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The influence of spatial and temporal noise on the detection of first-order and second-order orientation and motion direction

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Abstract

Thresholds for identifying the direction of second-order motion (contrast-modulated dynamic noise) are consistently higher than those for identifying spatial orientation, unlike first-order gratings for which the two thresholds are typically the same. Two explanations of this phenomenon have been proposed: either first-order and second-order patterns are encoded by separate mechanisms with different properties, or dynamic noise selectively impairs ("masks") sensitivity to second-order motion direction but not orientation. The former predicts the two thresholds should remain distinct for second-order patterns, irrespective of the temporal structure (static vs. dynamic) of the noise carrier. The latter predicts direction thresholds should be higher than orientation thresholds, for both second-order and first-order motion patterns, when dynamic (but not static) noise is present. To resolve this issue we measured direction and orientation thresholds for first-order (luminance) and second-order (contrast or polarity) modulations of static or dynamic noise. Results were decisive: The two thresholds were invariably the same for first-order stimuli but markedly different (direction thresholds ~50% higher) for second-order stimuli, regardless of the temporal properties (static or dynamic) and the overall contrast of the noise, or the drift temporal frequency of the envelope. This suggests that first-order and second-order motion are encoded separately and that the mechanisms encoding second-order stimuli cannot determine direction at the absolute threshold for spatial form.

Keywords: First-order motion; Second-order motion; Orientation; Direction; Visual noise

1. Introduction

Objects typically differ from their surroundings not only in terms of the intensity of light that they reflect (a "first-order" image characteristic), but also in terms of the textural properties (e.g. contrast, granularity) of their surface markings ("second-order" image characteristics). Whenever objects move the first-order and/or second-order attributes present in the retinal image also move and can give rise to vivid percepts of motion (Cavanagh & Mather, 1989). First-order motion processing has been studied extensively using luminance-defined, drifting, sinusoidal gratings, which have proved indispensable tools for probing the spatial and temporal properties of the visual mechanisms that respond to first-order motion. In a similar manner, the properties of the mechanisms that encode second-order motion have been studied using patterns that have only second-order motion but no consistent first-order motion. The most widely employed second-order motion stimulus of this type is one in which movement is defined exclusively in terms of image contrast. Typically the contrast of a field of spatially two-dimensional (2-d), random visual noise (the carrier) is modulated by a drifting sinusoidal waveform (the envelope), while the noise itself either remains static or is dynamic (uncorrelated over time) such that any luminance changes carry no net movement information (Chubb & Sperling, 1988).

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Although it has been shown by Johnston, McOwan, and Buxton (1992) that, in principle, first-order motion and second-order motion could be detected by the same (common) mechanism, studies that have compared the perception of luminance-defined gratings and contrast-defined gratings suggest that the two classes of motion may undergo separate processing. Indeed, a great deal of psychophysical, electrophysiological and neuropsychological evidence (e.g. Baker, 1999; Nishida, Ledgeway, & Edwards, 1997; Smith, 1994; Sperling & Lu, 1998; Vaina, Cowey, & Kennedy, 1999) favours the suggestion that second-order motion is encoded, at least initially, by distinct (separate) visual mechanisms to those used for encoding first-order motion (e.g. Wilson, Ferrera, & Yo, 1992).

One particular line of evidence regarding first-order and second-order motion processing that may pose problems for a unitary mechanism approach is that sensitivity to drift speed is quite different for first-order and second-order motion. Specifically, inferior temporal acuity is exhibited for second-order motion compared to that displayed for first-order motion and unlike first-order motion, the direction of second-order motion cannot be identified when the stimulus exposure is brief (Derrington, Badcock, & Henning, 1993; Ledgeway & Hess, 2002). Moreover, it is commonly accepted that, with the exception of very low drift rates, for first-order gratings, whenever the spatial structure (e.g. orientation) of the stimulus is visible, so is its drift direction (Watson, Thompson, Murphy, & Nachmias, 1980; Green, 1983). However, for second-order motion patterns (contrast-modulated noise), thresholds for identifying the direction of motion are consistently higher (performance is worse) than those for identifying spatial structure (Smith & Ledgeway, 1997, 1998). This provides evidence for a functional distinction between first-order (luminance-defined) and second-order (contrast-defined) motion processing.

1.1. First-order artifacts in second-order images?

For a second-order signal to be detectable, it must be presented in conjunction with a carrier, such as visual noise. Generally, noise carriers are generated by assigning individual screen pixels within a field of 2-d, binary random visual noise to be either "white" or "black" with equal probability. Although the use of a noise carrier (rather than a sinusoidal carrier) greatly reduces the risk of global distortion products (luminance artifacts) (Scott-Samuel & Georgeson, 1999), additional precautions must be taken against artifacts of a local nature. Even when the noise pixels are evenly distributed in the image as a whole (i.e. 50% "black" and 50% "white"), there will be local patches within it where the allotment of pixels is unequal and this imbalance may lead to a local luminance distortion resulting in a first-order motion signal (Smith & Ledgeway, 1997). First-order artifacts become a real problem when sensitivity to them is greater than sensitivity to the contrast modulation, the result being that detection may be erroneously based on first-order rather than second-order information. This will be reflected in a task that requires an observer to make a judgement regarding the spatial structure and the direction of movement of a motion pattern at threshold stimulus levels. If detection is mediated by a first-order mechanism, thresholds for the detection of spatial form (e.g. orientation) and the direction of motion will be comparable. However, if performance is markedly better for detecting spatial form than for discriminating the direction of motion, then it can be concluded with a high degree of certainty that detection was mediated by a "true" second-order mechanism (Ledgeway & Hess, 2002; Smith & Ledgeway, 1998).

Smith and Ledgeway (1997) measured thresholds for identifying the spatial structure (orientation) and drift direction of contrast-modulated static and contrast-modulated dynamic noise patterns and found that thresholds for identifying drift direction were consistently higher than those for identifying spatial structure for both types of stimuli. However, when they varied the size of the carrier pixels, they found that although pixel size had no effect on threshold separation for orientation and direction discrimination when a dynamic noise carrier was present, when a static noise carrier was used, thresholds converged when noise pixels were 'large' ($\geqslant\sim$4 arc min). This convergence was taken as evidence that first-order (luminance-based) motion artifacts may contaminate second-order stimuli under such conditions (see also Gurnsey, Fleet, & Potechin, 1998). These results led Smith and Ledgeway (1997) to conclude that the visual system includes a mechanism that is specialised for the detection of second-order motion and that this mechanism cannot specify the direction of motion at its absolute threshold. In addition, whilst it is possible that second-order form perception is based on a separate mechanism from that which detects second-order motion, this is unlikely since the two thresholds co-vary so closely as a function of drift temporal frequency (Smith & Ledgeway, 1998). Thus, it is more likely that they share a common basis. As such they concluded that like in the case of first-order information, second-order form and motion are based on a common initial filtering stage that feeds both processes, the only difference being that motion direction is extracted less efficiently.

