1994, 1995). If speed is estimated by monitoring the pooled output of a set of V1 or MT neurones and, by recruitment, the output of the subset processing each patch increases approximately linearly with log contrast, then one might expect results such as ours. The contrast–response functions of individual V1 and MT neurones generally do not show such a quasi-linear relationship with log contrast, indeed their responses are generally well described by sigmoidal (hyperbolic) saturating functions (at ~16% in both V1 and MT), although some neurones in both these areas do not saturate, (see Dean, 1981; Sclar, Maunsell & Lennie, 1990; Albrecht & Hamilton, 1982). However, given the wide range of saturation constants found (see Sclar *et al.*, 1990, Fig. 5), additional neurones would be recruited over nearly the entire range of contrasts potentially yielding an increase in perceived speed without much evidence of saturation. While this is a plausible explanation of our results, there is not enough known about how speed is encoded by cortical neurones to provide strong support for this conjecture.

Relation to other results on contrast and speed perception

In our previous study (Stone & Thompson, 1992), we noted that although there are a number of studies that have found speed perception to be contrast dependent (Thompson, 1976, 1982; Campbell & Maffei, 1981; Stone & Thompson, 1992; Müller & Greenlee, 1994; Hawken *et al.*, 1994; Ledgeway & Smith, 1994, 1995), some did not find such an effect (McKee *et al.*, 1986). Our proposed spatial contrast-normalization scheme is a failed attempt to reconcile these results. How then can this discrepancy be explained?

We previously emphasised the possibility that the discrepancy might be due to the use of simultaneous sequential forced-choice paradigms. In particular, we found preliminary evidence that the contrast effect on speed perception might be reduced when stimuli were presented sequentially. However, the present study and others (e.g. Verghese & Stone, 1995) have examined this issue more closely and have found no systematic difference between results obtained using simultaneous and sequential presentation.

Another difference between our study and that of McKee *et al.* is that we presented our stimuli perifoveally and they presented theirs foveally. Studies of the effect of spatial frequency on perceived grating speed have yielded conflicting results that may also result from foveal vs perifoveal stimulus presentation (Diener, Wist, Dichgans & Brandt, 1976; Smith & Edgar, 1990; Ferrera & Wilson, 1991). Our recent results (Thompson, Stone & Brooks, 1995) are suggesting that foveal stimuli are processed differently, with the contrast dependence of speed greatly reduced or even abolished when stimuli are presented in our experimental protocol with a short SOA (500 msec). At a longer SOA (5000 msec) the effect is present but reduced in amplitude from that seen perifoveally. Whether these results provide a resolution of the discrepancies between our results and those of McKee *et al.* is an issue we are actively pursuing.

Finally, the methodology used by McKee *et al.* (1986) was quite different from that in our experiments. Their results were obtained in a task where the speed of a grating patch, of one of six possible contrasts, was compared to that of the implicit mean of previous presentations. They found that this randomization of contrast produced no degradation of speed recognition Weber fractions over those measured at fixed contrast. However, if subjects were able to segregate the different stimuli from each contrast level and make comparisons within each group separately, this could explain the observed lack of contrast effect. They used six contrast levels in the expectation that this would prevent subjects from using such a strategy. However, recent experiments by Morgan (1992) and by Heeley and Buchanan-Smith (1994), both using a single interval design (like that of McKee *et al.*), demonstrate that subjects can use small differences in orientation or spatial frequency to segregate up to eight groups of stimuli. Perhaps such a strategy is also possible using contrast as the cue. Therefore, it is not unreasonable to propose that perceived speed is fundamentally dependent on contrast, and that subjects in the McKee *et al.* study treated each discrete contrast level independently thereby concealing this fact. Our future studies will test this proposal.

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