No dedicated second-order motion system

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The existence of a second-order motion system distinct from both the first-order and feature tracking motion systems remains controversial even though many consider it well established. In the present study, the texture contribution to motion was measured within and beyond the spatial acuity of attention by presenting the stimuli in the near periphery where the spatial resolution of attention is low. The logic was that when moving elements are too close one to another for attention to individually select them (i.e., crowding), it is not possible to track them. To test the existence of a dedicated second-order motion system, the texture contribution to motion was measured when neutralizing both the feature tracking motion system and the contribution of the first-order motion system due to preprocessing nonlinearities introducing residual distortion products. When the contribution of distortion products was *not* neutralized, texture substantially contributed to motion for spatial frequencies within and beyond the spatial acuity of attention. When neutralizing the contribution of distortion products, texture substantially contributed to motion for spatial frequencies within the spatial acuity of attention, but not for spatial frequencies beyond the spatial acuity of attention. We conclude that there is no dedicated second-order motion system; the texture contribution to motion is mediated solely by the first-order (due to residual distortion products) and feature tracking (at frequencies within spatiotemporal acuity of attention) motion systems.

Introduction

We recently revealed the existence of nonuniform preprocessing nonlinearities that previously have not been considered and that can enable the first-order motion system to process contrast-defined motion by introducing residual distortion products (i.e., luminance-defined motion of different polarities; Allard & Faubert, 2013). When neutralizing the texture contribution to motion due to residual distortion products, we found a substantial texture contribution to motion at low, but not at high temporal frequencies. These results question the existence of a dedicated second-order motion system sensitive to high temporal frequencies (as suggested by Lu & Sperling, 1995, 2001; Scott-Samuel & Georgeson, 1999), but nevertheless imply the existence of a motion system other than the first-order motion system sensitive to low temporal frequencies. The target of the present study was to investigate whether this motion system is a dedicated second-order motion system that is temporally lowpass (as suggested by Hutchinson & Ledgeway, 2006; Smith & Ledgeway, 1997) or the feature tracking motion system (as suggested by Allard & Faubert, 2008a, 2013; Ashida, Seiffert, & Osaka, 2001; Derrington, Allen, & Delicato, 2004; Derrington & Ukkonen, 1999; Ukkonen & Derrington, 2000).

In the current study, to neutralize the feature tracking motion system at low temporal frequencies, the stimulus was presented in the periphery where the spatial resolution of attention is low (Intriligator & Cavanagh, 2001). A feature tracking motion system would require attention to select a feature (e.g., a contrast-defined bar, Figure 1 bottom) and track its displacement. If attention resolution is too coarse to select a feature (i.e., crowding, e.g., Figure 1, right) then it should not be able to track it. Given that our stimulus was composed of drifting contrast-defined bars, simply viewing these bars in the periphery where attention resolution is low should be sufficient to neutralize the feature tracking motion system. Given that attention resolution is too coarse to individually select items when there are more than about 14 items distributed on an annulus (Intriligator & Cavanagh, 2001), feature tracking should be difficult when there are more than about 14 cycles per circumference (cpc).

The texture contribution to motion due to residual distortion products was neutralized by superimposing