Benton and Johnston (1997) modeled Smith and Ledgeway's (1997) findings by measuring the output of an (idealised) opponent motion-energy detector (Adelson & Bergen, 1985). They applied it to space-time images representing drifting contrast-modulations of static noise carriers and found little evidence for the existence of consistent first-order luminance artifacts. As such, Benton and Johnston (1997) speculated that the higher direction-identification thresholds (relative to those for orientation) observed when dynamic carriers were used (Smith & Ledgeway, 1997) was due to the fact that a far greater proportion of the energy present in the dynamic image carries "motion-direction" information than is present in static carriers. This increased motion-direction noise selectively elevates thresholds for direction discrimination but not for orientation identification. As such, the differences in performance could be due not to the operation of two separate systems but rather they may reflect an interaction between the nature of the tasks and the nature of the stimuli. However, Gurnsey et al. (1998) have also modeled the responses of motion-energy detectors to contrast-modulated images and have found evidence for the existence of detectable luminance artifacts as the size of the individual noise elements of the carrier increase (consistent with the proposals of Smith & Ledgeway, 1997).

The proposals of Benton and Johnston (1997) and Smith and Ledgeway (1997) make distinctly different predictions. If Benton and Johnston (1997) are correct, the presence of static noise and dynamic noise should have a differential effect on the two thresholds but this will be the same for both first-order and second-order motion. That is, orientation- and direction-identification thresholds should be similar (i.e. no threshold separation should be observed) for first-order and second-order motion when a static noise carrier is present. However, when a dynamic carrier is present, direction-identification thresholds for first-order *and* second-order motion should be higher (i.e. performance should be worse) than thresholds for identifying orientation. If Smith and Ledgeway (1997) are correct then thresholds for identifying orientation and direction should be similar for first-order motion patterns irrespective of the temporal properties of the noise carrier (whether it is static or dynamic). For second-order motion stimuli, however, thresholds for identifying drift direction should always be higher than those for identifying orientation, regardless of the carrier type (static or dynamic), unless second-order images are contaminated by a first-order artifact.

The aim of the present study was to test the above predictions using comparable first-order (luminance-defined) and second-order (either contrast-defined or polarity-defined) motion patterns that contained either static or dynamic noise carriers.

2. Method

2.1. Observers

Two observers, CVH (one of the authors) and JMM (a naïve subject), participated in the study. Both had normal or corrected-to-normal acuity and no history of any visual disorders.

2.2. Apparatus and stimuli

Stimuli were generated using *a Macintosh G4* computer and presented on a *Sony Trinitron Multiscan E530* monitor with an update rate of 75 Hz using custom software written in the C programming language. For precise control of luminance contrast the number of intensity levels available was increased from 8 to 12 bits by combining the outputs of the three digital-to-analog converters of the video card using a custom-built video attenuator (Pelli & Zhang, 1991). Images were presented in 'greyscale' on the colour monitor by amplifying the resulting 12-bit monochrome signal and sending this same signal to the red, green and blue guns of the display. The mean luminance of the display was 25.3 cd/m^2 and images were viewed binocularly in darkness at a distance of 139 cm. One screen pixel subtended 0.94 arc min of visual angle and the display area subtended 6° vertically and 6° horizontally.

To ensure that the second-order motion stimuli did not contain any gross luminance distortions, the monitor was carefully gamma-corrected using a photometer and look-up-tables (LUT). As an additional precaution, the adequacy of the gamma-correction was also checked psychophysically using a sensitive motion-nulling task (Gurnsey et al., 1998; Ledgeway & Smith, 1994; Lu & Sperling, 2001; Scott-Samuel & Georgeson, 1999).

Stimuli were 1 c/deg sinusoidal modulations of first-order (luminance) or second-order (contrast or polarity) motion and typically drifted at a temporal frequency of 1 Hz (except in Experiment 3 where envelope drift rate was systematically varied). In all cases, the total duration of a presentation interval was 853 ms and the modulation depth of the sinusoidal waveform was smoothed on and off by half a cycle of a raised cosine lasting 170 ms. In a similar manner the sinusoidal modulation was spatially windowed in the horizontal and vertical dimensions according to a half cycle of a raised cosine function with a half-period of 1.2°. This was done to minimise the presence of spatial and temporal transients. The motion stimuli used are shown schematically in Fig. 1a and b.

The first-order motion stimuli used were a conventional luminance-defined sinusoidal grating (LM), luminance-modulated static noise (LMSN) or luminance-modulated dynamic noise (LMDN). LMSN and LMDN were produced by adding a sinusoidal grating to a 1-bit, spatially 2-d, random noise carrier of 0.15 or 0.30 Michelson contrast. The noise carrier was generated by assigning individual (single) screen pixels (0.94 arc min, except in Experiment 2 where pixel size was systematically varied) to be either "white" or "black" with equal probability to ensure that there was no spatial variation in luminance within each noise element. In the case of LMDN, a new stochastic noise sample was used for each separate image in the motion

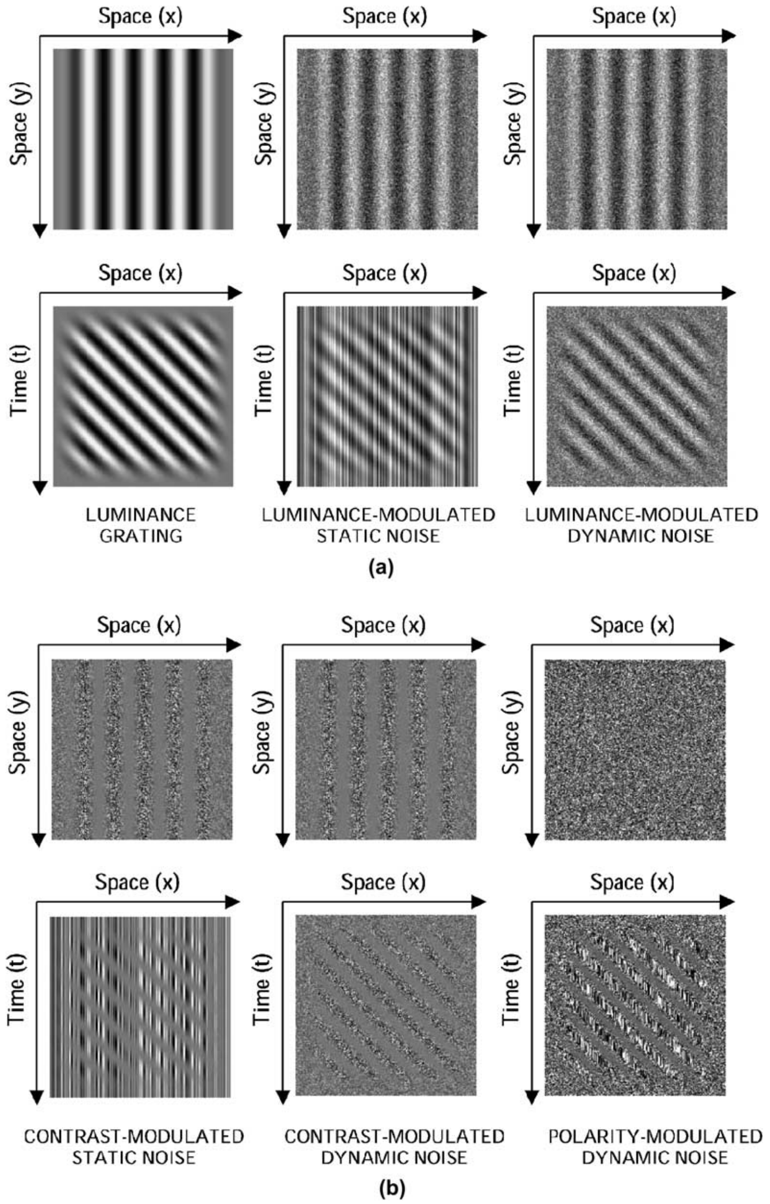

Fig. 1. Schematic examples of the motion patterns used in the study. Shown are space–space and space–time plots of: (a) first-order (LM, LMSN, LMDN) and (b) second-order (CMSN, CMDN, PMDN) motion stimuli (see text for details).

