Apparent speed increases at low luminance

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To investigate the effect of luminance on apparent speed, subjects adjusted the speed of a low-luminance rotating grating (0.31 cd/m^2) to match that of a high-luminance one (1260 cd/m^2). Above 4 Hz, subjects overestimated the speed of the low-luminance grating. This overestimation increased as a function of temporal rate and reached 30% around 10 Hz temporal rates. The speed overestimation became significant once the lower luminance was 2.4 log units lower than the high luminance comparison. Next the role of motion smear in speed overestimation was examined. First it was shown that the length of the perceived motion smear increased at low luminances. Second, the length of the visible smear was manipulated by changing the presentation time of the stimuli. Speed overestimation was reduced at shorter presentation times. Third the speed of a blurred stimulus was compared to a stimulus with sharp edges and the blurred stimulus was judged to move faster. These results indicate that the length of motion smear following a target contributes to its perceived speed and that this leads to speed overestimation at low luminance where motion traces lengthen because of increased persistence.

Keywords: speed perception, luminance, contrast, temporal frequency, spatial frequency, motion smear, visual persistence

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Introduction

While demonstrating the overcounting of items in motion (Afraz, Kiani, Vaziri-Pashkam, & Esteky, 2004) with a motor-driven rotating disk, we accidentally turned off the room lights, dropping the illumination on the test by several orders of magnitude. We were immediately struck by the extraordinary increase in the apparent rotation speed of the disk, which changed from the leisurely rotation of a clearly visible set of spokes to a busy blur of apparently high speed motion. The drop of illumination did not change the contrast of the display so the well documented slowing of apparent speed at lower contrasts could not be involved (Stone & Thompson, 1992; Thompson, 1982; Thompson, Brooks, & Hammett, 2006). However, given the rapid drop of illumination, it is possible that the adaptation state of the rods and cones produced a neural response that mimicked that for a low-contrast test. To evaluate the source of the increase in apparent speed we constructed a test apparatus that allowed us to compare relative speeds of high and low luminance tests, matched for contrast and presented simultaneously at different retinal locations to avoid adaptation effects. We again found that at low luminance the rotating stimulus appeared to move faster. We also discovered that this effect had been noted by others (Hammett, Champion, Thompson, & Morland, 2007) and so we added additional experiments that demonstrated that motion smear plays a causal role in the speed overestimate at low luminance.

The perception of the speed of moving objects is often crucial for our survival and yet numerous studies demonstrate large, systematic errors in speed judgments. For example, the apparent speed of color-, texture- and motion-defined objects is often significantly underestimated (Cavanagh, Tyler, & Favreau, 1984; Hawken, Gegenfurtner, & Tang, 1994; Pantle, 1992; Zanker, 1997). The apparent speed of low-contrast, luminance-defined stimuli is underestimated at low temporal rates but overestimated at higher rates (Thompson, 1982; Thompson et al., 2006). While the effects of luminance contrast on speed perception is important, the effects of illumination may be more critical in day to day speed judgments. Specifically, the visual system needs to make accurate speed judgments in both daytime and nighttime settings, where illumination changes but contrast does not. The effect of this dramatic luminance change on speed perception has not yet received much attention. Gegenfurtner, Mayser, and Sharpe (2000) showed that under scotopic light levels there is a decrease in the perceived speed of motion with decreasing luminance at rates below 4 Hz. In their study, deuteranopic subjects were tested and the procedure was set so that the stimuli solely affected the rod

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cells in the retina and thus the speed underestimation perceived there was due to the isolated stimulation of the rods. The effect of different levels of luminance under natural conditions in normal subjects in which rod and cone receptors both contribute on motion perception was first reported by Hammett et al. (2007). They found an increase in the perceived speed in the dimmer of two targets at speeds above 4 degree/sec. They proposed a ratio model of speed encoding that could account for distortions of speed at both low contrast and low luminance (Hammett et al., 2007; Thompson et al., 2006).

Despite the importance of speed judgments for visually guided action, and despite the sophistication of models of motion energy (Adelson & Bergen, 1985; van Santen & Sperling, 1984, 1985; Watson & Ahumada, 1985), there are no widely accepted models of speed perception. Some models propose normalization (dividing the motion energy by the stimulus contrast, Adelson & Bergen, 1985), others propose a two or three channel model with different velocity tuned units responding to slow, medium, and fast speeds (van Santen & Sperling, 1984, 1985; Watson & Ahumada, 1985), and others point to the secondary effects of motion such as motion blur and trailing traces (Barlow & Olshausen, 2004; Burr & Ross, 2002; Geisler, 1999) as cues to motion. Geisler's analysis of motion traces focused on their contribution to detection of direction and not speed, nevertheless, faster motion will necessarily generate more blur and so a longer trace. The effect of luminance on apparent speed may help distinguish among these models.