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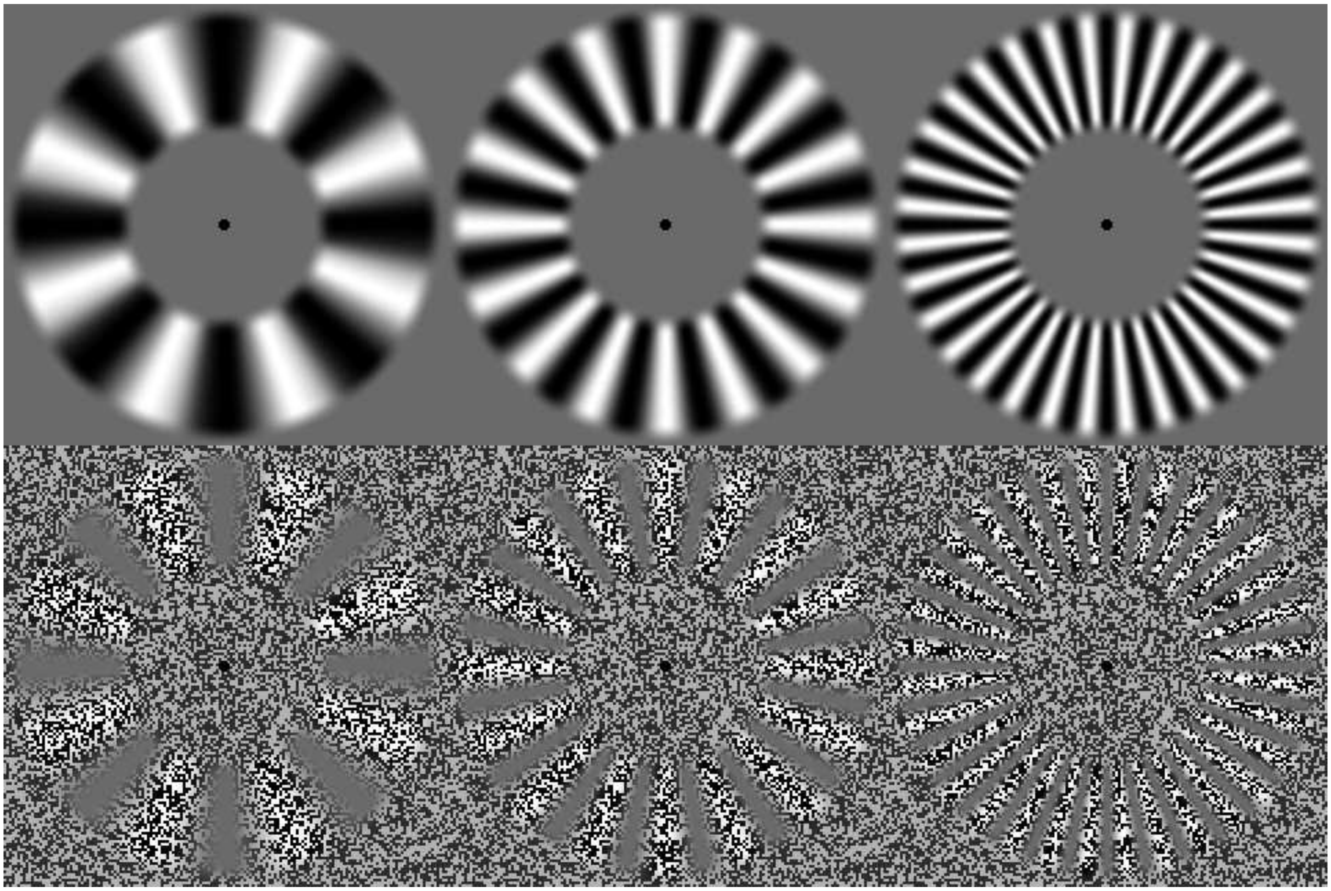

Figure 1. Examples of luminance- (top) and contrast-defined (bottom) stimuli with 8, 16, and 32 cpc. Bars were rotating clockwise or counterclockwise. When fixating at the black dot, it should be relatively easy to attentively select a bar when there are 8 cpc (left), but difficult when there are 32 cpc (right). To experience this, try counting them while fixating the black dot.

a high-contrast luminance modulation to the contrast modulation (both having the same spatiotemporal frequency and drifting in the same direction; Allard & Faubert, 2013). Thus, residual distortion products would sum with the luminance modulation for some units and subtract for others, thereby increasing or decreasing its effective contrast. As a result, residual distortion products would increase the response of some first-order motion units and reduce it for others, resulting in no or little gain on average. To measure the contribution to motion of superimposed luminance and contrast modulations, we opposed another luminance modulation drifting in the opposite direction. The texture contribution to motion was quantified as the contrast difference between the two opposing luminance modulations when no net motion was perceived. If the texture contribution to motion is solely due to residual distortion products, then no net motion should be perceived when the two opposed luminance modulations have the same contrast.

Experiment 1: Neutralizing feature tracking

The target of this experiment was to investigate if the texture would contribute to motion when neutralizing both the feature tracking motion system and the contribution of distortion products.

Method

Observers

Four naïve observers and one of the authors participated in this experiment. They all had normal or corrected-to-normal vision.