sequence. The amplitude (modulation depth) of the sinusoidal luminance modulation could be varied according to the following equation:

$$\text{Modulation depth} = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min}) \quad [\text{range } 0\text{–}1]$$

where $L_{\max}$ and $L_{\min}$ are the maximum and the minimum luminances in the image. When a noise carrier was present (i.e. in the case of LMSN and LMDN) these values corresponded to the maximum and the minimum mean luminances averaged over adjacent noise elements with opposite polarity in the image.

Second-order motion stimuli were composed of either contrast-modulated static noise (CMSN), contrast-modulated dynamic noise (CMDN) or polarity-modulated dynamic noise (PMDN). Contrast modulations were produced by multiplying, rather than adding, a drifting sinusoidal grating with the 2-d noise field. The amplitude (modulation depth) of the contrast modulation could be varied according to the following equation:

$$\text{Modulation depth} = (C_{\max} - C_{\min}) / (C_{\max} + C_{\min}) \quad [\text{range } 0\text{–}1]$$

where $C_{\max}$ and $C_{\min}$ are the maximum and the minimum local Michelson contrasts in the image computed over adjacent noise elements with opposite polarity.

For patterns defined by polarity, a sinusoidal modulation was created which determined the probability that individual pixel elements within the noise field would reverse their luminance polarity, i.e. the probability that a 'black' pixel would flip to 'white' or that a 'white' pixel would flip to 'black'. The probability of the polarity reversal (flicker) varied sinusoidally and the result was a travelling wave of flicker that produced a moving grating of smoothly drifting bars composed of flickering dots (Stoner & Albright, 1992). Such a stimulus can be described as second-order because the space–time averaged luminance of the pattern is constant across all parts of the pattern. The amplitude (modulation depth) of the PMDN motion patterns could be varied according to the following equation:

$$\text{Modulation depth} = (P_{\max} - P_{\min}) / (P_{\max} + P_{\min}) \quad [\text{range } 0\text{–}1]$$

where $P_{\max}$ and $P_{\min}$ are the maximum and the minimum probabilities of luminance polarity reversal occurring within the image.

2.3. Procedure

A single-interval, forced-choice procedure was employed. On each trial, observers were presented with a fixation cross, followed by the presentation of the motion stimulus. After the presentation of the stimulus, observers were cued to respond with two key presses, their tasks being to judge both the pattern's orientation (vertical or horizontal) and the direction of its motion (left, right, up or down). The direction of motion was always orthogonal to the pattern's orientation which was randomised on each trial.

The method of constant stimuli was employed in which seven modulation depth levels were presented, each ten times and the order of presentation was randomised. Each observer completed a minimum of four runs of trials for each condition and the order of testing was also randomised. Orientation- and direction-identification thresholds were derived separately by fitting Weibull functions to the data obtained from each run of trials. The mean modulation-depth threshold (corresponding to 75% correct) and the standard error of the mean were then calculated for each condition.

3. Results and discussion

3.1. Experiment 1: Thresholds for identifying the spatial orientation and drift direction of first-order and second-order motion patterns

In experiment 1, modulation-depth thresholds (the minimum modulation depth producing 75% correct performance) for identifying the spatial structure (orientation) and drift direction of first-order and second-order motion patterns were measured for two observers and at mean carrier contrasts (Michelson) of 0.15 and 0.3. First-order patterns were luminance-defined gratings (LM), luminance-modulated static noise (LMSN) and luminance-modulated dynamic noise (LMDN). Second-order patterns were contrast-modulated static noise (CMSN) and contrast-modulated dynamic noise (CMDN).

Fig. 2 shows modulation-depth thresholds for identifying the spatial orientation (filled columns) and the drift direction (unfilled columns) of luminance-modulated (first-order) motion patterns at noise carrier contrasts of 0.15 (Fig. 2a) and 0.3 (Fig. 2b). For both observers and at both carrier contrasts there was little variation (i.e. modulation-depth thresholds were extremely similar) regarding thresholds for identifying orientation or drift direction. Moreover, although the addition of a noise carrier (either static or dynamic) did result in slightly poorer performance overall (as found previously by Schofield & Georgeson, 2003; using stationary test patterns), importantly, thresholds for identifying orientation and direction were affected equally.

Fig. 3 shows modulation-depth thresholds for identifying the spatial orientation (filled columns) and the drift direction (unfilled columns) of contrast-modulated (second-order) motion patterns at carrier contrasts of 0.15 (Fig. 3a) and 0.3 (Fig. 3b). For both observers, performance for second-order motion patterns was much worse overall than performance for first-order motion patterns as reported previously (e.g. Smith, Hess, & Baker, 1994). Moreover, thresholds for identifying direction were always considerably higher (~50%) than those for identifying spatial orientation, regardless of carrier type (static or dynamic). This was true at both carrier contrasts tested (0.15 and 0.3).

Therefore the results of Experiment 1 clearly demonstrate that, irrespective of carrier type and carrier contrast, for first-order motion patterns, whenever the spatial structure of a stimulus was visible, so was its drift direction. For second-order motion patterns, that direction-identification thresholds were significantly higher than orientation-identification thresholds reflects the operation of a mechanism that is unable to detect motion at its absolute threshold. This relationship was also immune to the type (static or dynamic) and the contrast of the noise carrier.

3.2. Statistical analysis

To investigate whether or not the key observed differences in mean threshold performance shown in Figs. 2 and 3 were statistically significant, for each observer a separate two-way (9×2) analysis of variance (ANOVA) was performed on the data obtained for each run of trials. The factors were *stimulus type* (LM, LMSN,

