Global motion processing in human color vision: A deficit for second-order stimuli

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The investigation of the mechanism of global motion in color vision has been limited because the processing of the first-order chromatic RDK elements, based on low-level linear motion detectors, is impaired. Here we return to this problem by using second-order elements in a global motion stimulus. Second-order RDK elements were circular contrast-modulated (CM) envelopes of a low-pass filtered noise carrier. The stimuli were achromatic or isolated L/M- or S-cone opponent mechanisms. We measured simultaneously detection and motion direction identification thresholds at 100% motion coherence and at different RDK speeds with a 2-AFC paradigm. We found that direction identification thresholds were higher than detection thresholds for both chromatic and achromatic stimuli. The gap between these thresholds was greater for the chromatic than the achromatic stimuli and motion direction thresholds for the chromatic RDK were very high or impossible to obtain. We also measured global motion performance (RDK speed of 4 deg/s) by varying the coherence of limited lifetime RDK stimuli. Global motion thresholds could only be obtained for achromatic stimuli and not for chromatic ones. Within the limits of the present stimulus conditions, we found no global motion processing of second-order chromatic stimuli.

Keywords: second-order, global motion, psychophysics, color vision, contrast modulation

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Introduction

Global motion processing involves the integration across space of the motion of local elements into a global motion percept. It is well established that local and global motion of achromatic stimuli are processed in different cortical areas, local motion being processed in areas V1 and V2 (Hubel & Wiesel, 1968) and global motion in the higher cortical area, middle temporal area MT (Newsome & Paré, 1988). Global motion has been studied extensively using random dot kinematograms (RDKs) because these stimuli require the visual system to make a global motion judgement based on the integration of the motion of many small local elements (RDKs) and are thought to activate area MT (e.g., Edwards & Badcock, 1996; Newsome & Paré, 1988; Simmers, Ledgeway, Hess, & McGraw, 2003). The contribution of color vision to global motion processing remains controversial, with studies arguing both for a chromatic contribution (Ruppertsberg, Wuerger, & Bertamini, 2003, 2006) and against (Bilodeau & Faubert, 1999; Michna & Mullen, 2008). Michna and Mullen (2008) investigated global motion using first-order RDK elements and demonstrated that coherence thresholds with isoluminant chromatic stimuli are degraded in the presence of increasing luminance noise contrast, even though the detection of the purely chromatic RDK elements was unaffected. They argued that the motion processing of isoluminant red–green RDKs is based on an intrinsic luminance response, whereas the detection of isoluminant RDKs is purely chromatic. This finding agrees with previous studies using a similar luminance noise masking approach, which have found extensive luminance noise masking of first-order isoluminant chromatic motion, indicating the absence of genuine chromatic mechanisms for first-order motion (Baker, Boulton, & Mullen, 1998; Mullen, Yoshizawa, & Baker, 2003; Yoshizawa, Mullen, & Baker, 2000). We note that some studies, nevertheless, have suggested the presence of genuine chromatic linear motion mechanisms for optimal stimulus parameters but for stimuli concentrated in the central part of vision (small stimulus field of 4°; Cropper, 2005; Cropper, Kvansakul, & Johnston, 2009).

Second-order stimuli are defined by second-order statistics, for example, contrast modulation or variation of a first-order luminance or chromatic carrier. Low-level linear motion detectors are not able to detect the presence of second-order stimuli and higher order motion mechanisms are needed for detection and motion processing. There is considerable neurophysiological and psychophysical evidence showing that first-order and second-order stimuli are processed by separable motion mechanisms (Baker, 1999; Chubb & Sperling, 1989; Edwards & Badcock, 1995; Lu & Sperling, 1995; Schofield & Georgeson, 2003;

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Smith & Ledgeway, 1997, 1998; Vaina, Makris, Kennedy, & Cowey, 1998). There is also evidence that color vision supports high-order motion mechanisms that are genuinely chromatic (Baker, Boulton, & Mullen, 1998; Cropper & Derrington, 1996; Cropper & Wuerger, 2005; Lu, Lesmes, & Sperling, 1999; Mullen et al., 2003; Yoshizawa et al., 2000; Yoshizawa, Mullen, & Baker, 2003) although, in general, very few studies have directly investigated the role of color vision in second-order stimulus processing.

The investigation of the mechanism of global motion in color vision has been limited because the processing of the first-order chromatic RDK elements, based on low-level linear motion detectors, is impaired. Here we return to this problem by using second-order elements in a global motion stimulus. As there is evidence that color vision can support motion based on second-order processing (Baker et al., 1998; Cropper & Derrington, 1996; Mullen et al., 2003; Yoshizawa et al., 2000, 2003), this should allow access to and assessment of a global motion processing mechanism. This suggests that using second-order elements within a chromatic RDK stimulus may reveal a contribution of color to global motion processing that is purely color based.

Methods

Material and observers

A 14 bit per channel ViSaGe (VSG) graphics card from Cambridge Research Systems (CRS) was used to generate all the stimuli and was controlled using MATLAB version 7.70 (Mathworks 2008b). Stimuli were displayed on a carefully calibrated CRT monitor (Sony Trinitron GDM-500PST). Gamma correction was performed using the VSG calibration routine with the OptiCal photometer (from CRS). Spectral emissions of the red, green, and blue phosphors were measured using a Spectrophotometer SpectraScan PR-645. Look-up tables were created and used for the generation of the cone contrast space. The monitor was set to a spatial resolution of 1024×768 pixels and to a temporal refresh rate of 120 Hz. The white point of the monitor was set to half of its maximum luminance output and its luminance was 50 cd/m^2 (CIE chromaticity coordinates: $x = 0.284$ and $y = 0.286$).