Apparatus

The stimuli were presented on a 19-in. ViewSonic E90FB .25 CRT monitor with a mean luminance of 47 cd/m^2 and a refresh rate of 120 Hz. The Noisy-Bit method (Allard & Faubert, 2008b) implemented with the error of the green color gun inversely correlated with the error of the two other color guns made the 8-bit display perceptually equivalent to an analog display having a continuous luminance resolution. The monitor was the only source of light in the room. A Minolta CS100 photometer (Minolta, Tokyo, Japan) interfaced with a homemade program calibrated the output intensity of each gun. At the viewing distance of 57 cm, the width and height of each pixel were 1/32 degree of visual angle.

Stimuli and procedure

With uniformly oriented bars (e.g., vertical) presented in the periphery, observers could potentially attend only to a bar near the edge, which is less subject to crowding because it has only adjacent bars on one side. To avoid this undesirable effect, bars were presented on an annulus oriented on the radial axis and the modulation was on the meridian axis (Figure 1).

To measure the texture contribution to motion without compensating for distortion products, stimuli were composed of a luminance- and a contrast-modulated sine wave grating drifting in opposite direction (clockwise and counterclockwise). The contrast of the luminance modulation was manipulated to find the point at which no net motion was perceived. The luminance contrast when no net motion is perceived corresponded to the texture contribution to motion.

Both modulations had the same spatial (1, 2, 4, 8, 16, 32, or 64 cpc) and temporal (1.875 Hz) frequencies. The spatial window was an annulus between 5 and 9 degrees of eccentricity plus half-cosine smooth edges of 1°. The contrast of the contrast modulation was always maximized to 100% modulation depth (i.e., low and high contrast bars were of 0 and 40% contrast), the contrast of the luminance modulation was controlled by a 1-down-1-up staircase procedure (Levitt, 1971) of 200 trials with 0.05 log steps, which converged to the contrast of the luminance modulation at which no net motion was perceived (i.e., the texture contribution to motion). The initial phases of the modulations were randomized. The presentation time was 500 ms plus an onset and offset half cosine ramp of 125 ms. Observers were asked to fixated at a black dot presented in the middle of the screen and report their perceived net motion direction (clockwise or counterclockwise).

To measure the texture contribution to motion when neutralizing the distortion products, stimuli were composed of two luminance modulations and a contrast modulation. The contrast of the luminance modulation drifting in opposite direction to the contrast modulation was fixed to 25%. The other luminance modulation was drifting with the contrast modulation either in phase or in opposite phase. The contrast of this luminance modulation was controlled by a staircase procedure. Each block was composed of two staircases pseudorandomly interleaved for the two relative phase conditions, i.e., luminance and contrast modulations superimposed in phase and in opposite phase. Since luminance artifacts due to spatiotemporally homogenous preprocessing nonlinearities (i.e., global distortion products) are equivalent to adding a luminance modulation either in phase or in opposite phase to the texture modulation, global distortion products would increase the texture contribution to motion in one of these two phase combinations and reduce it, by the same amount, in the other. Averaging the measurements in these two phase conditions cancels its impact. Furthermore, this paradigm also enables the calculation of the global distortion product, which corresponds to half of the difference between the texture contributions to motion in these two phase combinations. Additional details on the calculation of the texture contribution to motion and global distortion product can be found elsewhere (Allard & Faubert, 2013; see also Cavanagh & Anstis, 1991, who first used such a technique for color motion).

Dynamic binary noise with elements of 2 × 2 pixels (i.e., 0.0625° × 0.0625°) resampled every four frames and 20% contrast was used as a carrier. To avoid luminance motion drifting cues within noise elements, there was no spatial or temporal luminance variation within each noise element. The carrier was presented over the entire screen and was visible at all times (i.e., it was not modulated by the spatial and temporal windows) to avoid introducing additional distortion products due to the carrier onset (Allard & Faubert, 2008a). A black fixation dot was continuously presented at the center of the screen.

