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Luminance texture increases perceived speed

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Abstract

Previous psychophysical experiments have demonstrated that various factors can exert a considerable influence on the apparent velocity of visual stimuli. Here, we investigated the effects of superimposing static luminance texture on the apparent speed of a drifting grating. In Experiment 1, we demonstrate that superimposing static luminance texture on a drifting luminance modulated grating can produce an increase in perceived speed. This supports the hypothesis that texture changes perceived speed by providing landmarks to assess relative motion. In Experiment 2, we showed that contrary to static luminance texture, dynamic luminance texture did not increase perceived speed. This demonstrates that texture must provide reliable spatial landmarks in order to generate an increase in perceived speed. The results of Experiment 3 demonstrate that perceived speed depends on the size of the area covered by texture. This suggests that luminance texture and the motion stimulus interacted with each other over a limited spatial scale and that these local responses are then pooled to determine the speed of the motion stimulus. In Experiment 4, we showed that static texture contrast could produce a greater effect than motion stimulus contrast on perceived speed and that these effects could still be observed at brief presentation times. We discuss these findings in the context of models proposed to account for phenomena in the perception of speed.

Keywords: Motion; Speed perception; Landmarks; Bayesian modeling; Texture

1. Introduction

In order to interact adaptively with the physical world, it is necessary for the perception of motion by the visual system to correspond with reasonable accuracy to the physical motion present in the environment. For instance, a predator attempting to capture an evading prey must have a reasonably precise estimate of the speed and direction in which his prey is moving in order to succeed. Motion velocity can also serve as a cue to determine other visual attributes such as depth (motion parallax). Given the importance of an accurate estimation of motion velocity to our functioning, it is surprising that a number of stimulus parameters other than speed itself can exert a significant influence on our visual perception of speed. For example, psychophysical experiments have demonstrated that factors such as the luminance contrast of motion stimuli (Blakemore & Snowden, 1999; Campbell & Maffei, 1981; Stone & Thompson, 1992; Thompson, 1982) the absence of luminance modulation in drifting chromatic gratings (Cavanagh, Tyler, & Favreau, 1984), and a luminance-modulated grating's spatial frequency (Campbell & Maffei, 1981; Priebe & Lisberger, 2004; Smith & Edgar, 1990) produce significant effects on human observers' perceived speed. These factors can even have consequences on behaviour, such as a tendency to drive faster in foggy conditions (Snowden, Stimpson, & Ruddle, 1998).

The presence of static luminance texture adjacent to a motion stimulus has also been found among the parameters influencing perceived speed. Previous research has reported that static luminance texture near a motion stimulus increases the perceived speed of motion relative to when the area near the motion stimulus is uniform (Blakemore & Snowden, 2000; Brown, 1931; Gogel & McNulty, 1983; Norman, Norman, Todd, & Lindsey, 1996). For instance, Gogel and McNulty (1983) report that the perceived speed

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of a moving stimulus increases with the density of reference marks. Moreover, it has been found that the perceived speed of a uniform moving disk increases with increasing levels of background texture contrast (Blakemore & Snowden, 2000). These authors also report that increasing the contrast of textured backgrounds can reduce or even eliminate the dependency of perceived speed on motion stimulus contrast. That is, the dependency of a uniform moving disk's perceived velocity on the luminance contrast between itself and the mean luminance of a textured background disappears as the contrast of the textured background was increased. Finally, it has also been reported that static luminance texture can facilitate other aspects of motion perception, such as motion detection (Bonnet, 1984) and motion integration (Lorenceau & Boucart, 1995).

Various accounts have been suggested for the effects of stationary luminance texture on perceived speed. Gogel and McNulty (1983) posit that reference marks produce an increase in perceived speed by providing landmarks to assess relative motion. An alternative explanation has proposed that the effects of static texture contrast on the perceived speed of a uniform moving disk is attributable to an increase in the visibility of the motion stimulus through second-order processes (Blakemore & Snowden, 2000). Simply put, a uniform moving disk that is set to a luminance close to the mean luminance of the background on which it is presented appears more visible when the background is textured than when the background is uniform. In the current series of experiments, we will investigate the effects of luminance texture on perceived speed in order to better understand the mechanism underlying its effects on perceived speed.

2. General method

2.1. Apparatus and stimuli

An Apple PowerMac G3 computer was used in order to generate the stimuli and collect the data. Stimuli were presented on an Apple studio display monitor with a 120 Hz frame rate. Lookup tables were used to gamma-correct gun outputs. Stimuli were generated and the data were collected using MATLAB and the extensions provided in the Psychophysics Toolbox (Brainard, 1997) and low-level Videotoolbox (Pelli, 1997).

A 38 cd/m^2 adapting field was present at all times during testing. A central fixation point was also present at all times during testing. On each trial, two vertical luminance-modulated sinusoidal drifting gratings (the standard grating and the test grating) were simultaneously presented directly below and above fixation. Each grating had a spatial frequency of 0.5 cycles/deg and was centered at 2.5 deg of eccentricity away from fixation through hard-edged circular apertures subtending 4 deg of visual angle in diameter. The standard grating drifted at a speed of 8 deg/s (4 Hz temporal frequency), either leftward or rightward, and the test grating drifted in the opposite direction. Both the test and the standard gratings were modulated at 10% Michelson contrast. In the various experiments, luminance texture was superimposed on the standard grating and no luminance texture was superimposed on the test grating.

2.2. Procedure

Participants were tested individually in a dimly lit room and viewed the display binocularly from a 57 cm viewing distance. Observers were instructed to maintain their gaze on a central fixation point at all times during testing. A two alternative forced-choice procedure was used in order to determine the effects of superimposing luminance texture on the apparent speed of motion stimuli.