Four observers, two naive (DK and NN) and two authors (KTM and LG), participated in the study. All have normal or corrected-to-normal acuity and normal color vision assessed with the Farnsworth-Munsell 100-hue test. Subjects were seated 82 cm from the screen in a darkened room, viewed the stimuli binocularly, and recorded their response after each trial using a response box (CB6 Response Box from CRS). Positive feedback was given when appropriate.

Stimuli

The stimuli, illustrated in Figure 1, were designed to activate second-order global motion mechanisms. They were composed of second-order RDK elements that were contrast-modulated (CM) envelopes of a static noise carrier. Elements had circular envelopes of 1.6° diameter with the edges smoothed using half a cycle of a raised cosine function with a period of 0.8° and a flat top of 1°. The noise carrier (presented in a circular window of 12° diameter) was flat spectrum (white) noise spatially low-pass filtered using a Butterworth digital filter. The filter had a cut-off frequency of 2 cycles/degree and reduced amplitude by 40 dB at 4 cycles/degree. The noise carrier was set to a fixed, clearly visible contrast (see Procedure section for details on the methods of threshold scaling). A low-pass filtered noise carrier was used in order to reduce or eliminate the presence of chromatic aberrations at high spatial frequencies, which may induce luminance artifacts (Flitcroft, 1989). In addition, a low-pass noise carrier has better visibility than flat noise because its spatial frequency spectrum is better matched to the low-pass contrast sensitivity function of human color vision (Mullen, 1985). The use of low-pass filtered noise carriers (large pixel size noise), however, may produce first-order (luminance) artifacts in second-order moving stimuli (Ledgeway & Hutchinson, 2005; Smith & Ledgeway, 1997). We tested for such luminance artifact intrusion in a control experiment (see Controls for luminance artifacts section).

The RDK elements appeared on the first frame at random positions. For the global motion task, the RDK elements had a limited lifetime duration of 240 ms after which they were repositioned at new random locations. If any elements reached the edges of the circular noise carrier window, they were "reborn" on the opposite edge of the window. All RDK elements moved at the same speed. The stimulus interval duration was 1 s and the whole stimulus was ramped on and off in a Gaussian

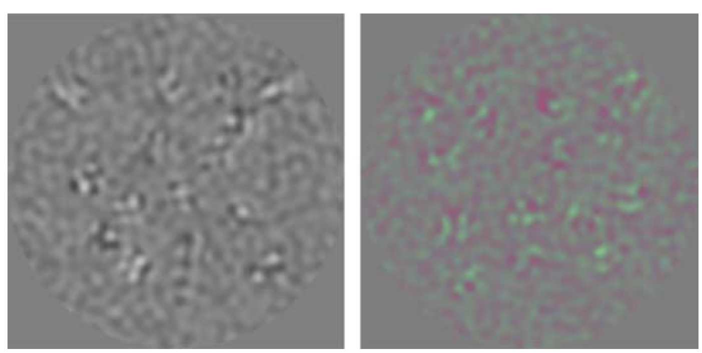

Figure 1. Example of one frame of the (left) second-order achromatic and (right) red–green stimuli. The fifteen RDK elements are set to a high contrast for clarity. Red–green stimuli are for illustration purpose only and are not isoluminant in this illustrative version.

temporal envelope (sigma = 250 ms) to avoid transient responses at the onset and offset of the stimulus presentation. For all the two-interval 2-AFC tasks, the inter-stimulus interval duration was 500 ms and a uniform gray screen of mean luminance with a fixation dot preceded and followed each stimulus presentation.

Color space

The stimuli were designed to isolate the three post-receptoral mechanisms: the L/M- and the S/(L + M)-cone-opponent mechanisms (red–green and yellow–blue, respectively) and the luminance (achromatic) mechanism. The chromaticity of the stimuli were represented using a three-dimensional cone contrast space in which each axis represents the quantal catch of the L-, M-, or S-cone types normalized with respect to the white point. Stimulus contrast and chromaticity were defined in the cone contrast space as the vector length and direction, respectively. The cardinal direction is defined as the direction in cone contrast space that lies orthogonal to two of the three post-receptoral mechanisms. Previous studies have estimated the L/M-cone-opponent, S-cone-opponent, and luminance mechanism directions to be: L–M, S–0.5(L + M) and aL + M (Cole, Hine, & McIlhagga, 1993; Sankeralli & Mullen, 1996, 1997). This yields luminance and blue–yellow cardinal stimulus directions of L + M + S (the achromatic direction) and the S-cone axis, respectively. The wide inter-subject variability found for the L-cone weight "a" in the luminance mechanism affects the specification of the red–green (isoluminant) cardinal direction. This direction was determined for each subject individually using a minimum perceived motion technique. Each observer varied the ratio of L- and M-cone contrasts with the method of adjustment in order to find the minimal perceived motion of a vertical Gabor of stationary envelope and drifting (3 Hz) 1 cycle/degree carrier. Ten measurements were obtained for each eye and ten from binocular measurements. Since no significant differences where found between monocular and binocular isoluminant points for each observer, the average of those 30 measurements were taken as the individual isoluminant point. The isoluminant points (the ratios of M-cone weight relative to L) were −1.1 for observer DK, −4.3 for NN, −3.52 for KTM, and −1.77 for LG.