Results and discussion

The texture contribution to motion when the contribution due to distortion products was not neutralized (Figure 2, left) was weaker when feature could not be tracked ($\geq$16 cpc), but was nevertheless not negligible and statistically above 0 [$t(4) > 5$, $p < 0.01$ for each spatial frequency]. This implies the existence of a motion system other than the feature tracking motion system sensitive to contrast-defined motion. This motion system could either be a dedicated second-order motion system or the first-order motion system due to distortion products. When the texture contribution due to distortion products was neutralized by the superimposition of a high contrast luminance modulation (Figure 2, right), texture contributed to motion only when the spatial frequency was low enough for features (i.e., contrast-defined bars) to be

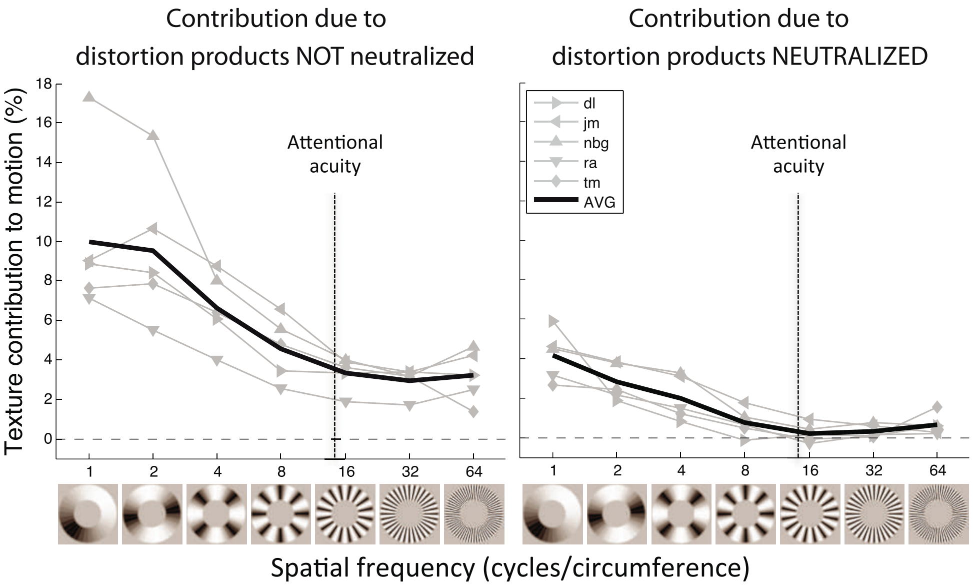

Figure 2. Texture contribution to motion when the contribution of distortion products was not neutralized (left) and neutralized (right). Attention resolution should be too low to individually select contrast-defined bars when there are more than about 14 distributed around an annulus (Intriligator & Cavanagh, 2001), which severely impairs the feature tracking.

selected by attention. There was no texture contribution to motion when the contribution due to distortion products was neutralized and when the spatial frequency was too high ($\geq$16 cpc) for the feature tracking (i.e., beyond the spatial acuity of attention). Statistically, the texture contribution to motion was significantly above 0 for the three lowest spatial frequencies [$t(4) > 3$, $p < 0.05$], but not for the four highest spatial frequencies [$t(4) < 3$, $p > 0.05$]. We therefore found no evidence of a dedicated second-order motion system.

Figure 3 shows the global distortion products measured as a function of the spatial frequency. When the spatial frequency was low enough to enable attention to track features [i.e., <16 cycles per degree (cpd)], there was a large variation observed between subjects; some showed negative and others positive distortion products. This may not be due to a "global distortion" per se (i.e., luminance artifacts due to spatiotemporally homogenous preprocessing nonlinearities), but simply that some observers were better at tracking the combination of a luminance and contrast modulations when they were in phase or in opposite phase. At spatial frequencies at which the feature tracking was neutralized (i.e., $\geq$16 cpd) and the contribution to motion was due to a low-level, energy-based motion system, the intersubject variation was much lower and the global distortion product was relatively constant as a function the spatial frequency. These results likely reflect the true global distortion product, which was low (<1% for all but one subject).