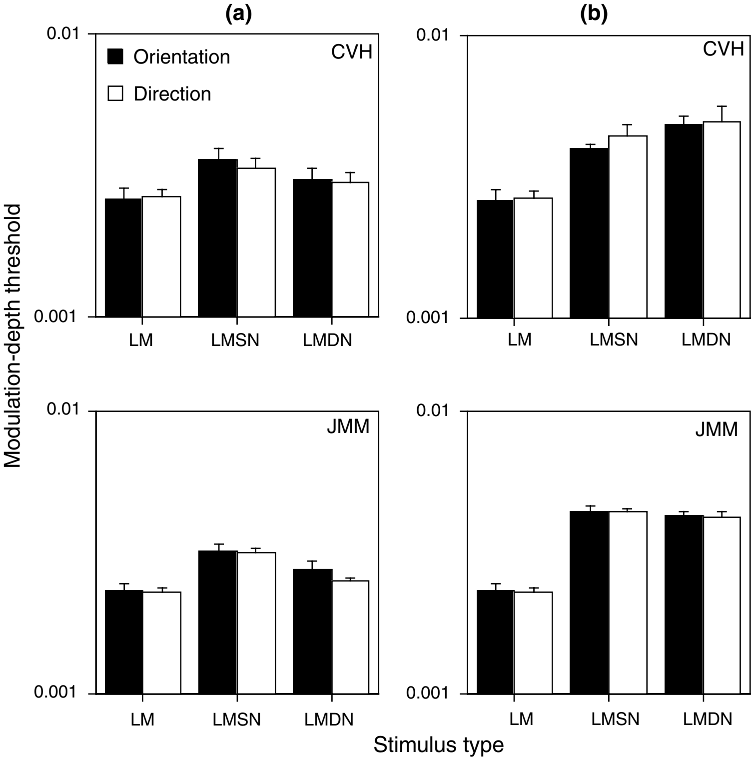

Fig. 2. Modulation-depth thresholds for two observers for identifying the spatial orientation (filled columns) and drift-direction (unfilled columns) of a luminance-defined grating (LM), luminance-modulated static noise (LMSN) and luminance-modulated dynamic noise (LMDN) at carrier contrasts of either 0.15 (a) or 0.3 (b). The spatial frequency and temporal frequency of the drifting luminance modulation was 1 c/deg and 1 Hz, respectively. Error bars above each column represent + 1 SEM.

LMDN, CMSN and CMDN for each of the two carrier contrasts tested, where applicable) and *identification task* (orientation and direction).

Statistical analyses revealed an identical pattern of findings for the two observers. There was a significant main effect of *stimulus type* [$F_{(8,27)} = 124.07$; $p < 0.0001$ for observer CVH and $F_{(8,36)} = 503.81$; $p < 0.0001$ for observer JMM]. Pairwise comparisons (Bonferroni corrected *t*-tests) revealed that thresholds for all first-order motion stimuli were significantly lower than those for the second-order motion stimuli at the 0.001 probability level. The main effect of *identification task* was also significant [$F_{(1,27)} = 85.88$; $p < 0.0001$ for CVH and $F_{(1,36)} = 118.11$; $p < 0.0001$ for JMM] indicating that orientation thresholds, when collapsed across stimulus type, were significantly lower than direction thresholds. Most importantly the interaction between *stimulus type* and *identification task* was significant [$F_{(8,27)} = 14.48$; $p < 0.0001$ for CVH and $F_{(8,36)} = 31.92$; $p < 0.0001$ for JMM]. Exploration of this interaction, using simple effects analysis, confirmed that thresholds for identifying spatial orientation were significantly lower than thresholds for identifying drift direction, but only when CMSN and CMDN patterns were used [at least $F_{(1,27)} = 32.12$; $p < 0.0001$ for CVH and $F_{(1,36)} = 11.66$; $p = 0.0016$ for JMM]. Thus, in summary, orientation-identification and direction-identification thresholds were the same for the first-order motion stimuli, irrespective of the presence or absence of a static or dynamic noise carrier. However, for second-order motion patterns direction-identification thresholds were always significantly higher than orientation-identification thresholds.

3.3. Experiment 2: The effect of carrier pixel size on thresholds for identifying the spatial orientation and drift direction of second-order motion patterns

The results of Experiment 1 clearly demonstrate that, when noise pixels are small (~0.9 arc min), the mechanism(s) by which contrast-modulated noise patterns are processed is unable to specify the direction of motion at its absolute (spatial) threshold. This was true of CMSN and CMDN patterns.

It has been argued however that static noise carriers can give rise to local first-order (luminance) artifacts in second-order patterns, especially when the noise pixels contained within the carrier are relatively large (Smith & Ledgeway, 1997). Nevertheless, if static noise is appropriately constructed (luminance cannot vary within each noise pixel), such artifacts are minimal. Therefore, in Experiment 2, the effect of carrier pixel size upon orien-

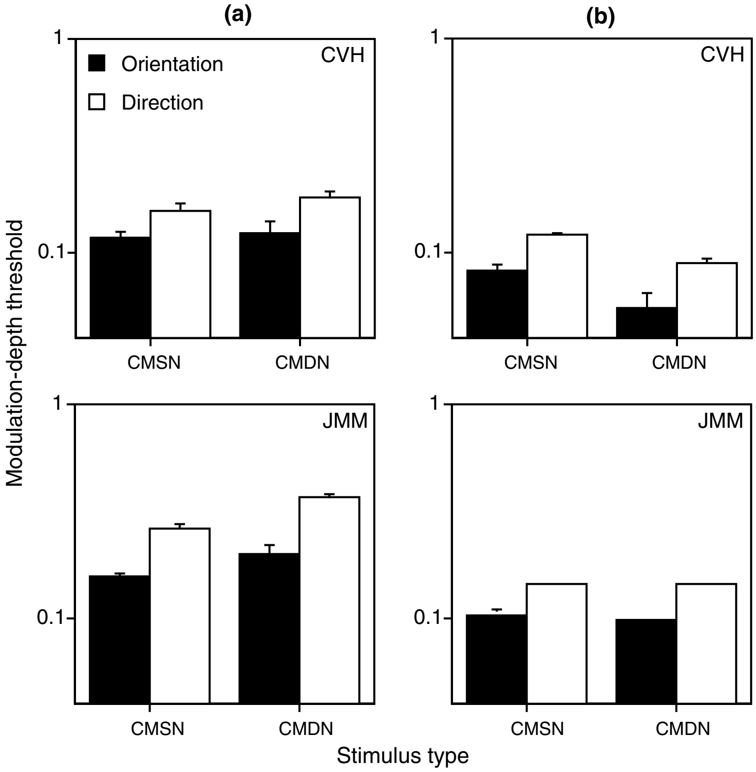

Fig. 3. Modulation-depth thresholds for two observers for identifying the spatial orientation (filled columns) and drift-direction (unfilled columns) of contrast-modulated static noise (CMSN) and contrast-modulated dynamic noise (CMDN) at carrier contrasts of either 0.15 (a) or 0.3 (b). The spatial frequency and temporal frequency of the drifting contrast modulation was 1 c/deg and 1 Hz, respectively. Error bars above each column represent +1 SEM.

tation- and direction-identification thresholds was measured for contrast-modulated static noise (CMSN) and contrast-modulated dynamic noise (CMDN) patterns. In addition, to demonstrate that the threshold separation observed for contrast-modulated noise patterns is indicative of a general mechanism sensitive to second-order motion (irrespective of how it is defined) rather than a mechanism that responds only to variations in image contrast, a polarity-modulated motion pattern (PMDN) was also included. Experiment 2 was identical to Experiment 1 except that the size of the carrier noise pixels was varied in equal logarithmic steps from 0.9 to 15 arc min.

Fig. 4a shows modulation-depth thresholds for both observers for identifying the spatial orientation (filled symbols) and drift direction (unfilled symbols) of contrast-modulated static noise patterns at each carrier noise pixel size. From Fig. 4a it is clear that for both observers, in general, thresholds for identifying direction were higher than those for identifying spatial orientation. However although there was a clear difference in performance for orientation and direction judgements when pixel size was small, thresholds appeared to exhibit a clear tendency to converge after the noise pixels exceed ~4 arc min in size. This coming together of thresholds was accompanied by a distinct improvement in the identification of direction. However, the two thresholds remained just separate even at the largest noise pixel size tested (15 arc min).

