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Attentional modulation of threshold sensitivity to first-order motion and second-order motion patterns

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Abstract

Previous studies [e.g. Vision Research 40 (2000) 173] have shown that when observers are required to selectively attend to one of two, spatially-adjacent patches containing either first-order (luminance-defined) or second-order (contrast-defined) motion, threshold sensitivity for identifying the direction of second-order motion, but not first-order motion, is enhanced for the attended stimuli. The processing of second-order motion, unlike first-order motion, may, therefore, require attention. However, other studies have found little evidence for differential effects of attention on the processing of first-order and second-order motion [Investigative Ophthalmology and Visual Science 42(4) (2001) 5061]. We investigated the effects of attention instructions on the ability of observers to identify the directions and spatial orientations of luminance-defined and contrast-defined motion stimuli. Pairs of motion stimuli were presented simultaneously and threshold performance was measured over a wide range of drift temporal frequencies and stimulus durations. We found: (1) direction discrimination thresholds for attended motion stimuli were lower than those for unattended stimuli for both types of motion. The magnitude of this effect was reduced when the observers were not given prior knowledge of which patch of motion (attended or unattended) they had to judge first. (2) Direction discrimination for first-order motion was similarly affected at all temporal frequencies and durations examined, but for second-order motion the effects of attention depended critically on the drift temporal frequency and stimulus duration used. (3) Orientation discrimination showed little or no influence of attention instructions. Thus, whether or not attention influences the processing of second-order motion depends crucially on the precise stimulus parameters tested. Furthermore under appropriate conditions the processing of first-order motion is also influenced by attention, albeit to a lesser extent than second-order motion.

Keywords: Second-order motion; First-order motion; Attention; Direction discrimination

1. Introduction

Most objects in the visual world are defined by changes in luminance (brightness) over space. The motion of these objects is correlated with a change in luminance over time in the visual image. The motion of this type of stimulus is often termed 'first-order' motion (Cavanagh & Mather, 1989). It is also possible for objects or motion to be defined by visual characteristics other than luminance changes. For example motion can be defined by textural aspects of the visual scene, for example changes in the contrast or the size of pattern elements. These patterns are often termed 'second-order' (Cavanagh & Mather, 1989). This paper is concerned with one type of 'second-order' motion pattern, contrast-defined motion.

Observers are able to discriminate the direction of contrast-defined motion (e.g. Badcock & Derrington, 1985; Chubb & Sperling, 1988; Henning, Hertz, & Broadbent, 1975). The mechanism that underlies this ability is not yet firmly established. It is possible that both luminance-defined and contrast-defined motion are processed by the same mechanism (Johnson, McOwan, & Buxton, 1992). Most theories, however, propose that luminance- and contrast-defined motion are processed by separate (distinct) mechanisms. Typically, these models propose that luminance-defined motion is extracted from the visual image by an array of linear spatio-temporal filters similar to those proposed by

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Van Santen and Sperling (1984), Adelson and Bergen (1985) or Watson and Ahumada (1985). The pathway for contrast-defined motion must, however, also contain one or more additional non-linear stages. Typically the visual signal is passed through a first stage of spatial-frequency-selective filters, the output of these filters is rectified and then analyzed by direction selective motion sensors (e.g. Chubb & Sperling, 1989; Lu & Sperling, 1995; Wilson, Ferrera, & Yo, 1992; Zhou & Baker, 1993). Alternatively the motion of some contrast-defined patterns might also be extracted by a high-level mechanism that identifies and tracks explicit image features before the direction of motion is resolved (Seiffert & Cavanagh, 1999; Ukkonen & Derrington, 2000). In either hypothesis, contrast-defined and luminance-defined motion are processed by separate mechanisms. Thus, the mechanism that analyses contrast-defined motion is likely to have more processing stages than that used for luminance-defined motion.

If the extraction of contrast-defined motion requires additional processing compared with first-order motion, it is plausible that it is more susceptible to the effects of attentional manipulations, either because there are more stages to be affected or because motion direction is resolved at a later, or higher, stage. Consistent with this, the duration that observers require to find an inconsistent patch of contrast-defined motion increases as they need to check more patches of motion (Allen & Derrington, 2000; Ashida & Osaka, 1998). It is possible that this is because attention is required to discriminate the direction of contrast-defined motion, however, these studies of search for contrast-defined motion can only indirectly address the role of attention in motion perception.