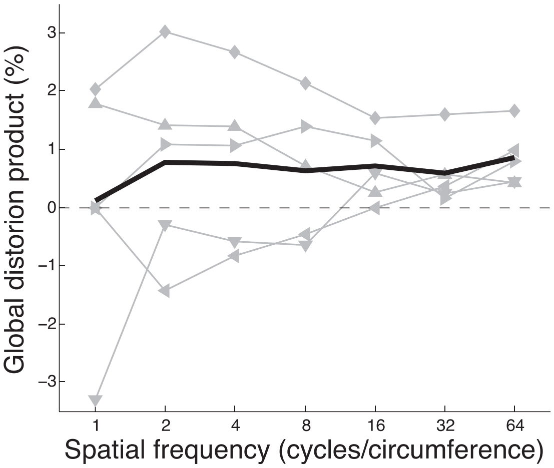

Figure 3. Global distortion products as a function of the spatial frequency. Legend as in Figure 2.

Experiment 2: Phase-dependent test

The results of the first experiment are consistent with the hypothesis that, when the spatial frequency was too high for the feature tracking motion system, the texture contribution to motion was only due to distortion products being processed by the first-order motion system. To directly seek the existence of such distortion products, the phase-dependent test (Lu & Sperling, 1995) was applied when the contribution due to distortion products were *not* completely neutralized (i.e., the contrast of the superimposed luminance modulation was low).

Method

The texture contribution to motion was evaluated when the phase of the superimposed luminance and contrast modulations differed by 0°, 90°, 180°, and 270°. Obviously, a phase interaction is expected to be weak when either the luminance or contrast modulation does not substantially contributing to motion. To equate the texture and luminance contributions to motion, the contrast of the luminance modulation was fixed to the texture contribution to motion when the contribution due to distortion products was not neutralized (Figure 2, left, ~4%) and the spatial frequency was fixed to a condition in which the feature tracking was neutralized (32 cpc). To neutralize the global distortion product, another luminance modulation drifting in phase with the contrast modulation was also superimposed. The contrast of this luminance modulation was fixed based on the measurement of the global distortion product at 32 cpc in the previous experiment (~1%). To measure the texture contribution to motion of these combined modulations, the contrast of a luminance modulation drifting in the opposite direction was manipulated by four interlaced staircases (one per phase difference). Again, the texture contribution to motion was defined as the contrast difference between the two luminance modulations when no net motion was perceived.

Results and discussion

Results showed that the texture contribution to motion depended on the phase interaction between the luminance and contrast modulations: The texture contributions to motion were greater when the phase difference between the luminance and contrast modulations were 0° or 180° than 90° or 270° [($t(3) = 3.5$, $p < 0.05$, Figure 4]. Although this phase interaction, taken alone, does not imply the nonexistence of a second-order motion system, it nevertheless implies at least some common processing *before* the motion extraction stage (because phase information is lost when extracting the motion energy) and thereby directly confirms the existence of residual distortion products within the first-order motion pathway. Indeed, this phase interaction cannot be explained by previous models explaining second-order motion processing. If luminance- and contrast-defined motion stimuli were processed separately up to the motion extraction stage then their processing should not interact. The processing of texture-defined motion by the gradient-based model (Benton, 2002, 2004; Benton & Johnston, 2001; Benton, Johnston, McOwan, & Victor, 2001; Johnston & Clifford, 1995; Johnston, McOwan, & Buxton, 1992) would also predict no phase interaction with a luminance modulation at the envelope spatial frequency because texture-defined motion would be processed by the first-order system at the carrier spatial frequency. Global distortion products (which were neutralized) would predict a phase interaction between the 0° and 180° conditions, not for 90° shifts. For a more elaborate argumentation in regards to how these three models fail to explain the phase interaction observed here see Allard and Faubert (2013).

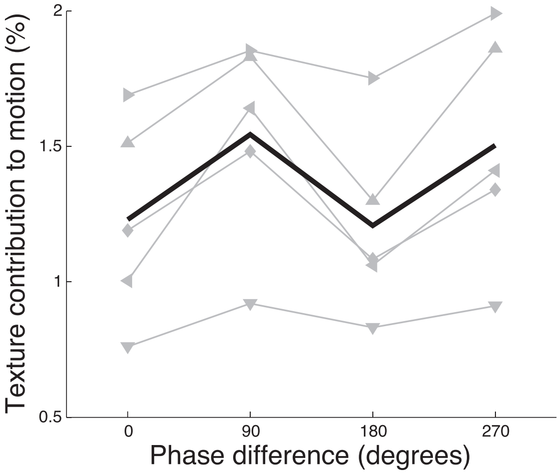

Figure 4. Texture contribution to motion as a function of the phase difference between the luminance- and contrast-defined modulations drifting in the same direction. Legend as in Figure 2.