In this article we explored the ability to perform speed matching over a 3.6 log unit range of luminance, keeping contrast constant. We showed that the perceived speed of moving radial gratings increases significantly at low luminance. In the first experiment we measured the effect of the speed of the rotating radial gratings on perceptual speed overestimation, when matching speed at two luminance levels. In the second experiment the effect of different levels of luminance on the perceived speed was investigated. Experiments three and four were designed to investigate motion smear as a possible underlying cause of the speed overestimation illusion under low levels of luminance. The visible trail that follows a moving object lengthens at higher speeds, and so has potential as a cue to speed (Francis & Kim, 2001; Ross, 2004). Interestingly, smear also lengthens with increased persistence and increased persistence is a hallmark of low luminance (Di Lollo & Bischof, 1995). Thus it is possible that the increase in persistence and hence the motion smear at low luminance leads to the increase in perceived speed. In the third experiment, we investigated the perceived persistence under different light levels to ensure that the lowest light levels used in our experiments cause a significant difference in the perceived persistence. In the fourth experiment, we manipulated the length of the visible smear trailing the moving patterns by changing the presentation time of the stimuli. The length of the smear could be no longer than the length of the stimulus's trajectory and our shortest presentation was less than the duration of persistence. We found that the shorter motion trace dramatically reduces the speed overestimation in low luminance. In the fifth experiment we compared the speed of a blurred stimulus with that of a sharp stimulus and found that a blurred stimulus is perceived to move faster than a stimulus with sharp edges. These data suggest a direct link between the perceived speed in low luminance and the motion smear behind moving objects. Finally it was shown that neither the reduced contrast nor a shift in spatial frequency pattern to lower spatial frequencies in a sharp-edge stimulus compared to a blurred stimulus can account for the speed overestimation effect. We concluded that the shape of the edges in a moving pattern is used as a cue to estimate its speed. A stimulus with sharp edges is perceived to move more slowly than one with blurred edges.

Experiment one

Methods

Participants

Three subjects participated in this experiment. Their ages ranged between 26 and 32. All subjects had normal or corrected-to-normal vision.

Apparatus

Stimuli were generated on a Macintosh computer with Vision Shell Software and were back projected on a small rear projection screen using a CTX video projector adapted with an additional +3 diopter lens to bring the image in focus at 33 cm from the projector. Subjects were positioned in a dark room in front of the screen, while the distance between the monitor and their eyes was 57 cm. Luminance was measured using a digital photometer (Minolta Chroma Meter CS-100).

Stimuli

Stimuli were radial gratings with 5 cycles of alternating black and white spokes. The gratings' luminance profile was a smoothed rectangular waveform in which the white spokes were wider than the black spokes. The gratings were presented on a black background and each had a diameter of 1.5 degrees. A small red fixation point was presented in the center of the display and the two gratings were centered 3.5 degrees on the left and right sides of the fixation point. The gratings rotated around their center in clockwise or anticlockwise direction (Figure 1). In half of the trials they rotated in the same and in half in the opposite directions. The grating had a luminance of

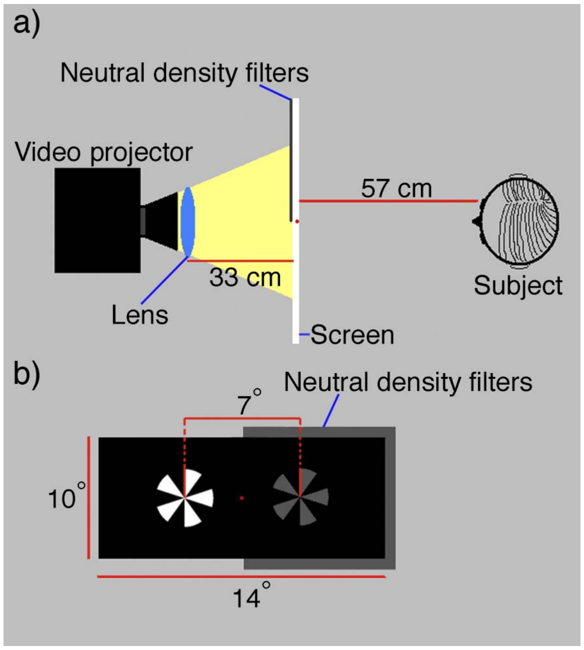

Figure 1. (a) A schematic top view of the experimental setup. Subjects viewed the screen from 57 cm distance. The stimuli were back projected on the screen using a video projector. To make low luminance stimuli, half of the screen was covered with neutral density filters. (b) A schematic display of the one frame of the moving gratings. Stimuli were radial gratings with black and white spokes presented on a black background and rotated around their center.

2500 cd/m^2 in its white spokes and 13.5 cd/m^2 in the black spokes for an average luminance of 1260 cd/m^2. The black surround had a luminance of 13.5 cd/m^2. To achieve lower luminances without changing contrast, neutral density filters were placed against the back of the rear projection screen on the right to reduce the light reaching the screen in both light and dark areas for the grating on that side.

Procedure

In each trial subjects had to fixate on the red fixation point and change the speed of the grating on the right side of the fixation point ("match grating") to appear the same as the grating on the left side of the fixation point ("target grating"). The "match grating" was initially presented at a random speed and the subjects changed its speed by moving the computer mouse to the left or right and pressed the "enter" button on computer keyboard when they thought that its speed was similar to the "target grating". The temporal rate of the target grating was chosen pseudo randomly among 5 possible speeds: 2, 5, 8, 11, and 14 Hz (0.4, 1.0, 1.6, 2.2, and 2.8 rotations per second, respectively). There were two conditions: a test condition and a control condition. In the test condition, the right half of the screen was covered with three 1.2 log unit neutral density filters (combined to give 3.6 log units of reduction, Figure 1). Thus the target grating was in the high luminance area with a mean luminance of 1260 cd/m^2 and the match grating was in the low luminance area with a mean luminance of 0.31 cd/m^2. In the control condition, the match grating and target grating both had the same mean luminance, 1260 cd/m^2. The subjects completed two blocks of each experimental condition each containing 20 trials at each of the 5 speeds.