More direct ways to address whether the mechanism that processes contrast-defined motion is affected by attention include increasing the attentional demands with a simultaneous distracter task. Performing a separate task, designed to distract the observer, has been found to have a detrimental effect on performance with contrast-defined motion (Ho, 1998), but the contrary result has also been reported (Allen & Derrington, 2001). Lu, Liu, and Dosher (2000) manipulated attention by instructing observers to attend to one of two, spatially-adjacent patches of moving contrast modulations. Observers subsequently reported the direction of motion in both patches. The direction of motion in the attended patch of contrast-defined motion could be discriminated at lower contrast modulation depths than the direction of motion in the unattended patch. With luminance-defined motion, however, observers could discriminate both attended and non-attended motion at the same pattern contrast (i.e. absolute sensitivity was little affected by attention instructions). They concluded that discriminating the direction of contrast-defined motion, but not luminance-defined motion, required attention. It is interesting to note, however, that in this study the observers always reported the direction of motion in the attended patch first. It is entirely possible that when asked to make two successive judgments of second-order motion direction, observers are simply more accurate at making the first judgment irrespective of the attention instructions given. The first aim of this study was to assess whether the attention effects found by Lu et al. (2000) were, in fact, confounded by the fixed temporal order in which the responses were made.

The second aim of the present study was to assess the interaction of attention with the mechanism for encoding contrast-defined motion over a range of drift temporal frequencies and durations. Several studies have suggested that the tuning of the mechanisms for encoding luminance-defined motion and contrast-defined motion are different, with sensitivity for contrast-defined motion greatly reduced at higher temporal frequencies (Derrington & Cox, 1998; Holliday & Anderson, 1994; Smith & Ledgeway, 1998 but see Lu & Sperling, 1995) or shorter durations (Derrington, Badcock, & Henning, 1993). Furthermore, Ledgeway and Hess (2002) have suggested that the mechanism for contrast-defined motion may be less direction selective than the mechanism for luminance-defined motion. This predicts that motion sensitivity will be reduced at low temporal frequencies and with brief durations, because under these conditions a great deal of directional ambiguity is introduced into the motion sequence (due to temporal smearing of the motion signal) which cannot be resolved by the second-order motion-detecting mechanism.

It is possible that attention plays a different role in motion discrimination when the motion mechanism has different sensitivities. When observers search for a patch of contrast-defined motion moving in the opposite direction from other patches (Ashida, Seiffert, & Osaka, 2001), their performance is much more dependant on the number of distracter patches at low temporal frequencies than at high temporal frequencies. This suggests that at low temporal frequencies, attention might play a greater role in contrast-defined motion perception. However, Ashida et al. (2001) only tested two temporal frequencies, this study aims to document the effect of attention over a larger range of temporal frequencies and durations.

2. Method

Methods were the same for all experiments, unless otherwise stated.

2.1. Observers

There were two observers, all had normal or corrected-to-normal vision and were experienced participants in psychophysical tasks.

2.2. Apparatus

The stimuli were presented on a *Nanao Flexscan 6600* monitor with a mean luminance of 27 cd/m2 and a frame refresh rate of 74.5 Hz. The screen was viewed binocularly at a distance of 62.9 cm in a dimly lit room. One pixel subtended 0.031° of visual angle. Prior to the experiment the relationship between the voltage input to the monitor and the luminance presented on the monitor was carefully measured and linearised using look-up-tables. For more accurate control of image luminance the three outputs of the computer's video card were summed using a video attenuator similar to that described in Pelli and Zhang (1991). This increased the number of available luminance levels from 2^8 to 2^{12}. The stimuli were generated on a PowerMac 7500/100 using Matlab, the Psychphysics Toolbox and the Videotoolbox (Brainard, 1997; Pelli, 1997).

2.3. Stimuli

Stimuli were drifting spatial modulations of either luminance or contrast presented above and below a central fixation point. The remainder of the screen was at mean luminance. There were two, spatially-separate, rectangular presentation windows, one above the fixation point and one below. Each window subtended 5°×4.4° with a center that was 6.9° from the central fixation point. Each window contained a 50% contrast, spatially 2-d, binary random noise carrier. Each noise element was square and composed of 4 pixels. The noise was dynamic and a new stochastic sample was used each time the stimulus was updated. See Fig. 1 for a diagram of the stimuli.

To make the luminance-defined stimuli a drifting, vertically-oriented, 0.5 c/° sinusoidal luminance modulation was added to the dynamic noise field. The luminance profile of this pattern can be summarized as

$$L_{(x,y,t)} = L_{\text{mean}}[1 + m\sin(2\pi fx + \phi + 0.5\pi t) + c_n R_{(x,y,t)}] \tag{1}$$

where $L_{(x,y,t)}$ is the luminance at each point in the stimulus, L_{mean} is the mean luminance, m is the luminance modulation depth or contrast of the sinusoidal waveform, f is the sinusoidal spatial frequency (0.5 c/°), ϕ is the initial spatial phase of the modulation (chosen at random on each presentation) and C_n is the contrast (0.5) of the noise carrier $R_{(x,y,t)}$ (chosen to be either −1 or +1 with equal probability).