Procedure

In order to make valid comparisons between the performance on the achromatic and chromatic global motion systems, we equated the visibilities of the achromatic and chromatic noise carriers. While a common method used to equate the contrast between chromatic and achromatic conditions is the threshold scaling method (equating supra-threshold contrast levels in terms of equal multiples of detection thresholds), this is not suitable for large distributed stimuli such as ours because achromatic and chromatic thresholds vary differentially across the visual field (Mullen, 1991; Mullen & Kingdom, 1996). An alternative method is to perform a visibility-matching task, in which observers judge the contrast between two stimuli (a reference stimuli and a test stimuli). This method has been shown to provide accurate and consistent contrast matching levels between achromatic and chromatic conditions (Switkes, 2008; Switkes & Crognale, 1999). We used this method in the present study. The reference stimulus was an achromatic noise carrier of fixed cone contrast set at eight times individual detection noise carrier threshold (determined in a preliminary study) and the test stimuli was a range of six contrast levels of red–green (or blue–yellow) noise carriers. We used a method of constant stimuli to determine the proportions of observer responses indicating which one of two successive intervals (the reference and the test intervals) contained the stimulus with the stronger contrast. A minimum of 40 trials per contrast level was used to fit a Weibull psychometric function using the psignifit toolbox version 2.5.6 described by Wichmann and Hill (2001a), yielding a 50% performance level to define the contrast value of the test that equates the reference stimulus.

A detection task was used to measure the detection thresholds for the contrast-modulated (CM) RDK envelopes against different RDK speeds. Detection thresholds were measured with a temporal two-alternative forced-choice (2-AFC) staircase procedure using either ten or fifteen RDK elements. The RDKs were static or moving coherently (all elements moving in the same direction, either right or left) with speeds ranging from 2 to 16 deg/s. We used a two-up one-down staircase that stopped at the sixth reversal: the contrast of the CM envelope was reduced after two correct responses by 25% in the first reversal and by 12.5% in successive reversals, and increased by 25% after one wrong response. A threshold value was calculated from the arithmetic mean of the five last reversals of that run and the final threshold was taken from the average of a minimum of four runs. RDK elements were then scaled using multiples of CM detection thresholds.

We also measured detection and motion direction thresholds simultaneously using a two-interval 2-AFC method of constant stimuli in which observers indicated which interval contained the moving RDK elements and in which direction they were moving (right or left). Fifteen RDK elements were used. Weibull functions were fitted for the two psychometric functions (detection and motion direction identification) using psignifit. Bootstrap analysis (1999 bootstrap simulations) with the bias-corrected accelerated method described by Wichmann and Hill (2001b) was used to determine the error bars (±1 *SD*).

In the global motion task, a proportion (%) of the total number of RDK elements moved in the same direction and the rest moved in random directions. We measured coherence thresholds by determining the minimum proportion of coherent RDKs that observers required to identify motion direction using a method of constant stimuli with different coherence levels, as described above. A one-interval two-alternative forced-choice (2-AFC) technique was used: the observers' task was to identify the direction of motion of the coherent RDKs, which moved either toward the right or the left. We used a minimum of 40 trials per data point and fit a Weibull function with the psignifit toolbox and used the 81.6% correct performance level to define the thresholds (% of coherent RDKs). Twenty-five RDK elements were used on this task.

Results

Equating achromatic and chromatic noise carrier contrast visibilities

Table 1 shows the results of the visibility-matching experiment for each observer. Values are cone contrasts that correspond to the point of subjective equivalence for matching the isoluminant red–green or blue–yellow noise carriers to the achromatic noise carrier reference stimulus.

Detection of achromatic and chromatic RDK elements

Figure 2 shows the CM RDK detection thresholds plotted as a function of the RDK speed (deg/s) using 10 or 15 RDK elements for two observers. Each detection threshold represents the minimal modulation depth of the RDK elements at which they are just visible from the noise carrier, e.g., a CM threshold of 0.4 means that the RDK elements are detected when their contrast is 40% higher than the noise carrier. The significance of the results was determined using a two-way ANOVA with two factors: color condition (achromatic, red–green, and blue–yellow) and speed. CM thresholds were significantly lower for achromatic stimuli than chromatic stimuli (for 10 dots: $F(1,4) = 13.5$, $P < 0.01$; for 15 dots: $F(2,6) = 8.35$, $P < 0.05$). Although performance for detecting moving RDKs is stable across the range of speeds assessed (no significant effect of speed for 10 or 15 dots: $F(3,4) = 0.26$, $P > 0.05$; $F(3,6) = 1.47$, $P > 0.05$, respectively), it decreased somewhat with increasing speed for the achromatic condition and increased slightly for the chromatic conditions. Observers reported having difficulty perceiving or were unable to perceive any motion in the RDKs at the element detection threshold in the achromatic and chromatic conditions, respectively; however, they were able to perform the detection task. Even for static RDKs (speed of 0 in Figure 2), we were able to measure detection thresholds, which are similar to the thresholds for the moving RDKs. Observers report using a contrast difference cue between the CM RDK elements and the noise carrier. A simultaneous detection and motion direction identification paradigm was therefore used in the next experiment, allowing a direct comparison between thresholds for RDK element motion direction and detection.