Results

The matched temporal rate is plotted as a function of the target temporal rate in Figures 2a–2c for individual subjects separately. The blue line shows the control condition where both target and match gratings had the same high luminance and the red line shows the test condition where the match had low and the target had high luminance. The plots show that all subjects overestimate the speed of the low luminance grating for temporal rates above 4–5 Hz. To match the low luminance grating speed to that of the fixed, high luminance grating, subjects decreased the speed of the low luminance grating. The temporal rate error, defined as the difference between the temporal rates of target and match (target − match) is plotted in Figure 2d as a function of the target (high luminance grating) temporal rate. This figure shows that the overestimation increases as the temporal rate increases. A repeated measure ANOVA showed a significant effect of both target temporal rate ($F(4) = 1101.881$, $p < 0.01$) and match luminance ($F(1) = 30.76$, $p < 0.05$) on the final matched speed. The interaction of target temporal rate and match luminance was also significant ($F(4) = 29.04$, $p < 0.01$) reflecting the increase in the effect of luminance on matched speed at higher velocities (Figure 2).

Experiment two

In this experiment the effect of different levels of luminance on the matched speed was investigated. With the target grating fixed at the highest luminance, the match grating was presented at four luminance levels spanning a 3.6 log unit range. We expect the apparent speed of the match grating to be highest at low luminance and decrease as luminance increases.

Methods

Participants

The three subjects from Experiment one also participated in this experiment.

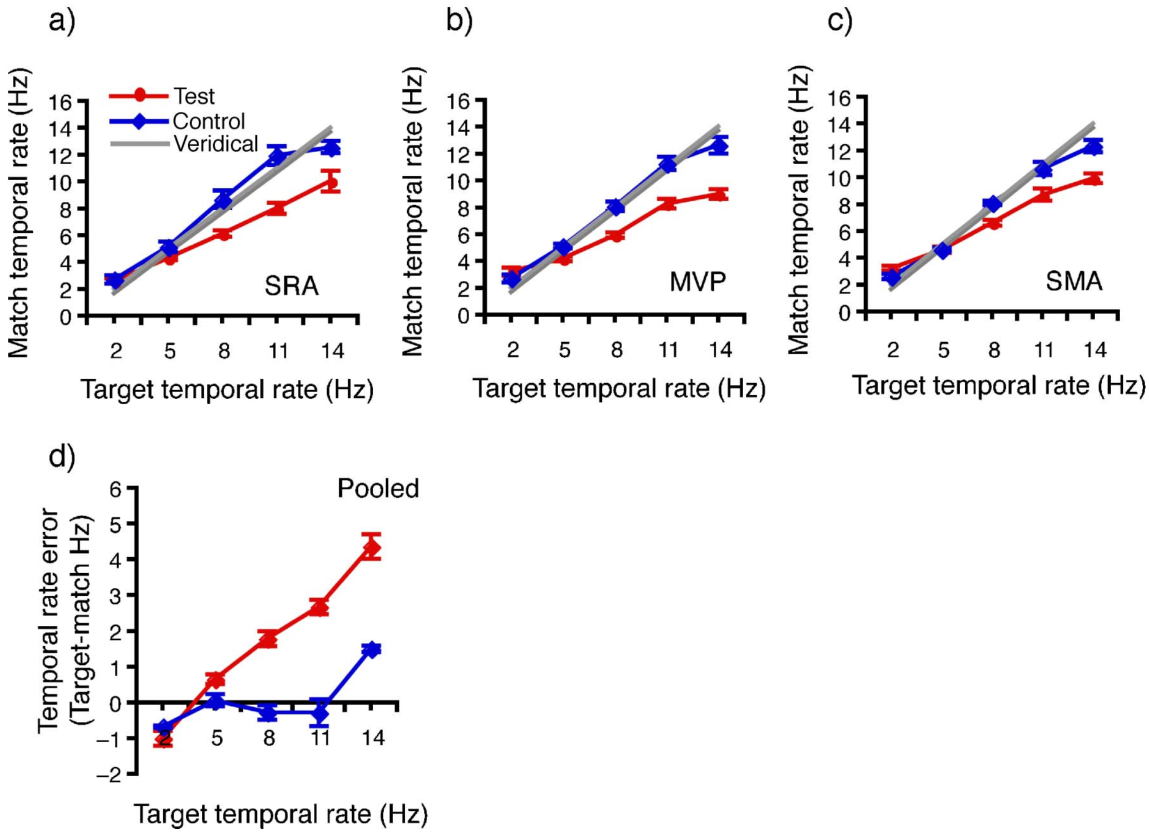

Figure 2. (a)–(c) Results of each subject plotted separately for target temporal rate versus matched temporal rate. Data for the control condition are plotted in blue (both match and target gratings had high luminance) and data for the test condition are plotted in red (the target grating had high and the match grating had low luminance). Lower match temporal rates for test compared to control condition shows the speed overestimation effect. The gray line shows the veridical match. Note that 10 Hz equals to 2 rps as the stimuli have 5 spokes. (d) Pooled data of all three subjects now showing temporal rate difference (target − match) as a function of the target grating temporal rate. Zero error indicates the perfect match to the target. Standard errors of the mean (±1 *SEM*) are shown as vertical lines.

Stimuli and apparatus

The setup was identical with that of the previous experiment except that 4 levels of filtering were used to control the luminance of the test grating. Luminances of 1260, 79.5, 5.01, and 0.31 cd/m^2 were set by covering half of the display with zero, one, two, and three 1.2 log unit neutral density filters, respectively.

Procedure

Subjects completed one block of 20 trials each with one of the four luminance levels of the match grating chosen pseudo randomly. The temporal rate and the luminance of the target stimulus in this experiment were always 10 Hz (2 revolutions per second) and 1260 cd/m^2. The procedure was otherwise the same as in the first experiment.