General discussion

When the features could not be tracked (≥16 cpc), the texture contribution to motion was weaker, interacted with a low contrast luminance modulation (which implies some common processing prior to motion extraction) and was completely neutralized by the superimposition of a high contrast luminance modulation (which neutralizes the contribution due to distortion products). We therefore conclude that the texture contribution to motion was not due to a dedicated second-order motion system. Rather, it is the combined result of the first-order motion system (due to residual distortion products) and the feature tracking motion system (when spatial frequency was lower than the spatial acuity of attention).

Contrast-defined motion processing in the periphery

In the current study, the stimulus parameters were set to maximize the texture contribution to motion due to a dedicated second-order motion system, so if such a motion system were effective in the near periphery, a substantial texture contribution to motion would have been observed. The spatial window was large (annulus of 5 to 9 degrees of eccentricity), the presentation time was long (>500 ms), the modulation contrast was maximized (100%) and the carrier contrast was substantial (20%). To show that this stimulus generated a texture contribution to motion that is similar to what is usually observed with contrast-defined motion, we measured the contrast modulation threshold required to discriminate the motion direction. The three observers tested (IL, RA, and TM) had contrast thresholds of 17%, 15% and 16%, respectively. These results show that, when the impact of residual distortion products was not neutralized, the motion response to the contrast-defined motion was substantial and similar to what is usually observed. Thus, the perception of texture-defined motion in the current study was clearly reliable and suprathreshold (i.e., ~6× threshold). Also note that the absence of texture contribution to motion could not be due to the fact that the carrier was dynamic since similar results were obtained with a static noise carrier (data not shown). Furthermore, if there was a dedicated second-order motion system enabling substantial texture contribution to motion at low temporal frequencies at fixation, then the texture contribution to motion due to this motion system would be unaffected by the superimposition of a high-contrast luminance grating (Allard & Faubert, 2013). Thus, we find no reason why a dedicated second-order motion system operating in the periphery, if it existed, would not enable some texture contribution to motion with our stimulus.

Consequently, the texture contribution to motion in the periphery that many studies attributed to a second-order motion system must have been due to the first-order or feature tracking motion systems. To determine if feature tracking may have enabled some texture contribution to motion in previous studies, it is important to consider the spatial frequency of the contrast modulations relative to the attentional acuity at the eccentricity at which the stimulus was presented. Since attentional acuity is quite low in the periphery, the spatial frequency does not need to be very high to disable the feature tracking motion system. In the current study, the lowest spatial frequency at which feature tracking failed was 16 cpc, a cutoff frequency which is consistent with previous findings (Intriligator & Cavanagh, 2001; Solomon, 2010). Given that attentional acuity scales with eccentricity (Intriligator & Cavanagh, 2001), this cutoff frequency should be independent of eccentricity in cycles per circumference (cpc) and decrease with eccentricity (e) in cycles per degree (cpd), that is, $16/2\pi e = 2.5/e$ cpd. In the current study, the stimulus was displayed between 5 and 9 degrees of eccentricity resulting in spatial frequencies between 0.28 and 0.5 cpd, which are lower than the ones used in most studies investigating contrast-defined motion in the periphery. Our conclusion that there is no second-order motion system operating in the periphery therefore suggests that the contribution of the feature tracking motion system in the periphery in most studies was negligible and that the texture contribution to motion was due to distortion products being processed by the first-order motion system.