On each trial, the test and the standard grating were presented simultaneously for a duration of 2 s. The position of the two gratings (top or bottom) and direction of drift (left or right) were counterbalanced from trial to trial. Following the presentation of the motion stimuli, observers were instructed to indicate which of the two gratings appeared to drift at a faster speed with a key press. No time limit was given for responding. The initial speed of the test pattern was set to 3–5 dB faster than the speed of the standard grating. In subsequent trials, a QUEST routine determined the speed of the test grating based on the responses given previously by the participants. In each block of testing, observers completed 24 trials per condition. The data were analyzed at the end of each block of trials in order to determine the point of subjective equality (PSE) between the speed of the test and the standard grating. The PSE values shown in the results sections constitute the mean PSE values obtained after three blocks of trials.

2.3. Observers

Three experienced psychophysical observers participated our experiments. Participants had normal or corrected to normal visual acuity. One of the observers (DN) is an author on this article and the remaining observers were naïve as to the purposes of the experiments.

3. Experiment 1

The purpose of Experiment 1 was to assess whether static luminance texture increases perceived speed by providing landmarks to assess relative motion or if the increase in apparent speed is solely attributable to an increase in visibility. One way to determine this is by superimposing static texture on the motion stimulus. This is because increasing the contrast of masking texture decreases the visibility of a target stimulus (Gegenfurtner & Kiper, 1992; Legge & Foley, 1980). Further, it has also been found that static luminance texture can interfere with the direction discrimination of luminance-modulated gratings (Cropper & Derrington, 1996; Lu & Sperling, 1996). If the decrease in the contrast dependency of perceived speed that occurs as texture contrast increases is solely attributable to an increase

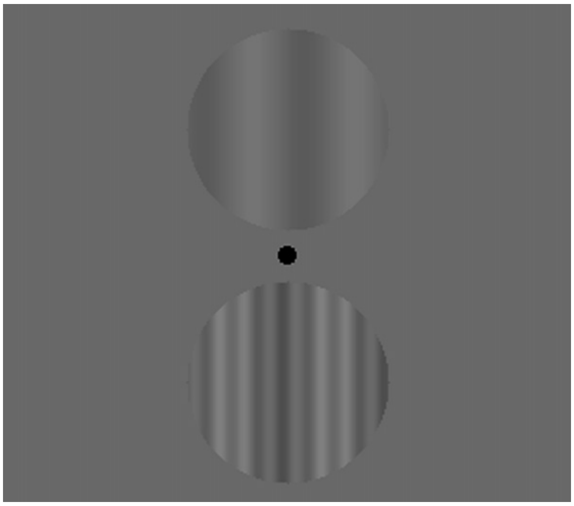

Fig. 1. Schematic illustration of the stimuli. (Top) A 10% Michelson contrast 0.5 cycles/deg sinusoidal test grating. (Bottom) A standard grating of identical spatial frequency and contrast was also presented. The standard grating drifted at 8 deg/s in a direction opposite to that of the test grating. A static luminance modulated sinusoid was added onto the standard grating.

in the visibility of the motion stimulus, then perceived speed should decrease with increasing levels of texture contrast. On the other hand, if the visual system uses static luminance texture as a landmark to assess relative motion, then adding luminance texture should produce an increase in perceived speed. In order to assess these possibilities, we investigated the effects of a superimposing static luminance texture at various levels of contrast on the perceived speed of a drifting grating.

3.1. Stimuli

A representation of the motion stimuli used in Experiment 1 is presented in Fig. 1. For the purposes of measuring the effects of static luminance texture on perceived speed, static luminance gratings were superimposed on the drifting standard grating. In order to investigate the effects of static pedestal spatial frequency on the apparent speed of the standard grating, perceived speed was measured at static texture spatial frequencies of 1, 2, and 4 cycles/deg. We measured perceived speed at pedestal contrasts of 0% (no stationary pedestal), 10%, and 40% Michelson contrast.

3.2. Results

The relative speed of the estimated PSE values is shown in Fig. 2 for each observer. In the no texture condition, the relative speed of the test grating which seems to move at the same speed as the standard grating was reasonably close to veridical speed. When static luminance texture was superimposed on the standard grating, our results show that increasing the contrast of the texture produced an increase in the relative speed of the test grating which perceptually matched the speed of the standard grating. This increase occurred at every tested pedestal spatial frequency. Although there are individual differences in the extent of the perceived speed increase, this increase can be observed for every participant: at the highest tested pedestal contrast, the physical speed of the test grating was always faster than the physical speed of the standard grating which it perceptually matched.

The results of Experiment 1 also demonstrate that the spatial frequency of a stationary pedestal grating has an effect on relative speed of the PSE. Within the tested pedestal spatial frequencies, increasing the contrast of a 1-cycle/deg static grating produced the largest increase in perceived speed. At this spatial frequency, the highest tested pedestal contrast produced, on average, a 42% increase in relative speed compared to when the pedestal was absent. In contrast, increasing the contrast of a 4 cycles/deg grating yielded the smallest increase in perceived speed. At this spatial frequency, the highest tested pedestal contrast produced, on average, a 17% increase in PSE values relative to when no pedestal was present.

3.3. Discussion

The results of Experiment 1 demonstrate that superimposing stationary luminance texture on a drifting grating produces a significant increase in perceived speed. Further, perceived speed increases with the contrast of superimposed stationary luminance texture. The effects of the stationary pedestal on the perceived speed of a spatially coextensive motion stimulus are consistent with previous reports on the effects of adjacent static luminance texture on the perceived speed of motion stimuli (Blakemore & Snowden, 2000; Brown, 1931; Gogel & McNulty, 1983; Norman et al., 1996).