	KTM	DK	LG	NN
Ach ref	0.12	0.125	0.11	0.14
R–G	0.058	0.038	0.035	0.052
B–Y	–	0.330	0.236	0.352

Table 1. Results for the noise carrier visibility-matching experiment: cone contrast values corresponding to the point of subjective equivalence (PSE) for matching the contrasts of the achromatic reference (Ach ref) with the red–green (R–G) or blue–yellow (B–Y) test stimulus for each observer. The achromatic reference stimulus (Ach ref row) was set to eight times each observer's detection threshold and a range of six contrast levels were chosen for the test stimulus (R–G or B–Y). The equivalent cone contrast values in the R–G and B–Y rows correspond to the 50% points in the psychometric functions (PSE). The standard deviations (*SD*s) for the determination of the equivalent cone contrast values are less than or equal to 0.001. Observer KTM was not tested on the B–Y condition.

Detection and motion direction identification of achromatic and chromatic RDK elements

We measured the sensitivity to the motion of the CM elements using a simultaneous detection and motion direction identification paradigm. Element motion coherence was 100%. For first-order stimuli, the detection and motion identification thresholds coincide in achromatic vision, e.g., as soon as a drifting luminance grating is visible to the visual system, its motion direction can be identified (except at very high spatial frequencies). In second-order vision, however, those thresholds generally differ, with detection/direction identification threshold ratios greater than one: more contrast is needed to identify the direction of motion of second-order stimuli than to detect them (Smith, Hess, & Baker, 1994; Smith & Ledgeway, 1997, 1998). In color vision, detection/direction identification threshold ratios for first-order stimuli are often found to be greater than one as motion direction cannot be identified near detection threshold (Cavanagh & Anstis, 1991; Cropper & Wuerger, 2005; Lindsey & Teller, 1990; Metha, Vingrys, & Badcock, 1994; Mullen & Boulton, 1992; Mullen et al., 2003; Yoshizawa et al., 2000).

Figure 3 represents an example of the psychometric functions for simple detection and motion direction