Undoubtedly, the strongest argument for the existence of a dedicated second-order motion system operating in the periphery was made by Smith and Ledgeway (1998). Although they found that the sensitivities to luminance- and contrast-defined motions dropped with eccentricity at similar rates, they found that detection and direction discrimination thresholds differed for contrast-defined, but not for luminance-defined motion processing. They interpreted these different processing properties as evidence that contrast-defined motion was processed by a dedicated second-order motion system (as they first argued in 1997). Smith and Ledgeway (1998) considered "a difference between orientation and direction thresholds as the hallmark of detection by a true second-order motion mechanism" (p. 407). This property difference is often cited as strong evidence for the existence of a dedicated second-order motion system (e.g., see reviews Burr & Thompson, 2011; Nishida, 2011). Unfortunately, the threshold difference between detection and direction discrimination for contrast-defined, but not luminance-defined stimuli does not necessarily imply distinct *motion* systems even though it suggests distinct *detection* systems. Specifically, such pattern of results suggests that the detection process is based on the output of motion detectors for luminance-defined motion, but not for contrast-defined motion in which case we would be more sensitive to detect a spatial property of contrast-defined motion (e.g., its shape) than to detect its motion. This does not necessarily imply that the direction discrimination of contrast-defined motion is not processed by the first-order motion system. The sensitivity of the system detecting a spatial property of contrast-defined motion can be greater than the sensitivity of the first-order motion system to distortion products, especially when using a dynamic noise carrier, which reduces the sensitivity of the first-order motion system. Furthermore, note that the absence of a dedicated second-order motion system would predict different detection and direction discrimination thresholds in the periphery. Given that the low spatial resolution of attention in the periphery compromises the tracking but not detection (e.g., bars in Figure 1 right are clearly detectable, but counting them is difficult), then detection should be good, while direction discrimination would be difficult for the feature tracking motion system and would have to rely on the strength of the distortion products relative to the sensitivity of the first-order motion system, which would be low with dynamic noise carriers. Thus, we would expect good detection thresholds and poor direction discrimination thresholds. Consequently, the results of Smith and Ledgeway (1998) do not imply a dedicated second-order motion system and are compatible with the hypothesis that contrast-defined motion direction discrimination is being processed by the first-order motion system due to residual distortion products.

To our knowledge, there is only one study that both systematically varied the spatial frequency of contrast-defined motion in the periphery and used spatial frequencies low enough for the feature tracking motion system. At about 9 degrees of eccentricity, Solomon and Sperling (1995) found that texture did not contribute to motion at high (i.e., >0.44 cpd) spatial frequencies (as first observed by Pantle, 1992, at 0.5 cpd at 8 degrees of eccentricity) but contributed to motion at lower spatial frequencies. These results are compatible with ours showing the existence of a motion system enabling texture contribution to motion only at very low spatial frequencies, which could be due to the feature tracking motion system. Their stimulus was presented within an annulus varying from 8 to 10 degrees of eccentricity and they found the cutoff spatial frequency at which motion could be perceived was about 0.44 cpd. At the eccentricity of 8°, the current study predicts a lower cutoff spatial frequency at about $2.5/8 = 0.31$ cpd. The cutoff frequency difference can be explained by the different stimulus configurations. The bars in our study were radially orientated and were all flanked by other bars, while the orientation of Solomon and Sperling's bars was constant across the annulus (tilted at 45°) so that, some bars were not flanked by others in some parts of the annulus. In fact, for spatial frequencies of 0.5 cpd and lower (i.e., roughly the conditions under which they observed a texture contribution to motion) there was less than one cycle visible on some parts of the annulus so that some bars were not flanked at all. This uncrowded condition certainly facilitated attention mechanisms to select and track the visible bar. Thus, Solomon and Sperling's results are compatible with ours with the exception that they found a slightly higher cutoff spatial frequency that can be explained by their stimulus configuration facilitating the feature tracking motion system.