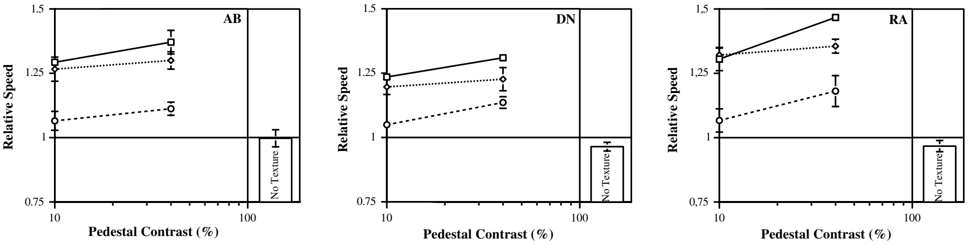

Fig. 2. Relative speed of PSEs for individual observers as a function of static texture contrast and spatial frequency. Results are shown for spatial frequencies of 1 (full line with squares), 2 (dotted line with diamonds), and 4 (dashed line with circles) cycles/deg. The white bar shows PSE values obtained in the absence of static luminance texture. Error bars represent ±1 SEM.

One of the interesting findings of Experiment 1 is that, within the tested texture spatial frequencies, the increase in perceived speed observed with increasing texture contrast depended on the spatial frequency of the texture. This suggests that previous reports of texture effects on perceived speed (Blakemore & Snowden, 2000; Brown, 1931; Gogel & McNulty, 1983; Norman et al., 1996) may also be dependent on the spatial frequency of the luminance texture. However, the finding that, among the tested spatial frequencies, the lowest (1 cycle/deg) pedestal spatial frequency produced the strongest increase in perceived speed and the highest (4 cycles/deg) pedestal spatial frequency produced the weakest increase in perceived speed was surprising to us. The reason for this is that, given the previous report that perceived speed increases with reference mark density (Gogel & McNulty, 1983), we expected the perceived speed of the standard grating to increase as the number of static grating cycles present within the aperture increased.

It has been proposed that some illusions in speed perception are attributable to contrast normalization errors (Cavanagh & Anstis, 1991; Stone & Thompson, 1992). That is, the response of low level units to a moving stimulus depends on both stimulus velocity and contrast. As a result, their responses must be normalized (i.e., divided) in order to obtain an unambiguous assessment of velocity. However, if the response of motion sensitive units is normalized by the response of units that are more sensitive to contrast, then they will be normalized by an inappropriately high value, thus underestimating the contribution of velocity to unit responses.

The proposed flaw in the normalization of the motion energy signal fails to account for results of previous research on the effects of static luminance texture on the perceived speed of a moving stimulus (Blakemore & Snowden, 2000; Brown, 1931; Gogel & McNulty, 1983; Norman et al., 1996). That is, if the motion energy signal is indeed normalized by an average contrast signal obtained over a wide area of the visual field (Stone & Thompson, 1992), it would presumably be normalized by a greater average contrast signal when there is texture present in the area surrounding the motion stimulus than when the background is uniform. This would predict a slower perceived speed in the presence of texture than when the background is uniform. Furthermore, the lower perceived contrast of a central region in the presence of texture in the surrounding region (Cannon & Fullenkamp, 1991; Murch & Hirsch, 1972; Snowden & Hammett, 1998) would also predict a slower perceived velocity, given that at low luminance contrasts, motion stimuli tend to yield a slower percept of motion (Blakemore & Snowden, 1999; Stone & Thompson, 1992; Thompson, 1982). In this case, static texture should not influence the perceived speed of a drifting stimulus. In either case, the proposed flaws in the normalization of the motion energy signal fail to account for the increase in perceived speed that occurs in the presence of static luminance texture. Blakemore and Snowden (2000) also discuss contrast normalization and conclude that it fails to account for the decrease in the contrast dependency of perceived speed in their experiments.

An alternative explanation for the effects of static texture on perceived speed posits that the effects of background texture contrast on the perceived speed of a uniform moving disk are attributable to a change in the disk's visibility through second order processes (Blakemore & Snowden, 2000). This is unlikely to account for the results of Experiment 1, given that the visibility of a luminance-modulated grating diminishes as the contrast of superimposed static luminance texture increases (Gegenfurtner & Kiper, 1992; Legge & Foley, 1980). Although we have no doubt that the visibility of the moving stimulus contributed to the results reported by Blakemore and Snowden (2000), it also appears unlikely that this factor alone can account for the reports of increases in perceived speed when texture is added adjacently to the motion stimulus (Brown, 1931; Gogel & McNulty, 1983; Norman et al., 1996). This is the case because adding texture adjacently to a grating produces a decrease in the latter's perceived contrast (Cannon & Fullenkamp, 1991; Chubb, Sperling, & Solomon, 1989; Snowden & Hammett, 1998).

4. Experiment 2

The results of Experiment 1 are congruent with the proposal that static luminance texture produced an increase in perceived speed by providing a reference to assess relative motion (Gogel & McNulty, 1983). If the effects of texture on perceived speed are attributable to a relative motion mechanism, then one might wonder how such a mechanism might behave in the presence of luminance texture that does not constitute a reliable spatial reference, such as dynamic luminance noise. Dynamic luminance noise also allows further investigation on the effects of stimulus visibility on perceived speed, given that it has been shown that this type of texture interferes with both the detection and direction discrimination of drifting luminance modulated gratings (Mullen, Yoshizawa, & Baker, 2003). In Experiment 2, we therefore sought to assess the effects of dynamic luminance texture contrast on the perceived speed of luminance-modulated stimuli.

4.1. Method

4.1.1. Stimuli

In order to compare the effects of luminance texture when it constituted a reliable spatial reference and when it did not, static or dynamic luminance noise was superimposed on the standard grating. We measured the relative speed of the PSE at three levels of noise contrast: 10%, 20%, and 40% Michelson contrast. The binary luminance noise had a grain size of 2 pixels (4 min of arc). In the dynamic noise condition, a new noise field was generated every four frames (30 Hz noise refresh rate).