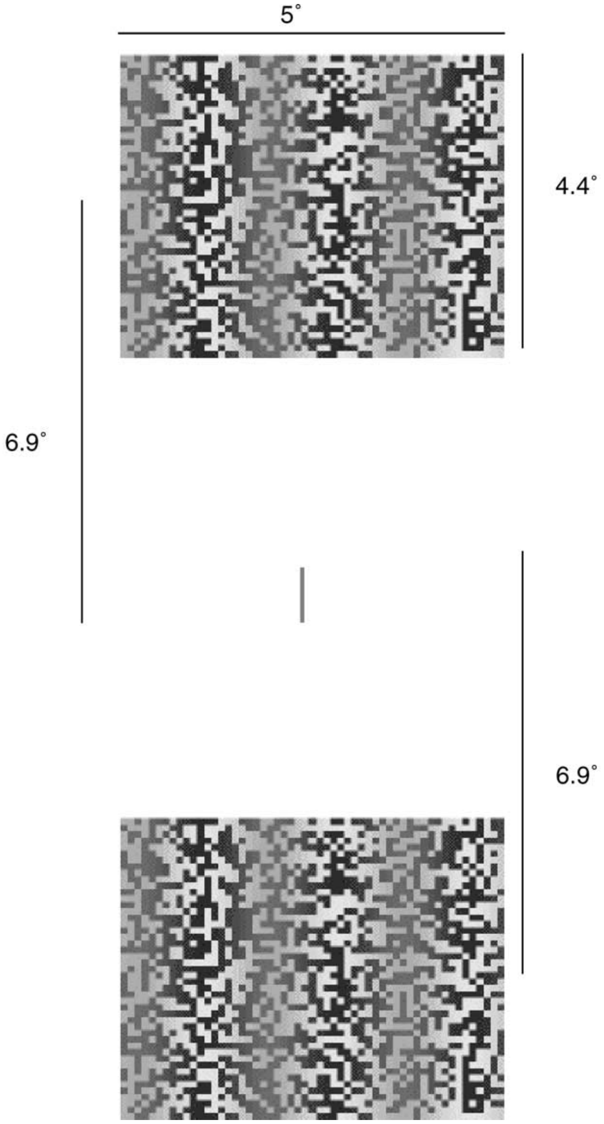

Fig. 1. Schematic diagram of the stimuli used in the experiments. In this example two patches of contrast-modulated noise are shown together with the pointer indicating which patch was to be attended. In the actual experiments the motion stimuli presented on each trial were either both second-order patterns (as in this example) or both first-order patterns (luminance-modulated noise). The direction of motion in each patch was independently randomized on every presentation and could be either leftwards or rightwards with equal probability.

For the contrast-defined motion stimuli the dynamic noise pattern was multiplied with a drifting, vertically-oriented, 0.5 c/° sinusoidal waveform. The luminance profile of this pattern can be summarized as

$$L_{(x,y,t)} = L_{\text{mean}}[1 + \langle\{1 + m\sin(2\pi fx + \phi + 0.5\pi t)\}c_n R_{(x,y,t)}\rangle] \tag{2}$$

where $L_{(x,y,t)}$, L_{mean}, m, f, ϕ, C_n and $R_{(x,y,t)}$ refer to the same parameters as Eq. (1).

To make the stimuli move the modulations were shifted by 90° (0.5π radians) between successive updates of the image, so each cycle consisted of 4 frames. When the stimuli were presented, however, we always presented an additional final frame where the modulation was in the same position as the first frame, thus when one cycle of motion was shown, we presented 5 frames. This was to remove any additional cues to motion direction from the change in position of the modulation.

2.4. Procedure

Observers judged the direction of motion (chosen randomly to be either leftwards or rightwards on each trial) in one or both of the presentation windows in a Two-Alternative-Forced-Choice (2AFC) design. The modulation depth or contrast of the moving patterns was varied using the method of constant stimuli such that performance varied from chance to perfect. In any run there were five levels of modulation depth or contrast.

On each trial stimuli were presented above and below the fixation point. The observer was cued to attend to either the upper or lower stimulus by a dark pointer that appeared in the center of the screen. The pointer was presented for 107 ms before the stimuli and for the full duration that the stimuli were presented. After the stimuli disappeared the observer was cued to respond. A second, lighter gray pointer indicated which of the two stimuli was to be responded to. In experiment 1 the response order was either randomized on each trial (the light gray pointer cued the observer to report the direction of the attended stimulus followed by the unattended stimulus or vice versa, with equal probability) or fixed (the observer was required to report the direction of the attended stimulus first and then the unattended stimulus second). In subsequent experiments, observers always indicated the direction of the attended stimulus followed by the unattended stimulus second. The observer indicated with a key press whether the modulation in the relevant stimuli moved to the left or the right. The pointer then pointed to the other patch and the observer indicated the direction of motion in that patch. Observers indicated that they were ready to move on to the next trial with a further key press. Each stimulus was presented at least 100 times. The order of presentation was randomized such that no stimulus at one visibility (modulation depth) could be shown $n+1$ times until all the other stimuli had been shown n times.