First-order processing of contrast-defined motion

It is now well established that there are at least two motion systems enabling the processing of contrast-defined motion. One effective at low speeds and low contrasts and another for high speeds and high contrasts. For instance, Seiffert and Cavanagh (1999) found that contrast-defined motion was processed by a position-based motion system (which suggests feature tracking) at low contrast and low speeds and by an energy-based motion system at high contrasts and high speeds. It has been shown that under some conditions the energy-based motion system processing contrast-defined motion could be the first-order motion system due to some form of artifact such as early nonlinearities (Scott-Samuel & Georgeson, 1999), nonlinearities at the contrast-normalization stage (Benton, 2004), local texture biases (Smith & Ledgeway, 1997) or low spatial frequency components in the carrier (Cropper & Johnston, 2001). Nonetheless, several authors using high contrast carriers found similar properties to the first-order motion system for the motion system processing contrast-defined motion and argued that this could not be due to any of these artifacts, so they concluded that there is a dedicated second-order motion system. The first- and second-order motion systems would have similar temporal frequency functions (Lu & Sperling, 1995, 2001), would be resistant to a static pedestal (Lu & Sperling, 1995, 2001) and would lose sensitivity with eccentricity at similar rates (Smith & Ledgeway, 1998). These authors argued that their contrast-defined motion could not be processed by the first-order motion system, but they did not consider residual distortion products, which was recently found to explain the texture contribution to motion at high temporal frequencies (Allard & Faubert, 2013) and in the periphery (except for very low spatial frequencies that can be processed by feature tracking). Thus, we conclude that the similar temporal sensitivity functions and sensitivity drops with eccentricity were observed because both stimuli were processed by the same motion system (i.e., first-order). This implies that under many conditions (especially for high contrast, high speed and/or in the periphery), energy-based contrast-defined motion processing could be due to distortion products being processed by the first-order motion system, not to a dedicated second-order motion system sharing similar properties with the first-order motion system.

Residual distortion products can also explain apparently conflicting results about interactions between the processing of luminance- and contrast-defined motion. Cross-attribute motion cancellation (Lu & Sperling, 1995) and masking (Allard & Faubert, 2008a) imply at least some common processing. However, the fact that luminance- and contrast-defined frames are not integrated to produce a coherent motion percept has been taken as evidence of distinct motion systems (Ledgeway & Smith, 1994; Mather & West, 1993). However, if contrast-defined motion were processed by the first-order motion system due to residual distortion products, then the same pattern of results would be expected. Since both luminance- and contrast-defined motions would be processed by the same first-order motion system, we would obviously expect cross-attribute masking and motion nulling. On the other hand, because residual distortion products correspond to luminance modulations of both polarities, some distortion products would combine in phase and others in opposite phase with the luminance modulation resulting in motion and reverse-motion, i.e., no net motion percept. Consequently, the fact that luminance- and contrast-defined interlaced frames are not integrated to result into a coherent motion percept does not imply distinct motion systems since this lack of interaction is expected if residual distortion products enable the contrast-defined motion processing.

Many studies have suggested the existence of a dedicated second-order motion system, but skepticism remains and the current study provides strong support for the opposite thesis. Some studies have suggested that a second-order motion system can operate at high temporal frequencies (Lu & Sperling, 1995, 2001; Scott-Samuel & Georgeson, 1999; Smith & Ledgeway, 1998) and in the periphery (Smith & Ledgeway, 1998; Solomon & Sperling, 1995), but we have concluded that the texture contribution to motion in these conditions are due to residual distortion products being processed by the first-order motion system. Thus, some texture contribution to motion under other conditions (i.e., at fixation and at low temporal frequencies) taken as evidence of a second-order motion system could also be due to residual distortion products being processed by the first-order motion system. Moreover, the current study shows that, contrary to certain claims, the use of dynamic noise carriers does not prevent contrast-defined leaking within the first-order pathway and different detection and direction discrimination thresholds do not imply that contrast-defined motion is not processed by the first-order motion system. In addition, previous findings taken as strong evidence of distinct luminance- and contrast-defined motion processing (e.g., luminance and contrast modulations not integrated into a clear motion percept) are also predicted by residual distortion products so they do not imply distinct motion systems. Consequently, the present study contradicts many central arguments made for the existence of a dedicated second-order motion system. Given the existence of residual distortion products enabling the first-order system to process contrast-defined motion and that contrast-defined motion processing is only due to such distortions for spatiotemporal frequencies beyond attentional acuity, we find no reason to suggest the existence of a dedicated second-order motion system that can operate only under the same conditions as the feature tracking motion system and there is no reason why a dedicated second-order motion system would be limited to central vision ($<5°$ eccentricity) or very low spatial frequencies (much lower than 0.5 cpd at which no texture contribution was observed). We conclude that contrast-defined motion is being processed solely by the first-order and feature tracking motion systems, not by a dedicated second-order motion system.

Keywords: motion, second-order, feature-tracking, residual distortion products

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