4.2. Results

The mean relative speed of the PSE as a function of noise contrast is shown in Fig. 3 for static and dynamic

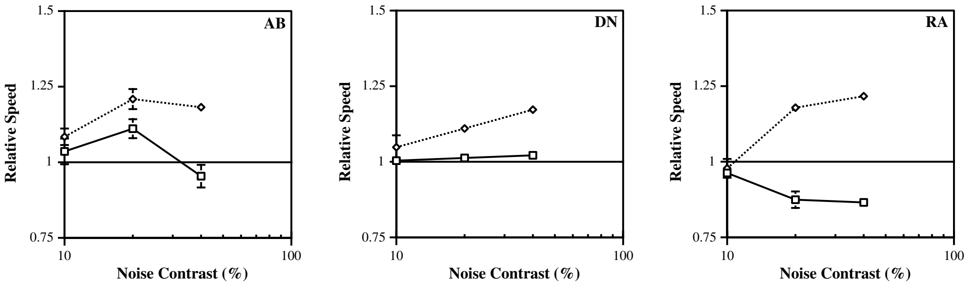

Fig. 3. Relative speed of PSE for individual observers as a function of noise type and noise contrast. Results are shown for dynamic (full line with squares) and static (dotted line with diamonds) luminance noise. Error bars show ±1 SEM.

luminance noise. As we can observe, increasing the contrast of static luminance noise produced an increase in apparent speed. In contrast with static noise, increasing the contrast of dynamic luminance noise did not produce a systematic increase in the apparent speed of the standard grating. In the dynamic noise condition, the speed of the test grating which matched the perceived speed of the standard grating remained close to the physical speed of the standard grating regardless of noise contrast. For one observer (RA), increasing the contrast of dynamic luminance noise produced a decrease in the relative speed of the PSE.

4.3. Discussion

The results of Experiment 2 demonstrate that superimposing static luminance noise on a drifting grating increases its apparent speed. This finding is consistent with the effects of superimposing a stationary pedestal grating on a drifting grating in Experiment 1. Unlike static luminance noise, increasing the contrast of dynamic luminance noise failed to produce a systematic increase in the apparent speed of a standard grating. For one observer, increasing dynamic luminance noise contrast even produced a decrease in perceived speed. This discrepancy between the effects of static and dynamic luminance texture could be explained by the fact that dynamic luminance noise cannot be used as a landmark to assess relative motion velocity, providing further support for the relative motion hypothesis. It could be argued that superimposing texture produces different effects on the visibility of drifting stimuli depending on whether it is static or dynamic. However, this appears unlikely given that superimposing luminance texture interferes with direction discrimination regardless of whether the texture is static (Cropper & Derrington, 1996; Lu & Sperling, 1996) or dynamic (Mullen et al., 2003).

Previous research on the effects of noise level on perceived speed has reported that the coherence level of RDKs fails to change the apparent speed of motion in (Zanker & Braddick, 1999). The failure of dynamic luminance noise contrast to elicit a systematic change in the perceived speed of the standard grating for two of our three observers in Experiment 2 is in agreement with this. The different effects of static and dynamic luminance texture on perceived speed raise questions about how these two types of texture are represented in the visual system and their different effects on the visual systems underlying the perception of speed.

Zanker and Braddick (1999) have suggested that the failure of RDK coherence level to produce a change in perceived speed is due to a large, but incomplete, segregation between the signal and noise motion components in the pooling process leading to the final speed estimate. These authors suggested that the independence of the speed percept from noise level in RDKs is achieved in two steps. The first step involves determining the direction of RDK motion. In the second step, perceived speed is determined by averaging exclusively from the units signaling the correct direction of motion. This proposal can account for the failure of coherence level to produce a change in the perceived speed of RDKs as well as the failure of dynamic luminance noise contrast to influence perceived speed in Experiment 2. However, by itself, this account fails to explain the increase in perceived speed with increasing static luminance texture contrast. Indeed, according to this proposal, static luminance texture should have had no effect on the perceived speed of the standard grating.

The segregation between the noise and signal motion components in RDKs may be attributable to a surface segregation mechanism. It has been mentioned that when drifting plaid patterns give rise to a percept of transparent motion, observers perceive the individual component gratings as two surfaces drifting one on top of the other (von Grünau, Dubé, & Kwas, 1993). This proposal is by no means at odds with the previously described explanation for the independence of perceived speed on the coherence level of RDKs. Indeed, the initial step of determining direction of motion may well form the basis on which the visual system identifies the texture and the motion components as belonging to two different surfaces.

The failure of dynamic noise contrast to produce an increase on perceived speed may, at first glance, seem at odds with the report that decreasing the proportion of dots moving in the same direction produces an increased perceived speed (Edwards & Grainger, 2006). This difference is likely due to the type of noise used: our random noise was randomly replotted every four frames whereas their noise dots were replotted so that they always moved at a constant velocity (constant walk stimulus). Because of this, the dynamic noise stimuli used in Experiment 2 did not contain relative motion whereas the constant walk stimuli did. Thus, both results are in agreement with previous suggestions that relative motion cues produce an increase in perceived speed (De Bruyn & Orban, 1999; Gogel & McNulty, 1983).

5. Experiment 3

The results of Experiments 1 and 2 demonstrate that the superimposition of static luminance texture on a drifting grating produces an increase in the perceived speed of motion. In Experiment 3 we will investigate how the visual system uses static luminance texture to reach a final assessment of velocity. It has been proposed that the visual system computes velocity in at least two processing steps (Adelson & Movshon, 1982; Heeger, Simoncelli, & Movshon, 1996; Khuu & Badcock, 2002; Simoncelli & Heeger, 1998; Smith, Snowden, & Milne, 1994). This entails first deriving local velocity estimates and then pooling together estimates at a second stage to obtain an overall estimate of motion velocity, arguably by averaging local speed information (Farell, 1999; Khuu & Badcock, 2002; Watamaniuk & Duchon, 1992).