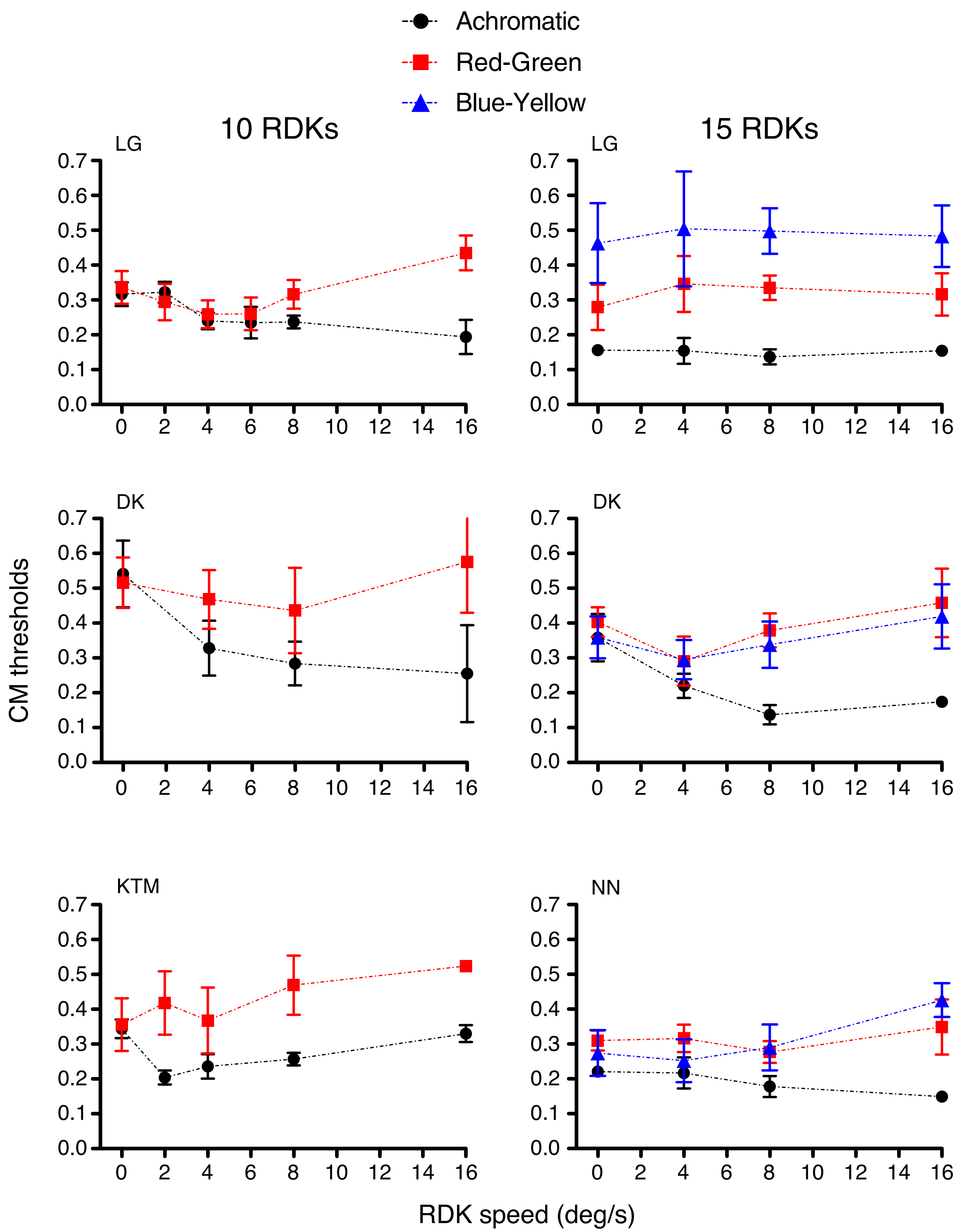

Figure 2. Contrast-modulated (CM) thresholds for the detection of the RDK elements plotted as a function of element speed for different observers. Each CM threshold represents the RDK modulation depth threshold. Ten or 15 RDK elements were used as marked. Black circles, red squares, and blue triangles are for achromatic, red–green, and blue–yellow conditions, respectively. Error bars represent ±1 *SD* and were determined from the bootstrap analysis.

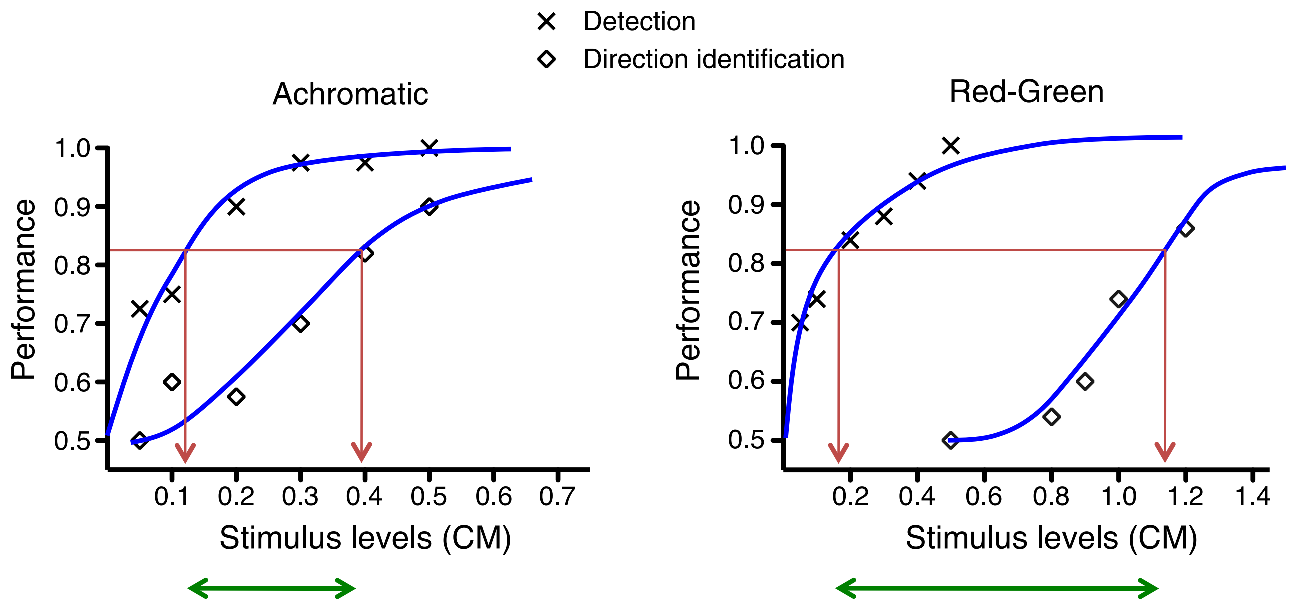

Figure 3. Examples of psychometric functions (observer's performance against stimulus levels expressed as RDK contrast modulation levels) for the achromatic (left graph) and red–green (right graph) conditions for one observer (DK). Performances for the detection and motion direction identification of 15 RDK elements were determined using the simultaneous detection/motion direction paradigm resulting in two psychometric functions per graph. The vertical red arrows point the thresholds at the 81.6% performance level. The horizontal green arrows show the gap difference between detection and motion direction identification thresholds.

identification for the achromatic and the red–green conditions for one observer (DK). The 81.6% threshold performance is indicated with the vertical red arrows. There is a large difference between detection and motion direction thresholds; however, the gap between those thresholds (horizontal green arrows in Figure 3) is considerably bigger for the chromatic condition than the achromatic one. We note that performance over 90% correct could not be obtained for the chromatic motion condition. All data for two subjects are shown in Figure 4, in which detection and motion direction thresholds are plotted as a function of element speed. Each pair of points (detection and direction thresholds) in Figure 4 is derived from the psychometric functions as shown as an example in Figure 3. Motion direction thresholds are significantly higher than detection thresholds (Figure 4) determined using a one-way ANOVA for achromatic stimuli ($F(1,3) = 37$, $P < 0.01$). Motion direction thresholds for the red–green chromatic