Results

Pooled data from all three subjects are plotted in Figure 3. Temporal rate error (target temporal rate − match temporal rate) is plotted as a function of luminance difference between target and match on a logarithmic scale [$\log_{10}$ (target / match)]. A repeated measure

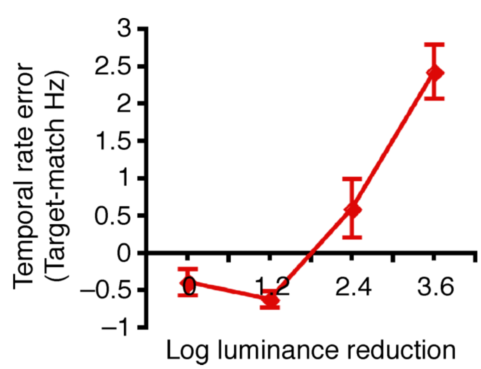

Figure 3. Pooled data from all subjects are plotted. The *x*-axis shows the luminance reduction [$\log_{10}$(target luminance / match luminance)] in logarithmic scale and the *y*-axis shows the difference between the temporal rate of the target and match (target temporal rate − match temporal rate). Zero error shows the perfect match to the target. Error bars show standard errors of the mean (±1 *SEM*).

ANOVA showed a significant effect of luminance on the temporal rate error ($F(3) = 77.2$, $p < 0.01$). Results showed that as the luminance of the match grating decreased, the amount of overestimation in speed increased. The overestimation did not occur until there was a 250-fold drop in the luminance.

Experiment three

At low luminance, studies show an increase in visual persistence. This effect, which is known as the "inverse intensity effect" (Di Lollo & Bischof, 1995), results in an increase in the perceived motion smear behind moving items at low luminance. This increase in motion smear may be a cause of speed overestimation in low luminance. This experiment was designed to explore the amount of visual persistence (and hence the motion smear) seen at luminance levels close to those used in our experiments. To measure persistence, we use the technique described by Ptolemy (150, translated by Lejeun, 1956) except for the change in the rotating light source from a glowing ember at one end of a stick attached to a cord and spun in a circular path by hand, to a white spot on a disc, illuminated by natural sunlight and spun by a motor. In either case, the speed at which the luminous spot appears to complete a continuous circle is used to measure the duration of visual persistence.

Methods

Participants

Three subjects participated in this experiment. Their age ranged between 26 and 32. All subjects had normal or corrected-to-normal vision.

Stimuli and apparatus

The stimulus was a white spot with diameter of one degree of visual angle that was located on a black disc with a radius of 7 degrees of visual angle. The dot was placed 4.5 degrees away from the center of the disc. This disc was rotated using an electric motor (EC Motomatic, DC motor generator) whose speed was controlled by a constant speed and torque control unit (Cole-Parmer).

Procedure

The experiment consisted of two different conditions: Low luminance and high luminance. In the high luminance (luminance of 1720 cd/m^2 for white dot and 80 cd/m^2 for black background) condition, the disc was placed in a room with no artificial light that was illuminated by sunlight on a day with a clear sky around noon. In the low luminance condition (luminance of 0.1 and 0.005 cd/m^2 for white and black, respectively), the disc was located in the same room in a day with cloudy sky around sunset. In each case, the subjects were told to increase the speed of the rotating dot until they perceive it as a continuous circle. Each subject completed three trials of each experimental condition.

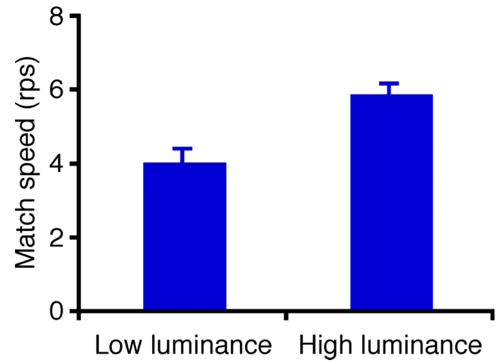

Figure 4. The speed at which the rotating dot appears as a continuous circle is plotted for the two luminance conditions (3 subjects). Higher speed was required at high luminances indicating that there was less persistence. Error bars show standard errors of the mean (±1 *SEM*).

Results

Figure 4 illustrates the data collected from all 3 subjects. The final matched speed is plotted as a function of luminance. The result demonstrates that the matched speed is substantially higher (by about 31%) in low luminance compared to high luminance condition ($t(2) = 7.20$, $p < 0.05$).

These two matched speeds provide a rough estimate of the duration of persistence for the two luminance levels: 244 msec at the low luminance and 169 msec at the higher luminance.

Experiment four

This experiment was designed to test the possible contribution of motion smear to the speed overestimation effect in low luminance. If the increase in visual persistence in low luminance causes an extended motion trace that leads to the speed overestimate, any change in the stimulus that decreases the length of the motion trace should diminish the overestimation effect. To change the trace length we changed the presentation time of the stimulus. Once the presentation time of the moving pattern is less than the duration of persistence, the length of the motion smear will be reduced (the trace cannot be longer than the motion path itself). For these short lifetime stimuli, we use duration of 100 msec, substantially briefer than the 244 msec persistence measured in Experiment three. If there is any relationship between the perceived speed in low luminance and the motion smear, there should be a decrease in the amount of speed overestimation with the short lifetime stimuli.

Methods

Participants

The three subjects from the first three experiments participated in this experiment.

Stimuli and apparatus

The apparatus was the same as the three first experiments. The stimuli were rotating random dot patterns 8 degrees in diameter, consisting of white dots with the size of 0.1 degrees of visual angle, on a black background. The random dot patterns each filled a circular region that rotated around its center point. A red fixation cross was presented in the center of the display and the centers of the two random dot patterns were 3.5 degrees to the left and to the right of the fixation point. The luminance of the white dots and black surround were 2500 and 13.5 cd/m^2, respectively, in the absence of the filters. Neutral density filters were attached to the screen to achieve lower levels of luminance.