When testing was carried out using contrast-modulated static noise patterns under similar conditions as those used by Smith and Ledgeway (1997) (i.e. luminance was allowed to vary within each noise pixel), although threshold separation was evident at the smallest noise pixel sizes ($\leqslant$2 arc min), by ~4 arc min the two thresholds were identical (Fig. 4b). This pattern of results was true for both observers and is the same as that found in Smith and Ledgeway's (1997) original study.

Fig. 5a and b shows the pattern of results found for contrast-modulated and polarity-modulated dynamic noise patterns, respectively. In Fig. 5a the modulation-depth thresholds for identifying the spatial orientation (filled symbols) and drift direction (unfilled symbols) of contrast-modulated dynamic noise are plotted for both observers as a function of noise pixel size. It is readily apparent that threshold separation (higher thresholds for identifying direction than for identifying orientation) was evident at all carrier noise pixel sizes. In Fig. 5b, modulation-depth thresholds for identifying the spatial orientation (filled symbols) and drift direction (unfilled symbols) of polarity-modulated dynamic noise are plotted for both observers as a function of

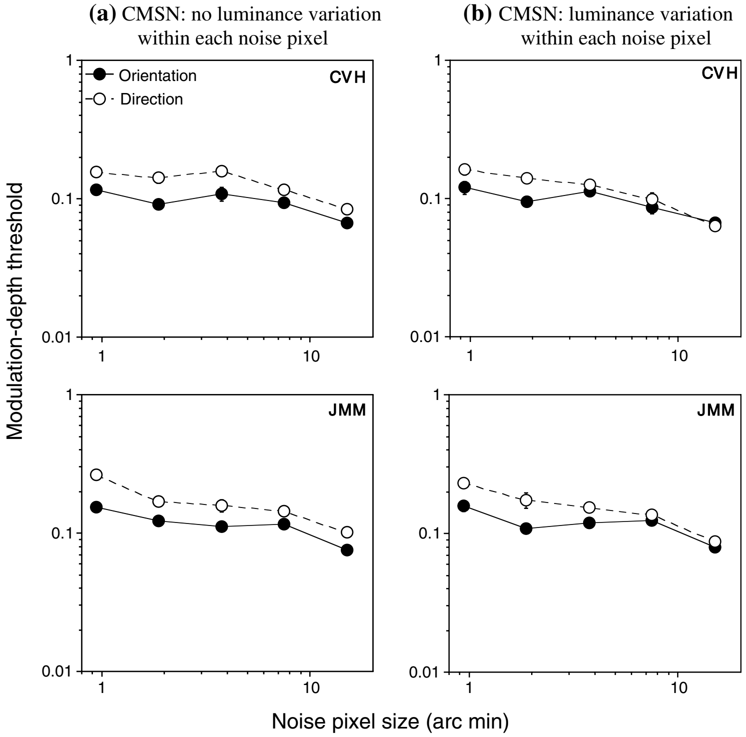

Fig. 4. Modulation-depth thresholds for two observers for identifying the spatial orientation (filled symbols) and drift-direction (unfilled symbols) of contrast-modulated static noise when (a) luminance could not vary within each noise pixel element and (b) under the same conditions as used by Smith and Ledgeway (1997) where luminance was allowed to vary within each pixel of the noise carrier. Testing was carried out over a range of carrier noise pixel sizes (0.94–15 arc min). The spatial frequency and temporal frequency of the drifting modulation was 1 c/deg and 1 Hz, respectively. The Michelson contrast of the 2-d noise carrier was 0.15. Error bars above and below each datum represent ±1 SEM.

carrier noise pixel size. Once more, threshold separation was clearly evident at all noise pixel sizes and for the two observers.

For both CMDN and PMDN patterns, increasing noise pixel size led to better performance for identifying both orientation and direction, except at a pixel size of ~15 arc min where performance actually declined. This worsening of performance was most likely due to the fact that at this pixel size, there was an increased risk of spatial under-sampling of the modulation signal within the image (4 noise pixels/spatial cycle). However, despite some differences in the level of performance, thresholds for orientation and direction co-varied closely at all carrier noise pixel sizes.

The results of Experiment 2 have demonstrated that, under the present testing conditions, performance was consistently worse for detecting drift direction than for identifying spatial structure (orientation) for all second-order stimulus types (CMSN, CMDN, PMDN) and at each carrier pixel size. However, two points should be noted: (1) In general, the degree of threshold separation observed for CMSN was typically not as large as that found for CMDN. (2) For CMSN, although thresholds were still marginally separate even at a pixel size of 15 arc min, the data did begin to converge by a pixel size of ⩾4 min. Hence, the findings of Experiment 2 suggest that if static noise carriers are appropriately constructed (i.e. luminance cannot vary within each noise pixel), then at least when noise pixels are small (<~4 arc min) performance will not be contaminated by first-order (luminance) artifacts. Threshold separation was clearly evident for both contrast-modulated and polarity-modulated dynamic noise patterns. This is good evidence that, rather than being a characteristic of a mechanism that is specialised only for encoding contrast, it may represent a general characteristic of the mechanisms that mediate second-order motion.

3.4. Experiment 3: Temporal sensitivity for first-order and second-order motion patterns

Temporal sensitivity functions (TSFs) for first-order motion have been measured previously (e.g. Watanabe, Mori, Nagata, & Hiwatashi, 1968; Kelly, 1979), and have produced bandpass tuning functions where sensitivity peaks at medium drift rates (~8 Hz). For second-order patterns, previous studies have produced lowpass temporal tuning functions for contrast-modulated stimuli, using flickering/pulsed stimuli (Derrington & Cox, 1998; Schofield & Georgeson, 2000). However, attempts to measure TSFs for second-order motion

