Global motion processing: Invariance with mean luminance

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We examine how global translational motion sensitivity varies with the mean luminance of the stimulus. Using DC-balanced, spatially narrowband micropatterns (radial Log Gabors) matched in terms of detectability (multiples above contrast threshold), we show that global translational motion sensitivity is invariant with the mean luminance. Contrast detection thresholds, however, show a characteristic spatial frequency dependence on mean luminance. Similar results were found for central and peripheral regions of the field and for a range of different micropattern velocities (2.1 deg/s to 84 deg/s). Thus, the sensitivity of global motion processing that occurs in extrastriate cortical areas, unlike the detectability of the stimuli themselves that occurs in lower visual areas, does not vary with mean luminance.

Keywords: global motion, spatial frequency, eccentricity, luminance


Introduction

The human visual system is able to operate over an impressive luminance range in excess of 10 log units. To maintain sensitivity over such a large operating range, compromises have to occur and a number of studies have concentrated on what these adaptations are for various visual functions (Hess & Nordby, 1990). Motion perception is a good example; this information is used to alert us about the relative motion of an object within the scene in the case of local motion and to guide our navigation through the world in the case of global motion. Although a number of studies have investigated whether motion sensitivity varies with mean luminance, there is no complete consensus. Some studies argue that for local motion processing, sensitivity is invariant with mean luminance (van de Grind, Koenderink, & van Doorn, 2000); others argue that different processing strategies are used at photopic and scotopic luminances for central vision (Takeuchi & De Valois, 1997, 2000), and yet others argue for significant perceptual slowing at low luminances for stimuli of low velocity (Gegenfurtner, Mayser, & Sharpe, 2000). In the case of global motion processing, a similar controversy exists. Some studies suggest invariant sensitivity across luminance (Lankheet, van Doorn, Bouman, & van de Grind, 2000; Lankheet, van Doorn, & van de Grind, 2002), while others argue that sensitivity either declines with reducing luminance in a contrast-dependent manner (McCollum et al., 2000) or is impaired at higher (6 deg/s and 13 deg/s) velocities (Billino, Bremmer, & Gegenfurtner, 2008). It is well known that contrast sensitivity has a two-part dependence on mean luminance (van Nes & Bouman, 1967). Initially, as luminance is reduced, contrast sensitivity remains invariant (the Weber region), after which it displays a square-root dependence (the Rose–de Vries region; van Nes & Bouman, 1967). The luminance at which the behavior switches from Weber to Rose–de Vries (termed the transition luminance) depends on the spatial frequency of the stimulus; the lower the spatial frequency, the lower the transition luminance and hence the more resistant the sensitivity is to changes in mean luminance. Thus, the effect of reducing mean luminance is strongly scale-dependent. This is also the case for temporally varying spatial stimuli (van Nes, Koenderink, Nas, & Bouman, 1967). This is an important issue because the use of spatial frequency broadband elements, such as dots (Billino et al., 2008; McCollum et al., 2000) and broadband noise (Lankheet et al., 2000, 2002), in studies of global motion has been ubiquitous and may be one of the main reasons why previous studies have come to such conflicting conclusions of the effects of luminance on global motion sensitivity. For example, the results using broadband dots have suggested that scotopic motion sensitivity exhibits velocity (Billino et al., 2008) as well as contrast dependence (McCollum et al., 2000). The role that spatial scale plays in these conclusions needs to be determined. A more complete understanding of the effects of mean luminance on global motion sensitivity requires controlling the spatial scale of the motion stimuli so that their detectability can be taken into account at different light levels. Furthermore, the role of eccentricity also needs to be assessed since there is evidence that the fovea...
and periphery use different motion detection strategies at photopic and scotopic luminances (Takeuchi & De Valois, 2009). They found that as retinal illuminance decreases, the relative contribution of a feature-tracking mechanism in the central retina becomes larger, while motion perception in the peripheral retina continues to depend on a biphasic, first-order motion mechanism.