Procedure

In each trial subjects had to match the speed of the random dot pattern on the right side of the fixation point (match) to appear the same as the random dot pattern on the left side of the fixation point (target), while fixating on the center of the screen. The match pattern was initially presented at a random speed and the subjects changed its speed by moving the computer mouse to left or right and pressed the "enter" button on the computer keyboard when they thought that its speed was similar to the target pattern. The rotation speeds of the target patterns were 0.25, 0.5, or 1 revolutions per second and the mean luminance was always 263 cd/m^2. The mean luminance of the match pattern was either equal to the target, or was reduced to 0.06 cd/m^2 using three 1.2 log unit neutral density filters. The target and match random dot patterns were either presented for an unlimited amount of time, or their presentation time was restricted to intervals of 6 frames (100 msec) with a one-second interval between the repeating motion episodes.

There were a total of 12 conditions in the experiment (3 speeds, 2 presentation times, 2 luminance differences), and each subject completed one block of each condition with 10 adjustment trials per condition. The blocks were randomly ordered across the subjects.

Results

Pooled data collected from all subjects are presented in Figure 5 where the difference between target speed and match speed are plotted as a function of target speed for long and short duration presentations.

With long presentation time the speed overestimation for the low luminance stimulus is again observed (28% overestimate at highest speed). However, this effect is not seen in the short presentation condition. A three-way repeated measures ANOVA (luminance × duration × speed) showed a significant effect of luminance ($F(1,2) = 54.35$, $p < 0.05$), duration ($F(1,2) = 23.53$, $p < 0.05$), and speed ($F(2,4) = 176.301$, $p < 0.01$) on the matched speed. There was also a significant interaction between the luminance and duration ($F(1,2) = 281.27$, $p < 0.01$). This was caused by the presence of a significant effect of luminance on the matched speed in the long presentation condition ($F(1,2) = 245.592$, $p < 0.01$), and the absence of this effect in the short presentation condition ($F(1,2) = 4$, $p = 0.184$).

Results of this experiment show that reducing the presentation time of the moving pattern decreases the overestimation of speed in low luminance. As changing the presentation time also varies the amount of motion

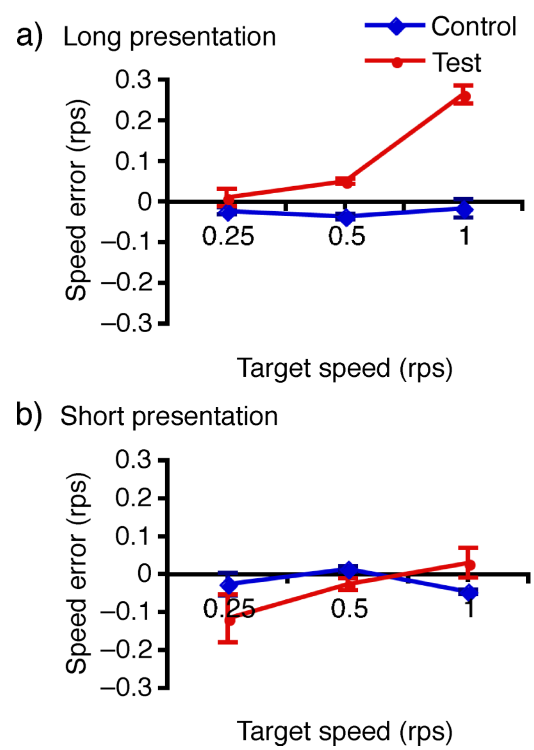

Figure 5. The difference between the target speed at low and high luminances is plotted as a function of target speed for (a) long and (b) short presentation times. The results show that the overestimation effect is stronger in the long presentation condition. Error bars show standard errors of the mean (±1 *SEM*).

smear, these results suggest that motion smear can be a cause of speed overestimation in low luminance.

However an alternative explanation could appeal to different states of motion adaptation across the different experimental conditions. Specifically, motion adaptation that required long presentation times and high luminance could produce the pattern of results seen in Figure 5. In the long presentation condition, the high luminance stimulus could induce more adaptation and thus it would be perceived to move more slowly. However, at short presentation durations, adaptation could not be a factor so that, as seen in the data, there would no longer be any perceived speed difference between low and high luminance tests.

To examine this adaptation hypothesis, we performed another experiment with two subjects and asked them to adjust the speed of a grating with short presentation time to match that of a grating with long presentation time (repeated at low and high luminance conditions). If there is more adaptation with long presentation times, the prolonged stimuli should appear slower than the stimuli with short presentation times and we would expect any difference due to adaptation to be greater at the higher luminance. However results showed that in high luminance condition, the grating with low presentation time did not appear more slowly (average speed error = −0.124, $t(1) = 1.44$, $p = 0.38$). At low luminance, the grating with longer presentation time was perceived to move faster, not slower, than the grating with short presentation time (average speed error = −0.23, $t(1) = 89$, $p < 0.01$), again contradicting effects of adaptation. Overall, these results clearly rule out the adaptation hypothesis. Thus decreasing the presentation time of a moving pattern leads to a decrease in its perceived speed, most probably through a reduction in the amount of motion smear.

Experiment five

In this experiment we wanted to directly test the possible contribution of motion blur in the matched speed of the moving objects. For this purpose we manipulated the amount of blur in the moving gratings and asked the subjects to compare the speed of a blurred moving grating to that of a non-blurred grating. To achieve the maximum amount of blur difference, a sinusoidal grating was used as the match stimulus and a square-wave grating as the target stimulus.

Methods

Participants

Three subjects, two from the previous experiments and one new subject, participated in this experiment. All subjects had normal or corrected-to-normal vision.

Apparatus

Stimuli were generated on a Macintosh computer with Vision Shell Software and were presented on a CRT monitor (Hitachi CM715, 1024 × 768, 100 Hz). Subjects were positioned in a dark room in front of the screen, while the distance between the monitor and their eyes was 57 cm. The monitor was calibrated for linearity prior to the experiment.