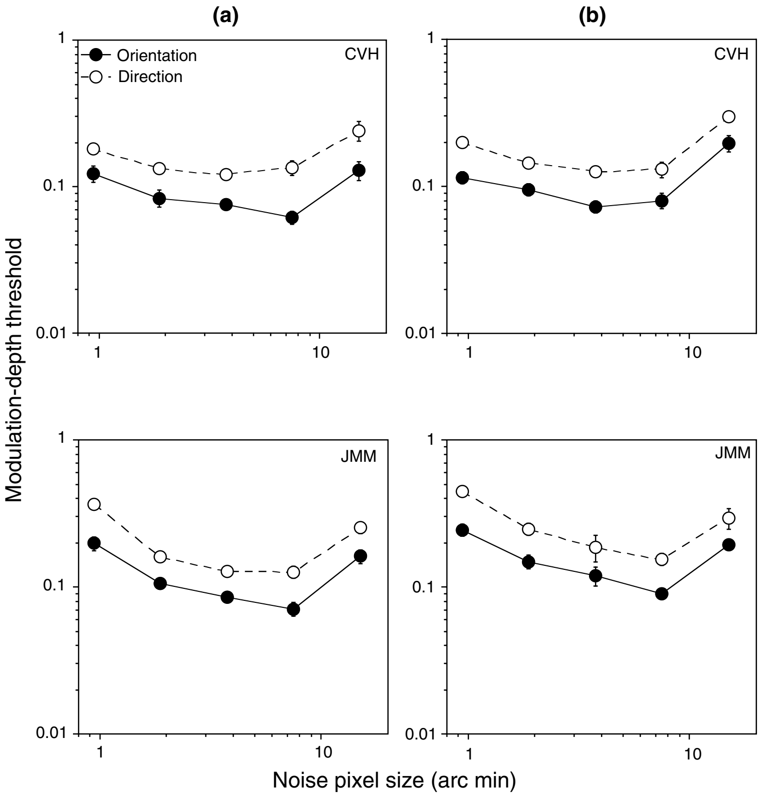

Fig. 5. Modulation-depth thresholds for two observers for identifying the spatial orientation (filled symbols) and drift-direction (unfilled symbols) of: (a) contrast-modulated dynamic noise (CMDN) and (b) polarity-modulated dynamic noise (PMDN) over a range of carrier noise pixel sizes (0.94–15 arc min). The spatial frequency and temporal frequency of the drifting modulation was 1 c/deg and 1 Hz, respectively. The Michelson contrast of the 2-d noise carrier was 0.15. Error bars above and below each datum represent ±1 SEM.

(e.g. Derrington, 1994; Holliday & Anderson, 1994; Lu & Sperling, 1995; Smith & Ledgeway, 1998; Lu & Sperling, 2001) have been somewhat equivocal in terms of their findings. The most relevant of these studies to the present work are those of Lu and Sperling (1995, 2001) and Smith and Ledgeway (1998), the findings of which will be briefly addressed in turn.

Using contrast-modulated static noise patterns, Lu and Sperling (1995) found that temporal acuity for second-order motion was comparable to that of first-order motion. However, Smith and Ledgeway (1998) proposed that Lu and Sperling (1995) had inadvertently measured sensitivity to local first-order motion artifacts rather than sensitivity to second-order motion per se. Smith and Ledgeway (1998) measured TSFs for contrast-modulated static and contrast-modulated dynamic noise patterns and found that whereas for CMSN, TSFs were bandpass and peaked at ~8 Hz (as found previously for first-order motion), for CMDN, TSFs were lowpass. In addition, whereas for CMDN patterns, thresholds for identifying direction were consistently higher than those for identifying orientation, for CMSN, thresholds for identifying orientation and direction were typically the same (when carrier noise pixels exceeded ~4 arc min). However, Lu and Sperling (2001) have shown that TSFs for identifying motion direction are bandpass for both luminance-modulated (first-order) and contrast-modulated (second-order) static noise and lowpass for luminance-modulated and contrast-modulated dynamic noise. As such, they proposed that the differences shown by Smith and Ledgeway (1998) were due to differences in the noise carrier (i.e. whether it was static or dynamic) and not due to the different types of motion (first-order or second-order).

In light of the current controversy surrounding the temporal sensitivity of second-order motion, we investigated the effect of noise carrier type (static versus dynamic) and contrast on TSFs for first-order (luminance-modulated) and second-order (contrast-modulated) motion patterns. Temporal sensitivity was measured under the same testing conditions as those employed in Experiment 1. That is using five stimulus types (LM, LMSN, LMDN, CMSN and CMDN) and two carrier contrasts (0.15 and 0.3). Testing was carried out over a five octave range of drift temporal frequencies (0.5–16 Hz) at an envelope spatial frequency of 1 c/deg. To aid comparison with previous studies such as Lu and Sperling (2001), modulation-depth thresholds are plotted as modulation sensitivity (the reciprocal of modulation depth at threshold).

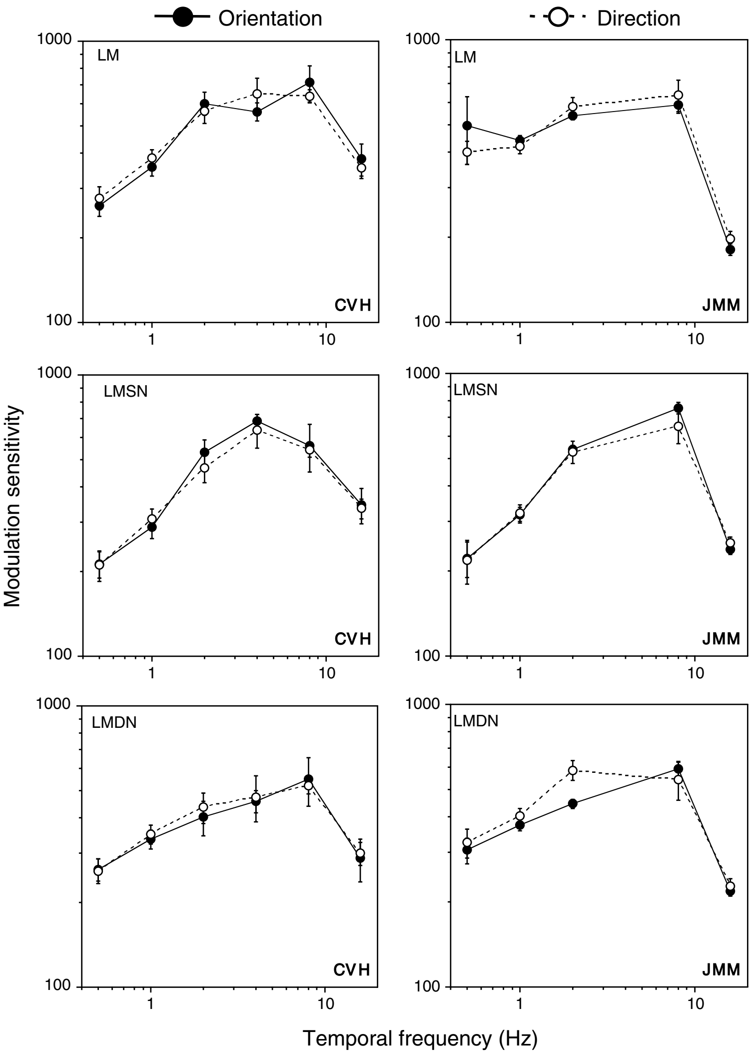

Fig. 6. Modulation sensitivity (reciprocal of modulation depth at threshold) plotted for two observers, CVH (left) and JMM (right), for identifying the spatial orientation (filled symbols) and drift-direction (unfilled symbols) of first-order motion patterns as a function of drift temporal frequency, at a carrier contrast of 0.15. First-order patterns were luminance-defined gratings (LM), luminance-modulated static noise (LMSN) and luminance-modulated dynamic noise (LMDN).