Psychometric functions were plotted comparing the percentage of correct direction judgments at each of the modulation depths or contrasts used. Separate psychometric functions were generated for the data obtained with the attended and unattended motion stimuli. Both were fitted with a Weibull (1951) function by a constrained maximum likelihood fit. Threshold performance was defined as the modulation depth or contrast required for 75% correct performance. To estimate error bars for this threshold, a boot-strapping technique was used. 10 000 bootstrapped replications were made of each fitted function and an estimate of threshold was made from each of these. The distribution of these thresholds was used to generate 95% confidence intervals for the threshold estimate. This method of error estimation reflects the error in threshold estimation from, for example, the fitting procedure, without assuming a Gaussian distribution for the raw data or the error distribution (Wichmann & Hill, 2001a, 2001b).

3. Results

These experiments measured the contrast, or modulation depth, required to discriminate the direction of luminance-defined or contrast-defined motion. Observers were instructed to attend to one of two patches of motion on the screen (both were either luminance-defined or contrast-defined) and then subsequently reported the perceived direction of motion in both the attended and unattended patches.

3.1. Experiment 1: response order

In one condition, observers always reported the direction of the attended motion first, followed by the unattended motion. In the other condition, the reporting order was randomized on each trial. Motion discrimination thresholds for both conditions are shown in Fig. 2a (observer HAA) and b (observer TL).

When the order of responses is not randomized (dark bars), we replicate the previous finding (Lu et al., 2000) of a difference in thresholds for attended and unattended contrast-defined motion. At both temporal frequencies, for both observers, the threshold for the unattended contrast-defined motion is much higher than the threshold for the attended motion. Indeed for one observer (TL) it was not possible to measure a reliable threshold for the unattended motion stimulus at the higher drift temporal frequency, because performance never reached the 75% correct performance criterion even at maximum contrast modulation depth. Unlike the previous study, however, we also find a similar difference between attended and unattended luminance-defined motion.

When the order of responses is randomized (light bars), for contrast-defined motion at 8 Hz the increased sensitivity for the attended stimuli disappears. For contrast-defined motion at 19 Hz the observers also had lower thresholds for the attended motion stimulus, although this is difficult to quantify due to the immeasurable thresholds in the non-random condition. For luminance-defined motion the difference in sensitivity between the attended and unattended stimuli is slightly reduced in one observer (compared to when the response order is not randomized) but there is still a significant difference between the thresholds.

It is possible that some of the difference in sensitivity for attended and unattended contrast-defined motion