Stimuli

The target stimulus was a square-wave radial grating 6.5 degrees in diameter with 5 cycles of alternating black and white spokes presented on a black background. In the test condition the match grating was a sinusoidal grating of similar size and number of spokes, and in the control condition the match grating was identical to the target grating. The two gratings were presented successively in the center of the display and rotated around their center in clockwise or anticlockwise direction. In half of the trials they rotated in the same and in half in the opposite directions. The grating had a luminance of 70 cd/m^2 in its white spokes and 30 cd/m^2 in the black spokes for an average luminance of 50 cd/m^2. The black surround had a luminance of 0.5 cd/m^2. The temporal rate of the target grating was always 5 Hz (1 rps).

Procedure

Subjects had to perform an adjustment task similar to the previous experiments except that in this experiment the match and the target stimuli were presented intermittently, each for one second, in the center of the screen. A red fixation point was presented in the center of the display when the target grating was presented, which turned green when the match grating was displayed. Each

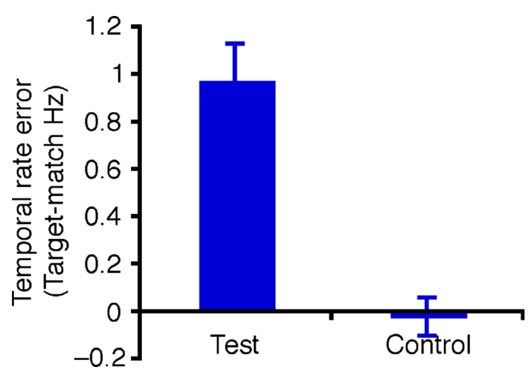

Figure 6. Temporal rate error (target temporal rate − match temporal rate) is plotted for both test and control conditions. In the test condition the target is a square-wave grating and the match is a sine-wave grating, and in the control condition both target and match are square-wave gratings. Results show that a sine-wave grating is perceived to move faster than a square-wave grating. Error bars show standard errors of the mean (±1 *SEM*).

subject completed one block of 12 trials for each experimental condition.

Results

Pooled data collected from all subjects are presented in Figure 6. Results showed that the speed of a sine-wave grating is significantly overestimated compared to that of a square-wave grating ($t(2) = 4.7$, $p < 0.05$). In other words an increase in the amount of blur while holding Michelson contrast fixed has caused an increase in the matched speed of rotating gratings.

Experiment six

Transforming a square wave to a sine wave smoothes the edges of the luminance profile by removing the high spatial frequency components. Is the speed overestimation that we observed for the sinusoidal gratings due to the smoothed edges or to the loss of high frequency components? Previous evidence on the effect of spatial frequency on perceived speed is mixed (Campbell & Maffei, 1981; Diener, Wist, Dichagans, & Brandt, 1976; Ferrera & Wilson, 1991; McKee, Silverman, & Nakayama, 1986; Smith & Edgar, 1990) so we focus instead on the presence or absence of sharp versus smooth luminance edges independently of spatial frequency. Specifically, we compared the apparent speed of a square-wave grating to that of a phase-scrambled version of the same grating. These two gratings have identical spatial frequency spectra but the square-wave grating has sharp luminance transitions and the phase-scrambled version has smooth luminance transitions.

Methods

Participants

Three subjects from the previous experiments participated in this experiment. All subjects had normal or corrected-to-normal vision.

Stimuli and apparatus

The apparatus was the same as previous experiment. The target stimulus was a square-wave radial grating 6.5 degrees in diameter with 5 cycles of alternating black and white spokes presented on a black background. In the test condition, the match grating was a phase-scrambled square-wave grating of similar size and spatial frequency, and in the control condition it was identical to the target grating. Other characteristics of the stimuli were similar to the previous experiment.

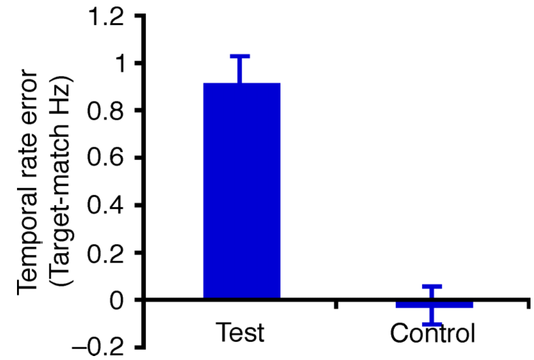

Figure 7. Temporal rate error (target temporal rate − match temporal rate) is plotted for two experimental conditions. In the test condition the target is a square-wave grating and the match is a phase-scrambled grating, and in the control condition both target and match are square-wave gratings. Results show that phase-scrambled stimulus appears to move faster than the square-wave stimulus. Error bars show standard errors of the mean (±1 *SEM*).

Procedure

The task was similar to the previous experiment. Subjects completed one block of each experimental condition. Each block contained 12 trials in which subjects were asked to adjust the speed of the match grating to that of the target grating.

Results

Pooled data collected from all subjects are presented in Figure 7. Results showed a significant effect of experimental condition on the matched speed of rotating gratings: The phase-scrambled grating is perceived to move faster than the square-wave grating ($t(2) = 8.76$, $p < 0.05$). These results indicate that the alignment of the square-wave grating's frequency components in sine phase (producing sharp luminance transitions) is crucial for its apparent reduction in speed. When the smooth luminance transitions of individual spatial frequencies are revealed by randomizing their phase alignments, they cause an increase in perceived speed. Therefore speed overestimation observed in sinusoidal gratings compared to square-wave gratings is more likely a result of the smoothed, blurred luminance edges than the difference in the spatial frequency profile of the stimuli.