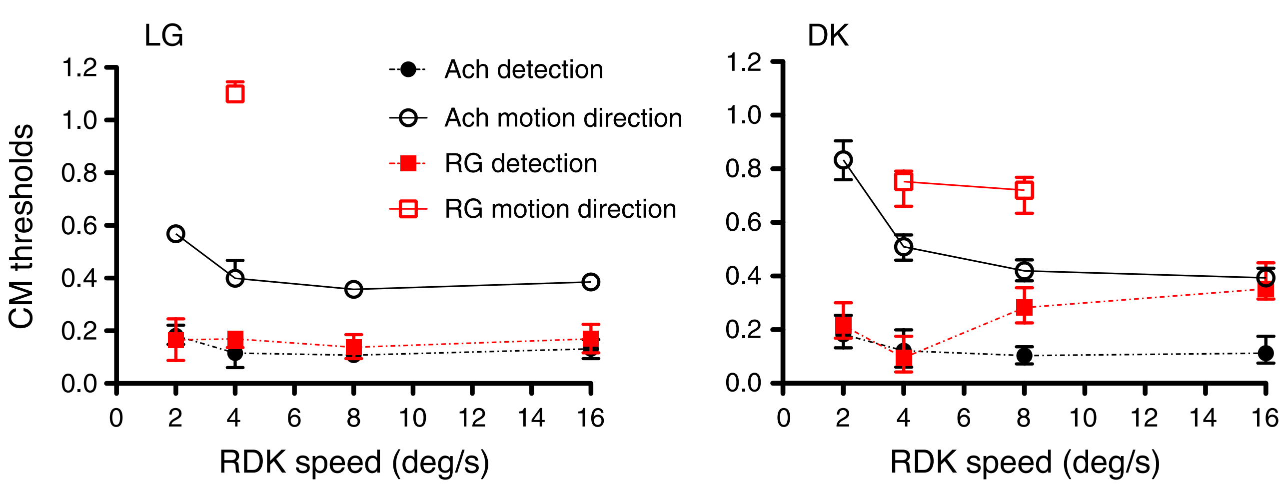

Figure 4. CM detection (filled symbols) and motion direction identification (unfilled symbols) thresholds of the RDK elements plotted as a function of element speed for two observers. Missing symbols are cases when performance was at chance level. Black circles and red squares are for achromatic (Ach) and red–green (RG) conditions, respectively. Error bars represent ±1 *SD* from the bootstrap analysis.

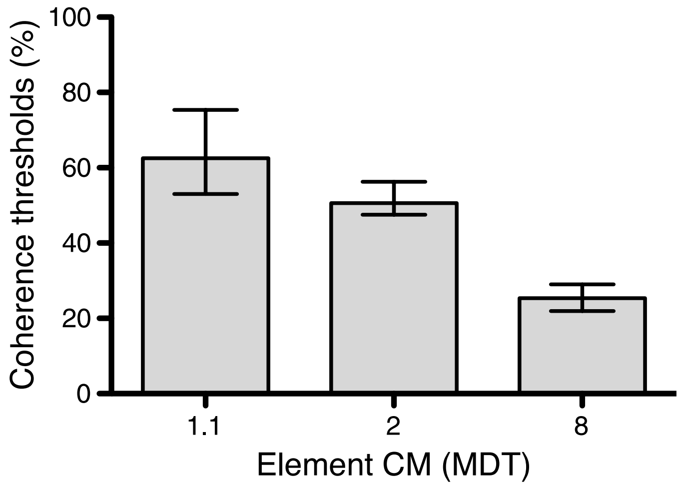

Figure 5. Coherence achromatic thresholds (% of 25 RDK elements moving in the same direction) for different RDK element contrast modulation settings expressed as multiples of RDK element detection threshold (MDT) shown for one observer. Chromatic coherence thresholds could not be obtained for any of the observers. Error bars represent ±1 *SD*.

stimuli were very high or impossible to obtain within the limits of the color gamut of our monitor, even at 100% coherence. For the blue–yellow condition, we could not get any motion direction thresholds and therefore we do not represent this condition in Figure 4.

In color vision studies, luminance artifacts may arise from a poor isoluminant point setting. Here, we were able to measure performance for an achromatic motion direction identification task but very rarely or not at all for the red–green or blue–yellow motion direction identification task, respectively (Figure 4). These results suggested that the color condition was uncontaminated by luminance artifacts.

Global motion experiment

We used limited lifetime RDKs (240 ms) and an RDK speed of 4 deg/s, which was the optimal speed for achromatic and chromatic conditions (see Figures 2 and 4). Figure 5 plots coherence thresholds (% of RDKs moving toward the same direction) for different settings of CM RDKs expressed as multiples of RDK motion direction thresholds (MDTs).

Coherence thresholds for red–green and blue–yellow RDKs were impossible to obtain within the limits of the color gamut of our monitor for any of the three observers. Once the coherence dropped below 100%, there was no reliable perception of motion in the chromatic stimuli.

Controls for luminance artifacts

In second-order stimuli, first-order local luminance artifacts may arise as a result of using low-pass filtered noise (large pixel size noise; Ledgeway & Hutchinson, 2005; Smith & Ledgeway, 1997). The use of fine pixel size noise has been shown to reduce the intrusion of local luminance artifacts in second-order experiments (Ledgeway & Hutchinson, 2005; Smith & Ledgeway, 1997). As a control experiment, we therefore used a fine pixel size noise and the same procedure as in Figure 4 to measure simultaneously detection and motion direction identification thresholds of RDK elements. The noise used in this task was the unfiltered noise described above, i.e., white noise. If first-order cues were used by the visual system, we would expect higher motion direction identification thresholds when using the unfiltered noise than the filtered noise.