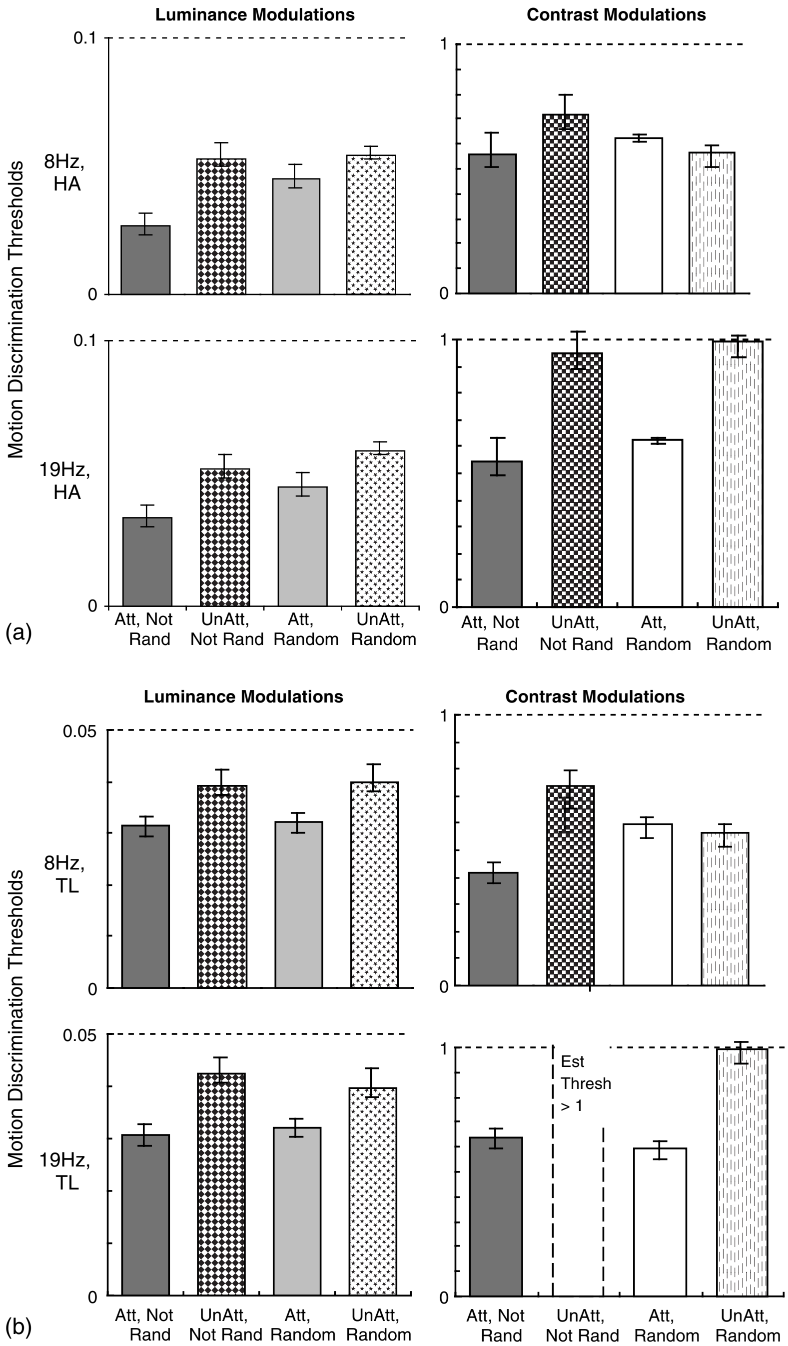

Fig. 2. Effect of randomizing the temporal order of two successive direction of motion judgments in an attention task involving the simultaneous presentation of two, vertically-separated, motion stimuli. Thresholds for discriminating the direction of motion (leftwards or rightwards) are shown in terms of contrast for luminance-defined motion and modulation depth for contrast-defined motion. Results are shown for luminance-defined motion (left) and contrast-defined motion (right), at 8 Hz (top) and 19 Hz (bottom). When the responses to the attended and unattended stimulus were not randomized, the observer always reported the direction of the attended stimulus first. Observer HAA (a), TL (b). The bars above and below each column represent the estimated 95% confidence limits for the thresholds.

stimuli found by Lu et al. (2000) was due to the fixed response order used. One possible explanation for this is, if the first reported stimulus is always the attended stimulus then this stimulus needs to be remembered for less time and accordingly gives slightly better performance. Memory may still play a role in the random order response condition. The attended stimulus might be more likely to be remembered well enough for a correct response in either response order. It is clear, however, that thresholds for the unattended stimuli are higher in some cases even when the response order is random. It also seems that changing the temporal

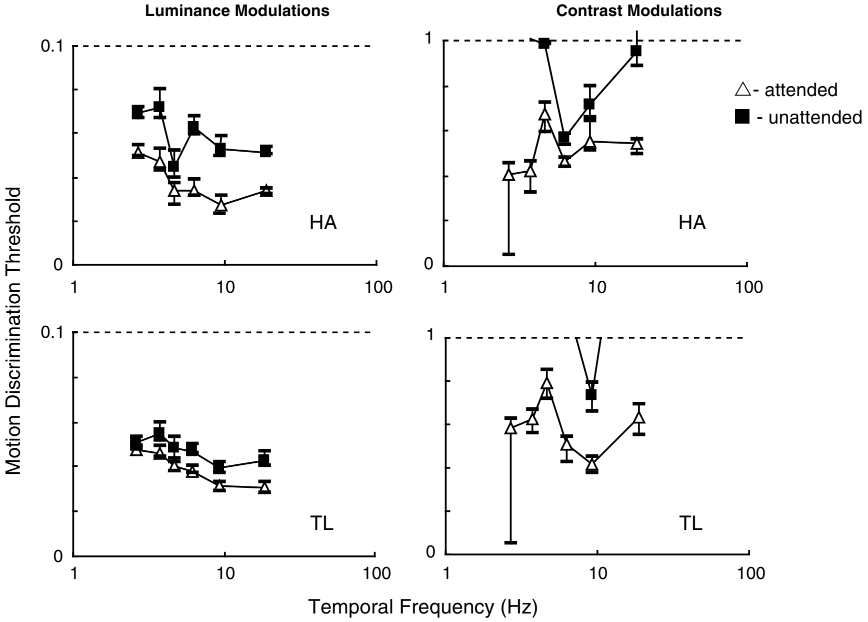

Fig. 3. Motion discrimination thresholds for attended and unattended motion stimuli as function of the stimulus temporal frequency, for two observers. The plot shows the contrast required to correctly discriminate the direction of luminance-defined motion (left) and the modulation depth required to discriminate contrast-defined motion (right). Thresholds for unattended motion are shown by solid symbols. Open symbols show performance with the attended stimuli. For some contrast-defined motion conditions the estimated threshold was greater than 1—these were considered unreliable and are not plotted. The bars above and below each data point (where visible) represent the estimated 95% confidence limits for the thresholds.