Experiment seven

Motion blur in a moving stimulus not only smears the stimulus but also causes a reduction in its effective contrast. The phase scrambling of the square wave in the previous experiment also revealed many smooth luminance transitions that were of lower contrast than the sharp step they replaced. However, we would expect that, at least for speeds below 8 Hz, as was largely the case in our experiments, decreasing the contrast should cause a *decrease* in the perceived speed (Stone & Thompson, 1992; Thompson, 1982; Thompson et al., 2006)—not the increase that we observed. This last experiment examined whether the effect of contrast in our stimuli is in line with previous experiments (and therefore acted in the direction opposite to the speed up we see for blurred stimuli) or in fact is the reverse of that previously reported.

Methods

Participants

Four subjects, two from the previous experiments and two new subjects, participated in this experiment. All subjects had normal or corrected-to-normal vision.

Stimuli and apparatus

The apparatus was the same as previous experiment. The stimuli were sine-wave radial gratings 6.5 degrees in diameter with 5 cycles of alternating black and white spokes presented on a black background. There were two experimental conditions. In the test condition the match grating had a Michelson contrast of 0.1 and in the control condition a Michelson contrast of 0.4. The contrast of the target grating was always 0.4. The mean luminance of the gratings was always 50 cd/m^2. Other characteristics of the stimuli were similar to the previous experiment.

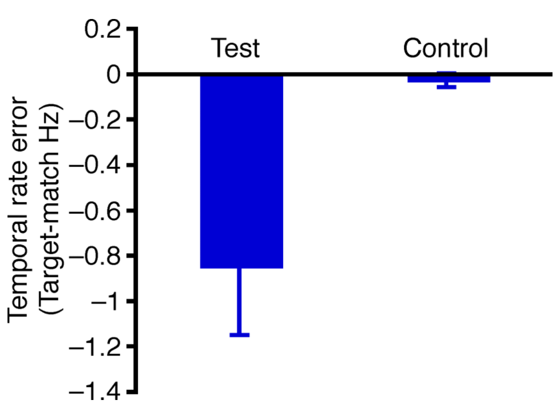

Figure 8. Temporal rate error (target temporal rate − match temporal rate) is plotted for two experimental conditions. In the test condition the target had a Michelson contrast of 0.4 and the match had a Michelson contrast of 0.1, and in the control condition both target and match had a Michelson contrast of 0.4. Results show that there is a decrease in the matched speed of a sine-wave grating as its contrast decreases. Error bars show standard errors of the mean (±1 *SEM*).

Procedure

The procedure was similar to the previous experiment. In each block of 12 trials subjects were asked to adjust the speed of a match grating with either 0.4 or 0.1 contrast depending on the experimental condition to that of a grating with 0.4 contrast, which rotated at 5 Hz (1 rps). Match and target grating were presented intermittently in the center of the screen each for 1 s. Subjects completed one block of each experimental condition.

Results

Polled data from all subjects is plotted in Figure 8. Consistent with Thompson's (1982) results, a low contrast grating was perceived to move more slowly than a high contrast grating ($t(3) = 2.7$, $p < 0.05$, one tailed).

There was therefore clear evidence of a *decrease* not an increase in the perceived speed of the low contrast grating. These results demonstrate that none of the overestimation effects reported in previous experiments can be attributed to a decrease in contrast resulting from the blurring of the moving patterns.

Discussion

The first experiment showed that a rotating grating at low luminance (0.31 cd/m^2) is perceived to move faster than an otherwise identical rotating grating that has a higher luminance (1260 cd/m^2). The speed overestimation increases with temporal rate starting from little or no effect below 4 Hz and rising to 30 percent overestimation at about 10 Hz. In the second experiment, the overestimation was found to occur only when the low luminance grating was at least 250 times (2.4 log units) lower in luminance and overestimation increased as the lower luminance decreased further from this level. In the third experiment the effect of luminance on perceived visual persistence was investigated and it was shown that the perceived persistence of moving objects, which is observed as a motion smear behind them, increases at low luminance. In the fourth experiment, the length of the motion smear was reduced by decreasing the presentation time of the stimulus. The speed overestimation effect was reduced at shorter presentation times in which there was shorter motion smear. In the fifth experiment it was shown that a square-wave grating is perceived to move slower than a sine-wave grating. In the last two experiments it was demonstrated that the increase in speed of blurred stimuli is not related to the decrease in spatial frequencies or contrast.

It has been previously shown that low contrast stimuli appear to move more slowly than high contrast stimuli if they move at 8 Hz or below. Above 8 Hz they appear to move faster (Stone & Thompson, 1992; Thompson, 1982; Thompson et al., 2006). This effect has been attributed to the temporal properties of magnocellular and parvocellular pathways (Perrone, 2005; Thompson et al., 2006). The effect of low luminance on speed perception observed here differs strongly from the effect of low contrast in that:

1. the speed shows an increase at low luminance rather than decrease; and
2. the increase is the same across a wide range of temporal rates, peaking at 10 Hz, showing no reversal.

Gegenfurtner et al. (2000) also tested speed perception at very low (scotopic) illumination conditions and reported a slowing of apparent speed for rates less than 4 Hz. It is possible that the absence of effects we noted at 4 Hz and below might reveal a decrease in perceived speed with further measurement. Nevertheless, our main result is a robust increase in apparent speed at low luminances across the range of rates from 4 Hz to 10 Hz. This is consistent with the findings of Hammett et al. (2007) who reported similar distortions in speed perception at low levels of luminance.