Figure 6 represents the detection (filled symbols) and direction identification (unfilled symbols) thresholds against

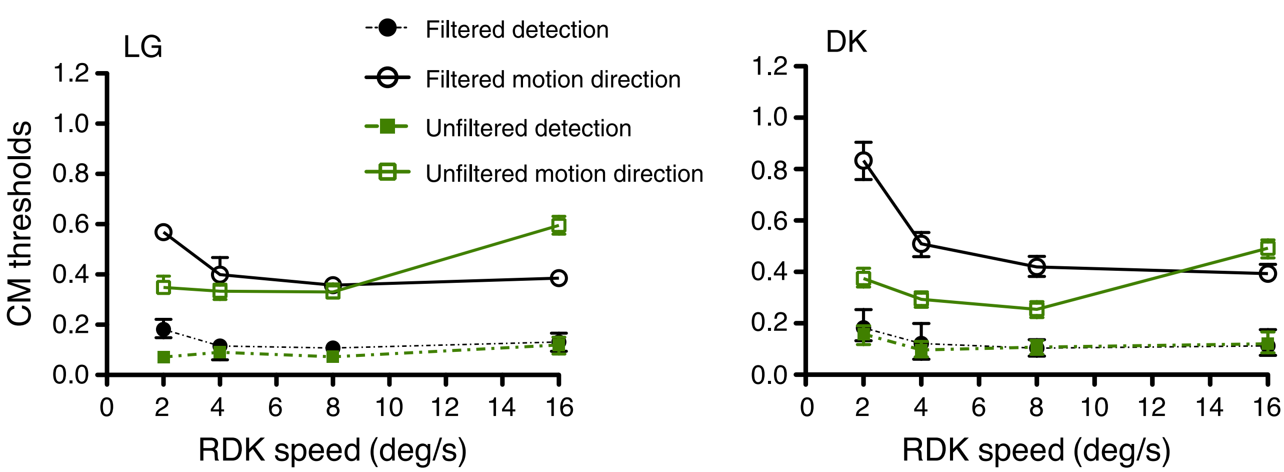

Figure 6. CM detection (filled symbols) and motion direction identification (unfilled symbols) thresholds of the RDK elements across different speeds for two observers. Black circle and green square symbols indicate when thresholds were obtained with low-pass filtered and unfiltered noise carriers, respectively. Error bars represent ±1 *SD*.

a range of RDK speeds when using the filtered (circles) and unfiltered (squares) noise carriers for two observers.

For both noise types, detection thresholds are similar (Bonferroni post-hoc test shows no significant difference between detection thresholds: $P > 0.05$), whereas motion direction identification thresholds are lower at low to mid RDK speeds when using the unfiltered noise (only significant difference at the lowest speed; Bonferroni post-hoc test: $t = 3.69$, $P < 0.01$). Only for the highest RDK speed (16 deg/s), we found higher motion direction identification thresholds when using the unfiltered noise. These results suggest no intrusion of luminance artifacts when using the filtered noise RDK speeds (large pixel size), except at the highest speed used (16 deg/s).

Discussion

The overall aim of the present study was to investigate the contribution of color to the global motion processing of second-order stimuli. A previous study has shown that the contribution of color to global motion for first-order stimuli was not mediated by a purely chromatic mechanism but was based on intrinsic luminance responses to the moving chromatic RDK elements (Michna & Mullen, 2008), since luminance masking noise elevated chromatic motion thresholds until motion could not be seen but did not affect detection thresholds. This is in agreement with previous work that shows no genuine color mechanisms for first-order motion processing of isoluminant stimuli (Mullen et al., 2003; Yoshizawa et al., 2000, 2003). On the other hand, a number of studies have shown that higher order motion processing can be mediated by purely chromatic mechanisms (Baker et al., 1998; Cropper & Derrington, 1996; Lu et al., 1999; Mullen et al., 2003; Yoshizawa et al., 2000, 2003). Based on these findings, we expected to find a contribution of color to the global motion processing of second-order stimuli, but instead we found no global motion processing of second-order red–green and blue–yellow isoluminant RDK stimuli.