It is possible that static texture produces an effect on perceived speed by changing the responses of units estimating velocity at a local level. This is compatible with the suggestion that landmarks and the moving stimulus only interact with each other over a limited spatial scale (Norman et al., 1996). If this is the case then static luminance texture would be expected to produce an increase in the responses of velocity-tuned units responsive to the motion stimulus whose receptive field lies on or near static texture. In such a case, the perceived speed of a drifting grating may be determined using a number of strategies. The first possible strategy that we will discuss is a “region of interest” approach, in which only the regions of motion stimulus covered by texture is used to determine stimulus speed. In such a case, one would expect speed perception to largely independent of the size of the area covered by luminance texture, provided that the textured area is large enough to be visible. The expected results for such a proposed scheme would resemble those expected if the motion stimulus and texture interact over a large scale. That is, perceived speed would increase rapidly as soon as texture is added and would not be affected by the size of the area occupied by the static texture.

A second possibility is that the visual system determines perceived speed by integrating local speed estimates. If this is the case, then increasing the area of the motion stimulus covered by static texture increases the response of more velocity-tuned units responsive to the motion stimulus. As a result, the overall population response of units responsive to the motion stimulus increases with the area of the motion stimulus covered by texture. As illustrated in the discussion of Experiment 1, this produces an increase in the final assessment of velocity. This predicts that perceived speed increases gradually as the area of a motion stimulus covered by texture increases. It is also possible that static luminance texture produces its effects on apparent speed by altering motion computation at the second stage, where local speed estimates are pooled together. If this is the case, one would expect apparent speed to be relatively independent of the area occupied by texture, given that this second stage is presumed to pool together unit responses from a large area.

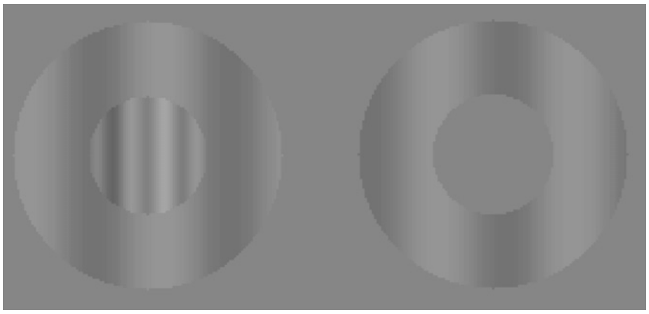

Fig. 4. Illustration of standard grating motion stimuli used in Experiment 3. The standard grating was a 0.5-cycles/deg 10% sinusoid grating drifting at a speed of 8 deg/s and was modulated at 10% Michelson contrast. A patch of texture (left) or a uniform grey occluder (right) was added to the drifting grating. The texture was modulated at 10% Michelson contrast vertical grating with a spatial frequency of 2 cycles/deg.

5.1. Methods

5.1.1. Stimuli

To assess how texture was used by the visual system to increase perceived speed, a circular patch of texture was added to the standard grating. A depiction of the standard grating stimulus used in Experiment 3 is shown in Fig. 4. The texture was a 2-cycles/deg vertically oriented sinusoidal grating, modulated at 10% Michelson contrast. Experiment 1 demonstrated that an increase in the perceived speed of the standard grating occurred reliably in these conditions. The stimulus area covered by the textured patch was manipulated from trial to trial: the patch could subtend 20%, 40%, 60% or 80% of the motion stimulus area. It is possible that texture could produce a change in perceived speed by encouraging observers to make their speed judgements based on the area of the standard grating that is not covered by static texture. In order to control for this potential confound, we also tested a condition in which a uniform grey patch with a luminance equal to the mean luminance of the grating (38 cd/m^2) occluded a portion of the standard grating.

5.2. Results

The results of Experiment 3 are shown in Fig. 5. These results show that the relative speed of the PSE increased gradually as the area of the motion stimulus subtended by static luminance texture increased. In contrast with superimposed static luminance texture, we found that increasing the size of a uniform patch that occluded the motion

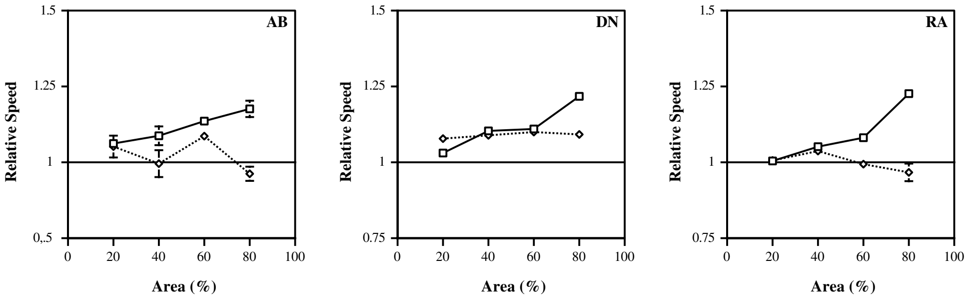

Fig. 5. Relative perceived speed of PSE for individual observers as a function of mask type and proportion of the motion stimulus area subtended by the mask. Results are shown for static luminance texture (full line with squares) and a uniform grey occluder (dotted line with diamonds). Error bars show ±1 SEM.

stimulus did not produce an increase in perceived speed. Increasing the area of the motion stimulus occluded by a uniform grey patch did not produce any systematic change in the relative speed of the PSE.