Why is speed overestimated under low illumination conditions? Hammett et al. (2007) proposed a model in which the speed is defined as the ratio of the activity of the cells in magnocellular and parvocellular pathways. They used this model to explain both speed underestimation at low contrast and speed overestimation at low luminance (Hammett et al., 2007; Thompson et al., 2006). Their model relies on the physiological characteristics of magnocellular and parvocellular pathways. Specifically, it has been reported that at scotopic luminance levels, the response of P cells is lost in noise whereas the M cells still give a robust response (Purpura, Kaplan, & Shapley, 1988). A decrease in luminance would therefore increase the M to P activity ratio and consequently, the perceived speed as well. However the ratio model does not explain our findings in experiment four. The speed overestimation in low luminance should not be modulated by presentation time if our perception of speed was solely defined by the M to P ratio.

Is our result already predicted by the known effects of luminance on apparent spatial and temporal frequency? The velocity of a moving stimulus is its temporal frequency divided by its spatial frequency. Therefore the perceived speed of an object is given by dividing the temporal frequency by the spatial frequency. Experiments have shown that low luminance will increase *both* perceived temporal and spatial frequencies (Peterson, Ohzawa, & Freeman, 2001; Virsu, 1974). In Peterson et al.'s (2001) studies of the effect of luminance on apparent temporal frequency, the authors suggest that the range of temporal frequencies that activate a cell shifts to lower rates at low luminance. The source of the shift is a lessening of the inhibitory component of the impulse response function rendering it less biphasic (onset excitation followed by inhibition) and more monophasic. The first consequence of this change is a reduced response to high temporal frequencies (the second is increased persistence). This lowered response to a given high frequency does not itself change the perceived frequency, but the authors argue that if temporal frequency is coded by labeled lines (a given cell's activity leads to perception of a particular rate), this shift in response range would cause a shift in perceived frequency. Cells that code for higher frequencies would now be responding to lower frequencies and the result would be that the apparent rate is higher than the actual rate. A similar argument can be made for spatial frequencies where cells inhibitory flanks are weakened at low luminance and their range of response then shifts to lower spatial frequencies. A test will then be perceived as having higher spatial frequency than its actual value.

These two effects ought to cancel out, resulting in no net change in the perceived speed, or if the effect on temporal frequency is greater, the result could explain our findings. If the effect of luminance on temporal frequency were 30% greater than on spatial frequency, for example, we would have our speed overestimate as well. However, the data do not support a greater effect on temporal than spatial frequency.

The reduction, at low luminance, of the inhibitory phase in temporal response not only affects response to high temporal frequencies, it also, as mentioned, increases the duration of visible persistence. Consequently, the smear that trails a moving object will lengthen. This trace or motion smear invariably accompanies motion and previous studies have demonstrated the contribution of the motion trail to the detection of motion (Barlow & Olshausen, 2004; Burr & Ross, 2002; Edwards & Crane, 2007; Geisler, 1999; Ross, Badcock, & Hayes, 2000) and to the perception of speed (Francis & Kim, 2001; Ross, 2004). Additionally it has been shown that cells at the V1 cortex of cats and monkeys and superior temporal sulcus (STS) of monkeys, and the human motion complex (MT+) are sensitive to motion streak information (Geisler, Albrecht, Crane, & Stern, 2001; Jancke, 2000; Krekelberg et al., 2003; Krekelberg, Vatakis, & Kourtzi, 2005). Clearly the faster the motion, the longer the trace behind the moving pattern. More to the point for our studies, it is also the case that the lower the luminance, the longer the trace (because of increased persistence).

We therefore propose that the motion smear, used widely by cartoonists in static drawings (Burr, 2000; Kim & Francis, 1998), is a cue to speed that is accentuated at low luminance and so would contribute to an increase in the apparent speed as luminance drops. The role of the motion trace in perceived speed suggests a direct link between persistence as measured by other techniques (Di Lollo & Bischof, 1995) and apparent speed. The results of experiments three and four are highly supportive of this view. The perceived persistence increases at low levels of luminance. Moreover, manipulation of perceived length of the motion smear by decreasing presentation time of the moving stimuli decreases the speed overestimation dramatically. Results of experiment five also support this hypothesis by demonstrating that the amount of blur in a stimulus can directly change its perceived speed: the larger the blur, the higher the speed. These findings suggest a direct causal relationship between the length of the motion smear in the moving objects and their perceived speed. Other than a change in the shape of the edges, when a stimulus is blurred, there is a shift in its spatial frequency pattern to lower spatial frequencies. Also depending on the original stimulus, smear might cause a decrease in its perceived contrast. Results of the last two experiments show that neither the loss of high spatial frequencies nor the decrease of contrast account for the increase of speed for blurred stimuli. A square-wave grating with scrambled phase (and blurry rather than sharp luminance profile) appeared to move faster than the same square wave with sharp edged luminance transitions (all components in sine phase). The increase in apparent speed is produced by blurring the luminance edges even when the spatial frequency content is unchanged. The decrease in contrast was found, as in previous articles, to decrease apparent speed and so any speed up seen in blurry stimuli that have lost contrast must be overcoming this loss of speed due to reduced contrast. The effect of motion smear in increasing perceived speed is therefore independent of any effects of contrast and spatial frequency content.

Whatever its cause, the results reported here reveal a major distortion in speed perception under low illumination. The luminance range used here is comparable with the luminance range of natural scenes under day and night conditions. Our results indicate that we perceive the speed of the moving items at night as faster than their actual speed. This fact should be considered in theoretical and modeling studies that attempt to explain and simulate human motion and speed perception as well as in practical applications of nighttime driving safety.

Conclusion

When the luminance of a moving grating decreases, its perceived speed increases. This effect depends on the luminance of the moving gratings, and it is also modulated by the duration of motion. We attribute the change in perceived speed to the increase in the length of the motion smear at low luminance.

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