Fig. 6 shows the results for first-order motion patterns (LM, LMSN and LMDN) for both observers at a carrier contrast (when present) of 0.15. From Fig. 6 it is evident that orientation- and direction-identification thresholds were generally similar for all stimulus types across the range of temporal frequencies tested. At this carrier contrast, the temporal sensitivity profiles for all first-order motion patterns exhibited a bandpass function, peaking at ~8 Hz. Fig. 7 shows temporal sensitivity to first-order motion patterns (LM, LMSN and LMDN) for both observers at a higher carrier contrast of 0.3 (when present). At this carrier contrast, the data remained bandpass for all carrier types (LM, LMSN and LMDN) with sensitivity peaking once more at ~8 Hz. However, the addition of a noise carrier (static or dynamic) did lead to some differences in the data, especially at a higher carrier contrast (0.3). First, adding a static carrier to luminance gratings resulted in poorer overall performance for identifying both orientation and direction. Furthermore, the addition of a dynamic noise carrier led to a greater impairment in performance. In particular, the addition of a static noise carrier (LMSN) appeared to produce a masking effect at low frequencies, resulting in a steeper low frequency roll-off than the no noise (LM) or dynamic noise (LMDN) conditions. The dynamic noise condition (LMDN) appeared to mask more equally across all frequencies, especially when the noise contrast was high (0.3). In this instance, the TSFs for luminance-modulated dynamic noise (LMDN) were considerably flatter than those in the no noise (LM) and static noise (LMSN) conditions. These findings are in agreement with those found previously by Schofield and Georgeson (1999, 2003) for stationary first-order (luminance-defined) patterns.

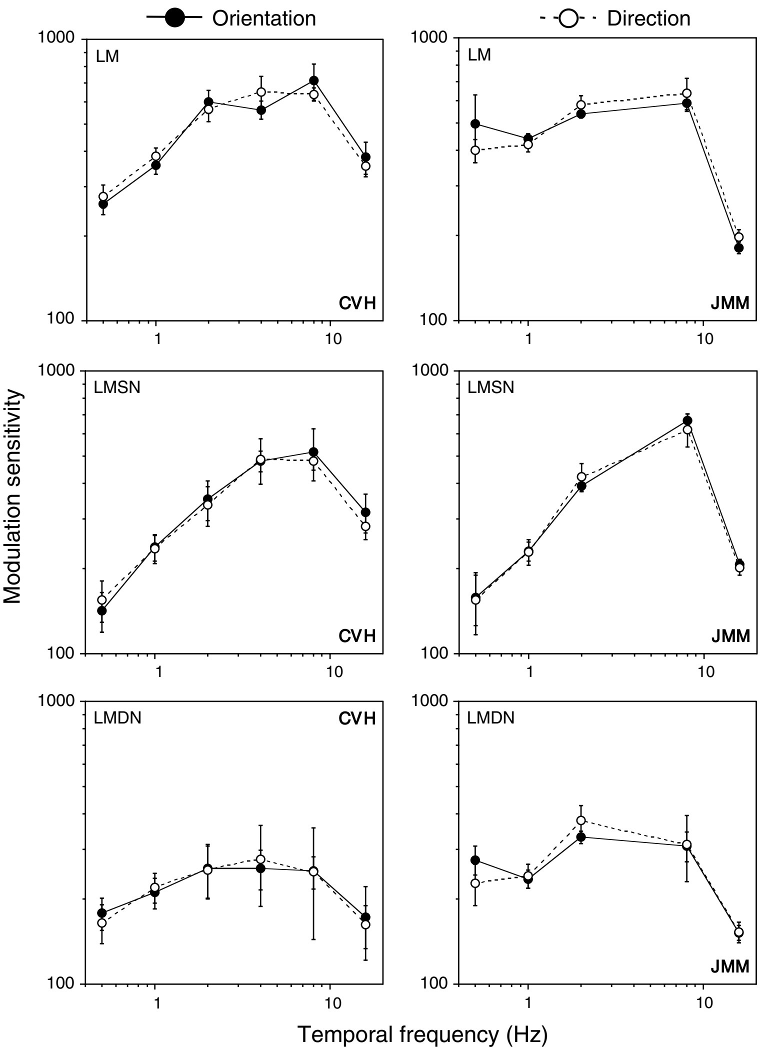

Fig. 7. Modulation sensitivity (reciprocal of modulation depth at threshold) plotted for two observers, CVH (left) and JMM (right), for identifying the spatial orientation (filled symbols) and drift-direction (unfilled symbols) of first-order motion patterns as a function of drift temporal frequency, at a carrier contrast of 0.3. For comparison purposes the data obtained with luminance-modulated gratings (LM) has been replotted from Fig. 6.

However, most importantly thresholds for identifying orientation and direction remained the same and the shapes of the temporal tuning functions remained generally bandpass in nature.

Fig. 8 shows the results for second-order motion patterns (CMSN & CMDN) for both observers at a mean carrier contrast of 0.15. In this instance, thresholds for identifying direction were consistently higher than those for identifying orientation for both types of second-order motion pattern. For contrast-modulated static noise (CMSN), the temporal sensitivity profile was slightly lowpass. However, for contrast-modulated dynamic noise (CMDN), the data were unmistakably lowpass in nature. Sensitivity to both stimulus orientation and stimulus direction remained relatively unchanged up until ~2 Hz, after which thresholds rose rapidly for both and were not measurable at temporal frequencies beyond ~6 Hz. Fig. 9 shows temporal sensitivity to second-order motion patterns (CMSN and CMDN) for both observers at a carrier contrast of 0.3. Once more, when the carrier was static the data exhibited a slight lowpass function. However, when a dynamic carrier was used, the data were again clearly lowpass in nature, with sensitivity to orientation and direction beginning to fall-off at frequencies greater than ~1 Hz. In this case, performance was not measurable beyond ~12 Hz. For contrast-modulated (second-order) motion patterns, although the overall shape of the tuning functions remained relatively unchanged, increasing carrier contrast did lead to better sensitivity overall. This is characterised both by slightly lower thresholds at each temporal frequency tested and by the higher temporal acuity limit found with a carrier contrast of 0.3.

The results of Experiment 3 have highlighted a number of pertinent issues. First, as demonstrated previously by Lu and Sperling (2001), the results presented

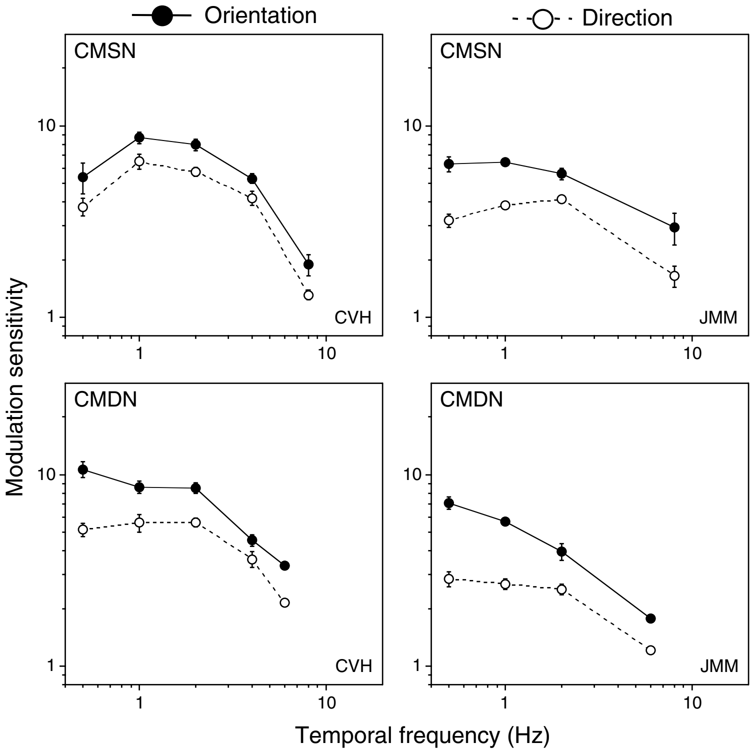

Fig. 8. Modulation sensitivity (reciprocal of modulation depth at threshold) plotted for two observers, CVH (left) and JMM (right), for identifying the spatial orientation (filled symbols) and drift-direction (unfilled symbols) of second-order motion patterns as a function of drift temporal frequency, at a carrier contrast of 0.15. Second-order patterns were contrast-modulated static noise (CMSN) and contrast-modulated dynamic noise (CMDN).