5.3. Discussion

The results of Experiment 3 show that increasing the area of the motion stimulus over which a static grating was superimposed produced a gradual increase in the perceived speed of the standard grating. Based on this finding alone, it could be suggested that superimposing texture increases perceived speed solely by encouraging observers to rely on the part of the motion stimulus that is not covered by texture to make their speed judgement. In order to control for this possibility, we also measured perceived speed in a control condition in which a uniform grey patch occluded the standard grating. Our results show that, in contrast with a superimposed grating, when a uniform grey patch partially occluded the standard grating, increasing the area covered by the patch did not produce an increase in perceived speed. The discrepancy between the effects of a uniform grey occluding patch and static luminance texture on perceived speed indicates that the effects of static luminance texture in Experiment 3 cannot be attributed to observers relying only on the area of the standard grating uncovered by texture to compute perceived speed. If it had been the case, a uniform grey patch would have produced that same effect as luminance texture because the unoccluded part of the standard grating is the only part of the grating that remained visible to make an assessment of speed.

The gradual increase in perceived speed when the area of the motion stimulus covered by the static grating increased also suggests that the area over which landmarks can be used in order to assess relative motion is fairly limited. That is, if the various local velocity estimators were able to use texture regardless of its location for local speed estimates, then perceived speed should have peaked rapidly, as opposed to the gradual increase reported here. This is consistent with earlier suggestions that the spatial area over which relative motion can influence perceived speed is limited (Norman et al., 1996). The gradual increase in perceived speed in Experiment 3 also rules out a mechanism in which perceived speed is derived by using solely the area where texture is present to compute motion velocity. Rather, it appears that the local speed estimates are pooled together in order to obtain the final assessment of speed.

6. Experiment 4

The results of the experiments reported in the previous sections of this paper show that the perceived speed of a drifting grating increased with the contrast of a superimposed static luminance pedestal. In Experiment 1, only the contrast of static luminance texture was manipulated: the standard grating remained constant at 10% Michelson contrast. Previous research has demonstrated that perceived speed is influenced by motion stimulus contrast (Blakemore & Snowden, 1999; Stone & Thompson, 1992; Thompson, 1982). It is possible that the contrast of superimposed texture could influence the relationship between motion stimulus contrast and perceived speed. Further, this experiment will allow the assessment of the possibility that the increase in apparent speed when static luminance texture is superimposed on the motion stimulus is attributable to an increase in the overall contrast of the compound stimulus. The purpose of Experiment 4 was therefore to assess and compare the effects of static texture and motion stimulus contrast on perceived speed.

6.1. Methods

6.1.1. Stimuli

In order to investigate the effects of motion stimulus and static texture contrast on the apparent speed of the standard grating, we obtained PSE measures at three different motion stimulus contrasts (10%, 20% or 40% Michelson contrast) and three different texture contrasts (0%, 10% or 40% Michelson contrast). Static texture spatial frequency was set to a 2-cycles/deg spatial frequency. We selected this spatial frequency because Experiment 1 demonstrated that an increase in perceived speed occurred reliably at this pedestal spatial frequency. The results of Experiment 1 demonstrated that increasing the contrast of a static grating set to this spatial frequency produced a reliable increase in perceived speed.

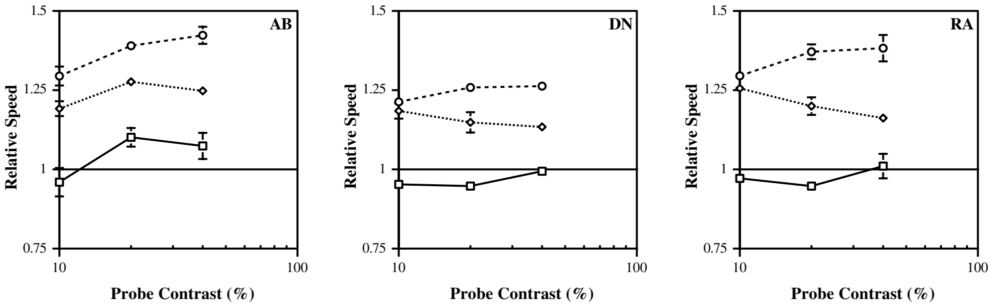

Fig. 6. Relative speed of PSE for individual observers as a function of motion stimulus and stationary texture contrast. Results are shown at 0% (full line with squares), 10% (dotted line with diamonds), and 40% (dashed line with circles) texture contrast. Error bars show ±1 SEM.

6.2. Results

The results of Experiment 4 are illustrated for each observer in Fig. 6. The relative speed of the PSE is plotted as a function of pedestal and motion stimulus luminance contrast. At all tested motion stimulus contrasts, increasing the contrast of static luminance texture yielded an increase in the relative speed of the PSE. Contrary to the stationary pedestal, increasing the contrast of the standard grating while maintaining pedestal contrast at a constant value did not consistently elicit an increase in the relative speed of the PSE.

6.3. Discussion

Within the stimulus parameters tested in Experiment 4, increasing motion stimulus contrast failed to produce a reliable increase in perceived speed. This may be attributable to the speed of the motion stimulus, as it has been previously reported that the dependency of perceived speed on motion stimulus contrast decreases at rapid velocities (Blakemore & Snowden, 1999; Gegenfurtner & Hawken, 1996; Thompson, 1982). The temporal frequency of the drifting standard grating was set to 4 Hz, which corresponds to the temporal frequency at which an important loss in the contrast dependency of perceived speed is reported to occur (Gegenfurtner & Hawken, 1996). If the failure of motion stimulus contrast to systematically increase perceive speed is indeed attributable to the temporal frequency at which we tested, our results show that even at these temporal frequencies the superimposition of a static pattern increases perceived speed. Unlike Blakemore and Snowden (2000), we did not find a systematic change in the dependency of perceived speed on motion stimulus contrast when the contrast of static texture varied.