frequency changes the magnitude of the difference in thresholds between attended and unattended stimuli, but only for contrast-defined motion. The next experiment was designed to investigate this explicitly.

3.2. Experiment 2: temporal frequency and duration

We tested the contrast, or modulation depth, required to discriminate the direction of motion in attended and unattended luminance-defined or contrast-defined motion at a range of different drift temporal frequencies. The motion stimuli always moved though one cycle (5 frames).

Fig. 3 shows that as before, the motion discrimination thresholds for the attended (open symbols) stimuli are lower than the thresholds for the unattended stimuli (solid symbols), for both observers. For luminance-defined motion, for all but one point, there is an approximately constant but significant difference between the thresholds for attended and unattended stimuli. For contrast-defined motion the difference between the two thresholds seems to depend critically on the temporal frequency. Once again for both observers it was not always possible to measure a reliable threshold for the unattended contrast-defined motion stimuli because performance failed to reach the 75% threshold level even when the modulation depth was unity. These data points would have (unrealizable) threshold values greater than 1 and, for illustrative purposes only, are indicated in the figure by the plotted lines that extend beyond the x-axes upper limit.

3.3. Experiment 3: duration

Fig. 4 shows thresholds for attended and unattended motion at 6.2 Hz as a function of stimulus duration (increasing number of temporal cycles) for the two observers. The thresholds for the unattended stimuli (solid symbols) are higher than the thresholds for the attended stimuli (open symbols). This is true for luminance-defined motion (left) and contrast-defined motion (right).

3.4. Experiment 4: spatial orientation discrimination task

We tested whether the differences found between performance with the attended and unattended stimuli were specific to motion processing mechanisms. Observers judged the spatial orientation (either horizontal or vertical) of moving stimuli at a range of durations and temporal frequencies. The direction of motion was always orthogonal to the spatial orientation and was randomized on each trial.

The contrast, or modulation depth, required to discriminate the orientation of luminance-defined or contrast-defined motion is approximately the same for attended and unattended stimuli (Fig. 5). There is more variation in the data of observer HAA (filled symbols) than TL (open symbols) but the differences between the

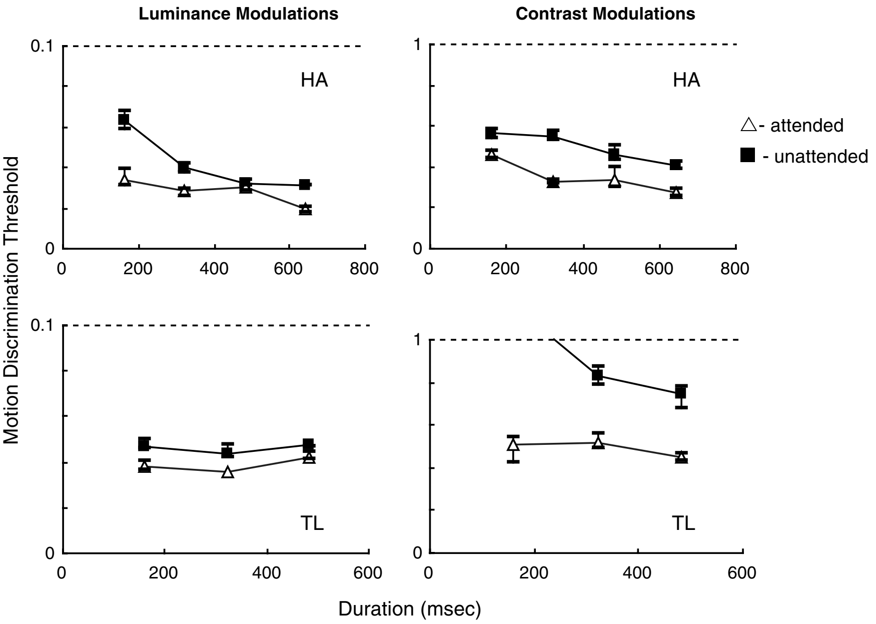

Fig. 4. Motion discrimination thresholds for attended and unattended motion stimuli as function of the stimulus duration, for two observers. The temporal frequency was 6.2 Hz. Data is shown for luminance-defined (left) and contrast-defined (right) motion stimuli. The contrast (or modulation depth) required to correctly discriminate the direction of unattended motion is shown by solid symbols. Open symbols show performance with the attended stimuli. The bars above and below each data point (where visible) represent the estimated 95% confidence limits for the thresholds.