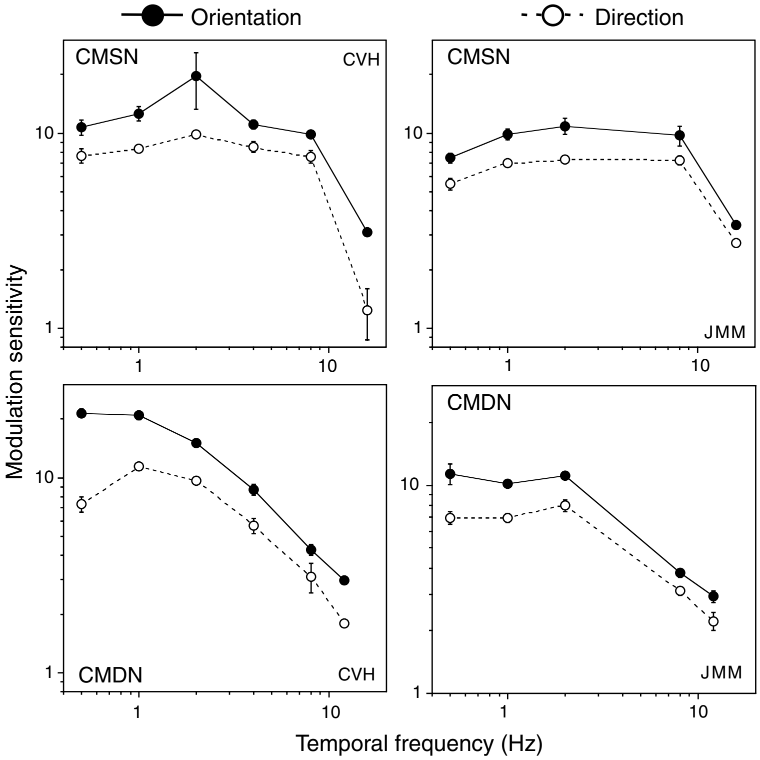

Fig. 9. Modulation sensitivity (reciprocal of modulation depth at threshold) plotted for two observers, CVH (left) and JMM (right), for identifying the spatial orientation (filled symbols) and drift-direction (unfilled symbols) of second-order motion patterns as a function of drift temporal frequency, at a carrier contrast of 0.3.

here show that the choice of carrier did affect the shape of TSFs for second-order motion. However, this was not the case for first-order motion patterns. Most importantly, thresholds for detecting orientation and direction were virtually identical for all types of first-order motion pattern (LM, LMSN, LMDN) whereas for second-order motion patterns (CMSN, CMDN), performance for detecting direction of motion was consistently worse than that for identifying orientation.

4. General discussion

This study has investigated the effects of the noise carrier upon thresholds for identifying the spatial orientation and drift direction of first-order and second-order motion patterns. In all conditions, for first-order patterns whenever the spatial structure of the stimulus was visible, so was the direction of drift. However, for second-order motion patterns, direction-identification thresholds were consistently higher than orientation-identification thresholds (when the noise carrier was dynamic or when static noise carrier pixels were small and there was no luminance variation within each noise element) and this is taken as evidence for the operation of a mechanism that is unable to detect motion at its absolute (spatial) threshold.

As far as temporal frequency sensitivity is concerned, static and dynamic noise carriers had differential effects on the shape of the resulting temporal sensitivity functions for second-order (but not for first-order) motion. However, for all carrier types and carrier contrasts, sensitivity to stimulus orientation and drift direction were virtually identical for first-order motion patterns and for second-order motion, performance for identifying orientation was consistently better than performance for identifying the drift direction.

These findings provide further evidence to support the separate detection of first-order and second-order motion in human vision. In agreement with other studies (e.g. Ledgeway & Hess, 2002), they have highlighted the fact that the mechanism(s) that extract motion from second-order images may have a number of different properties to those that encode first-order motion. That is, the results suggest that the motion sensors that encode second-order motion may have different response characteristics to those that encode first-order motion although most models either explicitly or implicitly assume that they are the same (e.g. Wilson et al., 1992). In addition, the present results have reinforced the findings of previous work (e.g. Lu & Sperling, 1995, 2001) that the choice of carrier (static or dynamic) may affect the shape of TSFs, at least for second-order motion patterns. But, most importantly, it is also clear that any functional differences, such as differences in performance for detecting orientation and motion direction, are consistent with the operation of two separate motion-detecting systems.

The results of this study may pose a number of potential problems for Benton and Johnston's (1997) speculative hypothesis concerning differences in performance between contrast-modulated static noise and dynamic noise, in Smith and Ledgeway's (1997) study. They suggested that it reflected an interaction (selective masking) between the nature of the threshold tasks used and the nature of the stimuli, rather than the operation of two distinct motion-detecting systems (i.e. a first-order motion system responding to local luminance artifacts and a second-order motion system sensitive to drifting contrast modulations). In particular they proposed that dynamic noise carriers might be expected to have a more detrimental influence on direction-identification thresholds than orientation-identification thresholds because they contain approximately twice as much motion direction noise as static noise carriers. This motion noise masking explanation, however, neglects a number of important issues. First, Benton and Johnston's (1997) proposal cannot account for the finding that thresholds for identifying the orientation and drift direction of contrast-modulated noise patterns can be very different even when static noise (albeit composed of relatively small noise elements) is used, as in the present study (see also Smith & Ledgeway, 1997, 1998). Furthermore, if the motion noise masking explanation is correct then direction-identification thresholds for first-order motion should also be higher than those for orientation when a dynamic (but not a static) noise carrier is employed. The results of the current study do not offer support for this prediction.

Benton and Johnston (1997) based many of their assertions on the fact that when they modeled the responses of motion-energy detectors to contrast-modulated static noise patterns, they found no evidence of luminance artifacts in the output of their implementation of the standard motion energy model (c.f. Adelson & Bergen, 1985). However, other studies (e.g. Gurnsey et al., 1998) that have modeled the responses of motion-energy detectors to contrast-modulated images containing static noise carriers have found some evidence for the existence of detectable luminance artifacts as the size of individual noise elements of the carrier is increased, in line with the proposals of Smith and Ledgeway (1997, 1998). The discrepancy between the modeling results of the two studies remains unclear. However, the results of the experiments described in the present study have shown empirically that, rather than being a characteristic of dynamic noise carriers, poorer performance for detecting the direction of motion than spatial structure (orientation) is indeed a defining characteristic of a system that is specialised for analysing second-order motion patterns.

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