The results of Experiment 4 demonstrate that increasing the contrast of static luminance texture produces an increase in the relative speed of the PSE, providing further evidence that static luminance texture increases the perceived speed of moving stimuli. These results are in agreement with the previously reported effects of texture on perceived speed (Blakemore & Snowden, 2000; Brown, 1931; Gogel & McNulty, 1983; Norman et al., 1996) as well as with the results of Experiment 1. This provides further evidence for the involvement of static texture in the computation of speed, arguably through a mechanism sensitive to relative motion.

The results of Experiment 4 rule out the possibility that the effects of luminance texture contrast on perceived speed are due to an increase in the overall contrast of the compound stimulus in the presence of a static pattern. That is, the luminance difference between the darkest and brightest portions of the texture plus motion stimulus was greater than when the drifting grating was presented alone. This proposal, however, is at odds with existing computational models of early-level motion extraction. For instance, motion energy detectors are insensitive to static stimuli (Adelson & Bergen, 1985). Indeed, the pedestal test takes advantage of this feature in order to investigate the mechanisms underlying motion perception (Lu, Lesmes, & Sperling, 1999; Lu & Sperling, 1995). The results of Experiment 4 demonstrate that increasing the contrast of the motion stimulus itself did not produce a systematic increase in perceived speed: adding a 10% contrast static pattern to a 10% contrast drifting grating produced a greater increase in perceived speed than doubling the contrast of the drifting grating. Further, the contrast between the brightest and darkest parts of the motion stimulus increases regardless of whether we superimpose static or dynamic luminance noise, yet we found that only static noise produces increases in perceived speed. The difference between the brightest and darkest parts of the compound stimulus is also unaffected by the spatial frequency of the static pattern, yet we found an effect of static pattern spatial frequency on perceived speed. Finally, the increased contrast proposal cannot account for the effects of static texture on perceived speed when it is located adjacent to the motion stimulus.

7. General discussion

The results of our experiments demonstrate that the apparent speed of a motion stimulus increases with the superimposition of static luminance texture and that perceived speed increases with the contrast of the stationary pedestal. These effects of static texture on perceived speed are in agreement with previous reports of increases in perceived speed in the presence of static luminance texture adjacent to the motion stimulus (Blakemore & Snowden, 2000; Brown, 1931; Gogel & McNulty, 1983; Norman et al., 1996). It is also interesting to note that the effect superimposed static pattern contrast on perceived speed is inconsistent with a model of velocity computation that is highly resistant to the superposition of static patterns (Johnston, McOwan, & Benton, 1999).

Blakemore and Snowden (2000) attributed the effects of texture contrast on the apparent speed of a uniform moving disk to changes in the disk's visibility through second order processes. In the present experiments, the increase in perceived speed cannot be readily attributed solely to an increase in the visibility of the standard grating because the visibility of luminance-modulated stimuli diminishes when the contrast of superimposed luminance texture increases (Gegenfurtner & Kiper, 1992; Legge & Foley, 1980). However, this does not imply that second order processes are not involved in the computation of motion velocity, as it has been demonstrated that the amplitude of contrast modulation changes the perceived speed of drifting contrast-modulated noise (Ledgeway & Smith, 1995).

One of the novel findings of our experiments is the effect of pedestal spatial frequency on the increase in perceived speed. As mentioned in the discussion of Experiment 1, we expected perceived speed to increase with the number of texture cycles present (i.e., at higher spatial frequencies), given the finding that perceived speed increases with reference mark density (Gogel & McNulty, 1983). It appears unlikely that changes in the visibility of the pedestal between 1 and 4 cycles/deg can account for these results, given that sensitivity to luminance modulated gratings is high at these temporal frequencies (Mullen, 1985). The dependence of perceived speed on pedestal spatial frequency in Experiment 1 also raises the question of whether this effect occurs because of the growing similarity between the probe and pedestal spatial frequencies as the spatial frequency of the pedestal decreased, or whether lowering pedestal spatial frequency *per se* produces faster perceived speeds. In order to better understand this effect, we believe that the effects of pedestal spatial frequency on perceived speed merit further investigation. This might also shed light on whether the increase in perceived speed in our experiments shares a common mechanism with induced motion contrast, which depends on the spatial frequency of the inducer and of the test (Ido, Ohtani, & Ejima, 1997).

It could be suggested that the effects of static luminance texture on perceived speed are attributable to an effect of texture on motion adaptation. Indeed, motion adaptation is known to produce a decrease in the perceived speed of motion stimuli moving at a constant velocity (Gibson, 1937; Wohlgemuth, 1911). Further, it has also been reported that superimposing static luminance texture produces a decrease in MAE durations (Smith, Musselwhite, & Hammond, 1984). We believe that a number of facts argue against this interpretation. First, in the current experiments, motion stimuli were presented for relatively brief time periods (2 s), leaving little time for motion adaptation to take place. The fact that a noticeable increase in apparent speed with stationary texture contrast nevertheless occurred argues against the notion that the effects of static texture contrast on perceived speed are solely attributable to an effect of texture on motion adaptation. Further, although adding texture peripherally to the motion stimulus or making it spatially coextensive with the motion stimulus both increase perceived speed, they produce different effects on motion adaptation. That is, adding static texture peripherally to the motion stimulus produces an increase in MAEs (Day & Strelow, 1971; Strelow & Day, 1975) whereas making it spatially contiguous with the motion stimulus decreases MAEs (Smith et al., 1984). Thus, it would be difficult for motion adaptation to account for the effects of adjacent luminance texture on perceived speed.

The results of our experiments demonstrate that, while static luminance texture produces a change in the apparent speed of a superimposed motion stimulus, texture that provides no reliable relative motion cues such as dynamic luminance noise does not. This indicates that static luminance texture produces different effects than dynamic luminance texture on the mechanism underlying the perception of speed. The failure of dynamic luminance noise contrast to produce an effect on perceived speed is also consistent with the suggestion that signal and noise motion components are largely segregated in the pooling process leading to the computation of speed (Zanker & Braddick, 1999).