Even for chromatic RDK stimuli of 100% coherence, when global mechanisms are not strictly necessary for the determination of motion direction, we found second-order motion processing to be extremely poor for isoluminant red–green stimuli or non-existent for blue–yellow stimuli, whereas for achromatic stimuli, matched in visibility to the chromatic stimuli, it was possible to measure motion performance in all cases. These results suggest that the visual system has minimal or no input of color contrast to second-order motion processing under our stimulus conditions. Some previous studies have been able to measure motion direction thresholds using different types of chromatic second-order stimuli (gratings, beats, or CM noise) that activated higher order chromatic mechanisms (Cropper & Derrington, 1996; Cropper et al., 2009; Mullen et al., 2003; Yoshizawa et al., 2000, 2003). Differences between these studies and ours may be due to differences in the stimuli employed or due to the type of higher order motion mechanism recruited. In the present study, we used low-pass filtered noise to prevent luminance artifacts arising from chromatic aberrations and to ensure that the chromatic noise carrier was within the visible part of the spatial contrast sensitivity function of human color vision (Mullen, 1985; see Stimuli section). We also used RDK envelopes in which the contrast energy is confined within small areas instead of the larger bands of envelope gratings used in other studies. These differences in the stimulus configuration may explain the difference in the results between studies. We were limited in the minimum and maximum sizes we could choose for the RDK elements as using larger elements would decrease the element density due to the limited size of our monitor and fewer elements would be available to integrate into a global percept. We could not use smaller sized RDK elements due to the relatively large spatial scale of the low-pass filtered noise carrier. Smaller RDK elements could have been used by filtering the noise with a higher frequency cut-off; however, the results may have been compromised by the intrusion of luminance artifacts due to chromatic aberrations. The color gamut of the monitor also represents another limitation on the maximum cone contrast that can be displayed. If other displaying methods that increase the color gamut such as laser techniques were employed, a contribution of color to global motion processing might have been revealed. Under the present stimulus conditions, we were unable to measure any second-order global motion for the chromatic system.

In some cases, the motion discrimination of second-order stimuli may be mediated by higher order motion mechanisms such as attention tracking (e.g., of grating bars or stimulus beats) of positional changes of the contrast modulation (Cavanagh, 1992; Seiffert & Cavanagh, 1998, 1999). Several studies show the existence of third-order motion mechanisms that may be used to locate salient features of a stimulus and track their position (Lu & Sperling, 1995, 2001; Sperling & Lu, 1998). Here we designed the stimuli in order to minimize attention tracking or third-order motion processing by using RDK elements, which require the integration of all the elements within the circular noise window to determine motion direction. By using RDK speeds greater than 2 deg/s, which were shown to not involve attention tracking mechanisms (Seiffert & Cavanagh, 1999), and by using limited lifetime elements that avoid tracking individual RDK elements, we were able to isolate the second-order mechanism and avoid intrusion of third-order motion mechanisms. In the motion experiment (Experiment 3), even with a stimulus (100% coherent motion), that may potentially facilitate attention tracking or third-order processing, observers had difficulty or were unable to see any motion in the isoluminant stimuli, suggesting that no third motion processing is involved in our stimulus configurations.

In second-order vision, previous studies using achromatic stimuli (Ledgeway & Hutchinson, 2005; Smith et al., 1994; Smith & Ledgeway, 1997, 1998) have shown that performance for identifying the motion direction of second-order stimuli may be mediated by the intrusion of first-order local (luminance) artifacts (Baker et al., 1998; Benton & Johnston, 1997; Ledgeway & Hutchinson, 2005; Smith & Ledgeway, 1997, 1998). Smith and Ledgeway (1997) showed that large pixel size noise increases the likelihood of using first-order cues during a second-order motion task. The clustering of large pixels with similar luminance values increased the probability of a first-order mechanism response when the envelope moved over the noise. Benton and Johnston (1997), however, consider that the motion direction induced by such luminance artifacts is not directionally correlated with the second-order motion direction. A way to reduce such luminance artifacts is to use small pixel size noise where clustering over a large area is less probably due to the fine pixel size (Ledgeway & Hutchinson, 2005; Smith & Ledgeway, 1997). In the present study, it might be argued that motion performance for the second-order achromatic stimuli arises from a first-order cue in the motion of RDK elements due to the large pixel size of the low-pass filtered noise carrier. Experiment 3 and the control experiment showed, however, that first-order cues are not used. First, detection and motion direction identification thresholds differ greatly (Figure 4), whereas a typical finding in second-order studies (Ledgeway & Hutchinson, 2005; Metha et al., 1994; Smith & Ledgeway, 1997, 1998) is that detection and motion direction thresholds coincide when first-order cues are used. Second, if first-order cues are used, the results should be similar for the chromatic and achromatic conditions, but we could rarely measure any motion thresholds in the chromatic conditions. Finally, we show in the control experiment that by using a fine grayscale pixel size noise carrier, which reduces the likelihood of luminance artifacts, the gap between the detection and direction thresholds was not increased compared to the low-pass filtered noise, suggesting no luminance artifact intrusion when using the filtered noise.

Conclusions

In summary, we find that performance for identifying the motion direction of second-order chromatic stimuli is much poorer or non-existent compared to the achromatic one, even at 100% coherence. We have shown that performance for second-order achromatic stimuli was not confounded by first-order cues or third-order cues. At a global motion processing stage, it has been shown previously that first-order motion fails for the chromatic system (Bilodeau & Faubert, 1999; Michna & Mullen, 2008). Here we conclude that, within the limits of the stimulus presentation and under the spatial and temporal conditions used, second-order chromatic global motion also fails. These results suggest that the cortical area MT, which is involved in global motion processing, does not receive functional inputs from the chromatic system but solely from the achromatic system. Although several neurophysiological and fMRI studies have shown that cells in area MT respond to chromatic motion (Gegenfurtner et al., 1994; Mullen, Dumoulin, McMahon, de Zubicaray, & Hess, 2007; Saito, Tanaka, Isono, Yasuda, & Mikami, 1989; Seidemann, Poirson, Wandell, & Newsome, 1999; Thiele, Dobkins, & Albright, 2001; Wandell et al., 1999), our results suggest that these responses are not functionally chromatic at the psychophysical level but may instead be luminance-based.

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