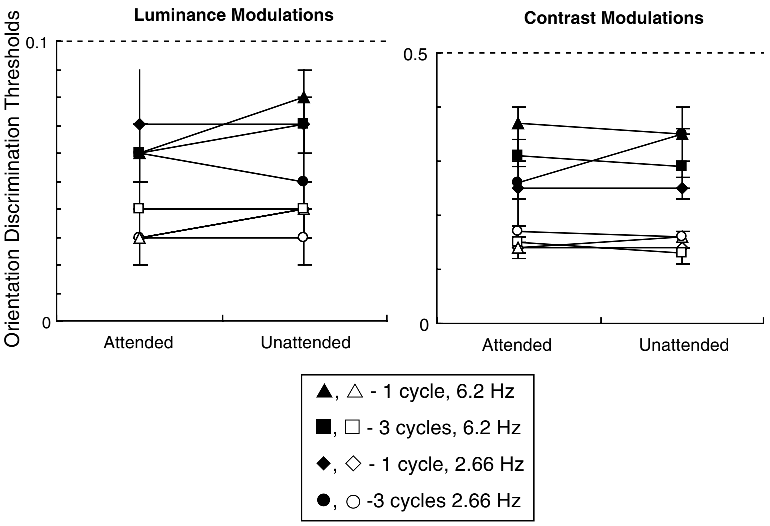

Fig. 5. Contrast (or modulation depth) to discriminate the orientation of a moving luminance-defined (left plot) or contrast-defined (right plot) attended or unattended moving pattern. Data for HAA is shown by filled symbols, data for TL is shown by open symbols. Thresholds were measured over a range different temporal frequencies and for different durations, as indicated by the different symbol shapes. The bars above and below each data point (where visible) represent the estimated 95% confidence limits for the thresholds.

thresholds for the attended and unattended stimuli are small and not significant.

4. Discussion

We investigated observers' ability to discriminate the direction of motion of attended and unattended luminance-defined motion and contrast-defined motion. Our key findings were

- Discrimination thresholds were lower for the attended motion than the unattended motion.
- For contrast-defined motion the magnitude of the difference between thresholds for unattended and attended stimuli depended critically on temporal frequency.

We find that the difference in motion discrimination thresholds found by Lu et al. (2000) is not entirely due to the order of observers' responses (experiment 1). The larger difference in thresholds between unattended and attended stimuli for contrast-defined moving patterns, compared with luminance-defined motion stimuli, was not due to differences in the efficacy with which the spatial structure (e.g. orientation) of the two varieties of moving patterns could be extracted (experiment 4). This latter control has previously been tested only with static versions of the moving stimuli (Ashida et al., 2001). Indeed our results suggest that attention instructions that have little, or no, effect on the ability to discriminate the orientation of moving stimuli, can have a considerable influence on thresholds for discriminating the direction of these same stimuli. This finding is important as it suggests that any effects of attention on threshold performance are largely specific to the processes that serve to encode the direction of motion.

Several previous studies have found results that are consistent with the idea that attention influences the mechanism that processes contrast-defined motion (Allen & Derrington, 2000; Ashida et al., 2001; Ho, 1998; Lu et al., 2000). Our data extend these findings to a greater range of temporal frequencies and durations. Like Ashida et al. (2001) we find that attention appears to have a greater effect on performance with contrast-defined motion at low temporal frequencies. Furthermore we find that there is also an increase in the effects of attention at higher temporal frequencies. It can be noted that in our experiments attention was manipulated by instructions but not motivated by external (e.g. financial) reward. This might tend to minimize the effect of attention and we expect that had we incorporated external rewards the effects of attention might have been larger, but it is likely that the same pattern of results would have been found.