On the whole, our results are congruent with previous suggestions that a relative motion mechanism underlies the effects of static patterns on the apparent speed of a motion stimulus (Gogel & McNulty, 1983). This is also in agreement with the explanation given for the effects of signal intensity on the perceived speed of constant walk stimuli (Edwards & Grainger, 2006). It has also been found that relative motion contributes to other motion phenomena, such as motion aftereffects (MAEs) (Swanston, 1994; Wade & Salvano-Pardieu, 1998; Wade, Spillmann, & Swanston, 1996). MAE studies using dichoptic viewing found that presenting a static pattern in the surround to the nonadapting eye fails to influence the MAE in the adapting eye (Symons, Pearson, & Timney, 1996). This suggests that relative motion intervenes relatively early in the visual pathways, prior to binocular integration. Similar experiments on the effects of relative motion on perceived speed could determine whether texture also changes perceived speed by intervening relatively early in visual processing.

The effects of superimposing static luminance texture on the perceived speed a drifting grating raise questions about the mechanism underlying the increase in perceived speed. That is, texture could be used by the visual system as a landmark so long as its contrast remains at supra-threshold levels. Thus, if, as suggested, static luminance texture produces increases in perceived speed by serving as a landmark to assess relative motion (Gogel & McNulty, 1983), then our results show that the visibility of these landmarks influences perceived speed.

The effects of static luminance texture on the apparent speed of motion stimuli raise questions on how texture influences the motion signal. The increase in perceived speed with increasing size of the area occupied by texture in Experiment 3 indicates that texture facilitates the initial assessment of speed over a limited spatial scale, suggesting that static patterns produce their effect on perceived velocity by affecting local estimates of velocity. These results also rule out a "region of interest" scheme in which only the local estimates corresponding to the area of the motion stimulus covered by texture are used in order to compute speed. Rather, in agreement with previous suggestions (Farell, 1999; Khuu & Badcock, 2002; Watamaniuk & Duchon, 1992), it appears that the final assessment of velocity is based on an integration of local velocity estimates over the area covered by the motion stimulus.

It has been proposed that a velocity-contrast mechanism (Nakayama & Loomis, 1974) could account for the effects of background motion speed on the perceived speed of target dots (Loomis & Nakayama, 1973). This suggestion is supported by the discovery of cells responding optimally when motion in the receptive field center was in the opposite direction to motion in the receptive field surround in the pigeon tectal area (Frost & Nakayama, 1983) and in cortical areas MT and MST of the macaque (Lagae, Gulyas, Raiguel, & Orban, 1989; Tanaka et al., 1986). Such a velocity-contrast mechanism is unable to account for the finding that increasing the speed of dots in a surrounding annulus decreases the apparent speed of dots drifting in a central area, regardless of whether the dots in the central and peripheral areas drifted in the same direction or in opposite directions (Norman et al., 1996). These authors propose a rectification of the velocities of both the center and the surround prior to the computation of speed. Although this could account for the effects of the effects of annulus speed on the apparent speed of motion in a central region, as pointed out by the authors, it could not satisfactorily explain why the addition of stationary texture produces an increase in perceived speed. A center-surround mechanism of the type described by Nakayama and Loomis (1974) also has difficulty, in its original form, accounting for the results of Experiment 1, in which the static texture and the motion stimulus were spatially coextensive rather than occupying adjacent areas.

It has been proposed that the human visual system computes velocity by comparing the activity of two broad temporal channels: a low-pass channel and a band-pass channel (Harris, 1980; Smith & Edgar, 1994). Recently, a computational model based on this was developed in order to account for the dependency of perceived speed on motion stimulus contrast (Thompson, Brooks, & Hammett, 2006). This model computes speed by dividing the low-pass channel response by the band-pass channel response. The band-pass channel, as formulated by these authors, is unresponsive to static stimuli (0 Hz temporal frequency). In contrast, the response of the low-pass temporal channel is increased by the superimposition of static patterns on a drifting grating. As a result, the model predicts a decrease in reported speed when a static pattern is superimposed on a drifting grating, the opposite of the effect of luminance texture on perceived speed. Thus, in the form described by Thompson et al. (2006), the ratio model cannot account for the effects of superimposing stationary luminance texture on motion stimuli.

An alternative framework to explain motion phenomena comes from a Bayesian model of velocity perception (Weiss, Simoncelli, & Adelson, 2002), in which observers make use of prior knowledge that slow speeds are more common than fast ones in order to determine motion velocity. This model was capable of predicting the increase in perceived speed that occurs with increasing motion stimulus contrasts. In the Bayesian model, motion stimulus contrast produces its effect on estimated speed by altering the likelihood function, reflecting the change in sensory activity that occurs with changing contrasts. This is consistent with the notion that static luminance texture influences perceived speed by providing additional relative motion information. Implementation of the Bayesian principle that the visual system has a bias favouring slow speeds has been proposed in a model that determines speed based on the population responses of speed-tuned units (Priebe & Lisberger, 2004).

The effects of static luminance texture on the apparent speed of motion could therefore be potentially expressed within such a framework. This would also have the advantage of making it possible to express the effects of static luminance texture on the responses of the units underlying speed computation in a manner that is more formal than the suggestion that texture serves as a landmark to assess relative motion. One possibility is that static luminance texture modulates the response of speed-tuned units to a motion stimulus. That is, while texture would not, by itself, elicit a change in unit responses, presenting it along with a motion stimulus would generate a greater activation than presenting the motion stimulus alone. However, the best way to implement texture within such a model remains to be determined. Electrophysiological data may provide insight on how to model the effects of static luminance texture on the responses of units underlying the computation of speed.

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