We also find that thresholds for luminance-defined motion are different for the unattended and attended stimuli. Processing of luminance-defined motion is likely to begin in V1 and continue later in MT/V5 (e.g. Smith, Greenlee, Singh, Kraemer, & Hennig, 1998; Zeki et al., 1991). It is thus unsurprising that attention should modulate performance with this stimulus since is known that attention modulates the neural activity in V1 (Gandhi, Heeger, & Boynton, 1999; Somers, Dale, Seiffert, & Tootell, 1999; Watanabe, Sasaki, et al., 1998) as well as in Macaque and human MT/V5 (e.g. O'Craven, Rosen, Kwong, Treisman, & Savoy, 1997; Treue & Martinez Trujillo, 1999). Previous studies comparing luminance-defined and contrast-defined motion have suggested that attention does not affect performance with luminance-defined motion. When luminance-defined motion is presented at many multiples of threshold, and is therefore readily visible, it seems not be influenced by attention (Allen & Derrington, 2000; Ashida et al., 2001; Horowitz & Treisman, 1994). This may, however, reflect a performance ceiling: performance is already at such a level that minor fluctuations are not readily apparent. Ashida et al. (2001) tested search performance with luminance-defined motion at low visibility and with a binary noise mask. Under these conditions, search performance was consistent with some role of attention. This does not, however, explain why Lu et al. (2000) found no difference between thresholds for attended and unattended motion, unlike the present study as in both cases the motion stimuli were presented in conjunction with a superimposed binary noise mask (c.f. carrier) and at threshold stimulus levels. One final explanation for the difference in results between the studies rests on the numbers of trials used. In this study, observers performed hundreds of trials, whereas in the study of Lu et al. observers performed thousands of trials (Lu, personal communication). Zanker (1999) showed that performance with both luminance modulations and two forms of second-order motion improves with practice. Over the first 20 or so sessions performance changes were similar for first-order and second-order motion stimuli. Over a longer training period of 3 or 4 months, differences emerged. Performance improvements (learning) for second-order moving patterns were slower and stronger. The differences between the data of Lu et al. and the present paper may reflect different stages on the perceptual learning curve. As sensitivity improves with practice, the magnitude of attention effects reduces. This is consistent with our conclusion (see below) that the mechanisms for luminance-defined and contrast-defined motion are different but both affected by attention.

Manipulating attention seems to have more of an effect on observers' performance with contrast-defined motion than their performance with luminance-defined motion. That attention has some effect on performance with contrast-defined motion is also consistent with previous imaging studies. The areas involved in the processing of contrast-defined motion may include many of those involved in processing luminance-defined motion, such as V1 and MT/V5 as well as areas such as V3 (Dupont, Sary, Peuskens, & Orban, 2003; Seiffert, Somers, Dale, & Tootell, 2003; Smith et al., 1998). It is still a subject of debate as to exactly what role each of these areas plays, however the activation of each of these areas can be changed with attentional manipulations. There are, however, some previous findings that appear inconsistent with our findings. Distracter tasks, assumed to limit the amount of attentional resources available, have been found to have only a small, or no, effect on performance with contrast-defined motion (Allen & Derrington, 2001; Ho, 1998). It is possible that performing a distracter task and being instructed to attend explicitly to motion act in different ways. It is also interesting to note that both these studies presented the motion stimuli for relatively long durations. In Allen and Derrington (2001), duration was the manipulated variable and Ho (1998) presented stimuli for approximately 2 s.

Ledgeway and Hess (2002) have proposed that the mechanism that processes contrast-defined motion may have broader direction tuning (and hence poorer direction selectivity) than the mechanism that processes luminance-defined motion. This predicts that performance with contrast-defined motion will deteriorate at short durations and improve at higher temporal frequencies. It is possible that attention can affect mechanisms for both luminance- and contrast-defined motion but the effects are only exhibited in performance when sensitivity is low and/or the task difficulty increases. This predicts that manipulating attention will affect performance most when the temporal frequency of contrast-defined motion is low, which we find. This also predicts that manipulating attention will have less effect on contrast-defined motion when durations are long. This is suggested by our data (Fig. 5) and also by comparison with other research. Furthermore this could explain the increase in the effect of attention found at high temporal frequencies. As temporal frequency increased, duration decreased (since we presented one cycle of the stimulus). A mechanism with broad direction tuning will also have low sensitivity at short durations (brief presentations introduce spurious motion energy in the opposite direction giving rise to directional ambiguity), predicting a greater effect of attention—as we found.

Under several stimulus conditions (e.g. high temporal frequency), attending to motion seems to affect observers' performance with contrast-defined motion more than their performance with luminance-defined motion. Attention has been proposed to modulate the gain of neurons in visual motion areas of the Macaque (Treue & Martinez Trujillo, 1999). A greater effect of attention for contrast-defined motion may reflect that the mechanisms that process these stimuli are susceptible to greater modulations in gain than the mechanisms for luminance-defined motion, but the exact way that attention interacts with motion processing mechanisms remains unclear. What is clear, however, is that attention does not interact in the same way with the mechanism that processes contrast-defined motion as it does with the mechanism that processes luminance-defined motion, although in both cases the magnitude of attentional effects may be modulated by sensitivity. The magnitude of the effect of attention on performance with contrast-defined motion depends strongly on temporal frequency. This in itself lends further support to models of motion processing which postulate that, at least initially, first-order motion and second-order motion are encoded by distinct visual mechanisms.

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