Here we used an array of spatial frequency band-pass elements to measure how the detectability of such stimuli vary with light level. After ascertaining this, we assessed how global motion sensitivity for stimuli equated for detectability varies with light level. To do this, we set all global motion stimuli to a fixed multiple (i.e., ×3) above their contrast detection threshold at all light levels. We did this for a range of stimulus spatial frequencies and image velocities. We also investigated two different regional arrangements of elements, one designed to test central vision where the elements are distributed just within a central region and another designed to test peripheral vision where the elements are distributed in an annular peripheral region. Our model of global motion processing involves two different stages in series (Morrone, Burr, & Vaina, 1995). The first involves the contrast-dependent local motion analysis associated with the processing of small directionally selective receptive fields in area V1 followed by the integration of these local motion estimates within much larger receptive fields of the type typically found in extrastriate areas V5/MT and MST. By separately estimating the contrast-dependent motion effects and the coherence sensitivity for equi-detectable stimuli, we hope to understand how luminance may affect the processing at these two separate stages of motion analysis and whether this is dependent on where the image is located within the visual field (e.g., central vs. peripheral).

Our results show the expected space-dependent changes in contrast sensitivity that others have reported previously for stationary and flickering stimuli. Once these low-level changes have been factored out by using stimuli of equal suprathreshold contrast, coherence sensitivity was found to be invariant with mean luminance at all the spatial scales investigated. Similar conclusions were found for stimuli located in central and peripheral parts of the field.

### Methods

#### Stimuli

The stimuli were random micropattern kinematograms (RMK) made of limited lifetime, circular, isotropic, and band-pass Log-Gabor microelements. Radial Log Gabors have the advantage of a restricted bandwidth without DC (Aaen-Stockdale & Hess, 2008; Hess & Aaen-Stockdale, 2008). The motion was left/right translational. Two stimuli arrangements were used; one involved just a central arrangement (central vision), the other an annular arrangement (peripheral vision). The number of micropatterns, duration, and interstimulus intervals were the same for all experimental conditions. Each stimulus frame had 50 microelements, initially randomly distributed over an aperture area, be it central or annular (peripheral). In order to vary spatial scale of the elements (i.e., 0.5 c/d, 1 c/d, and 5 c/d), we used three different viewing distances (30 cm, 60 cm, and 3 m). We have previously shown that coverage (not element density) is the important factor when comparing elements of different scale for this motion task (Hess & Aaen-Stockdale, 2008). This resulted in the use of self-similar arrays to test different spatial scales. As a consequence, the central field radii were 12°, 6°, and 1.2° and peripheral annular stimulations extending from 12° to 24°, 6° to 12°, and 1.2° to 2.4° (Table 1). Each microelement moves uniformly for 100 ms (lifetime of 6 frames) at one of a range of speeds (2.1 deg/s, 4.2 deg/s, 21 deg/s, 42 deg/s, and 84 deg/s) (see Table 1). Once their lifetime expires, the microelements were randomly relocated inside the circular aperture. When moving outside the circular aperture, the microelements were repositioned on the opposite side of the circular aperture relative to their motion direction. The temporal phase of each element was randomized in the first frame of each motion sequence, so they appear and disappear randomly in time (according to a uniform distribution). The RMK motion lasts 500 ms (30 frames).

Radial Log-Gabor elements were generated in the Fourier domain according to

\[
\text{RadLogGauss}(f) = \exp\left(\frac{-\left(\log(f/f_0)\right)^2}{2\left(2\log(\text{sigmaOnf})^2\right)}\right)
\]

where the constraint of $\text{RadLogGauss}(0)=0$,\(^{1}\)

then converted to the spatial domain after inverse Fourier transform:

\[
\text{RadLogGabor}(r) = \text{inv FFT}(\text{RadLogGauss})
\]

where $f$ is the radial frequency, $f_0$ is the peak frequency, and $\text{sigmaOnf}$ defines the spatial bandwidth (1/1.5 corresponding to about 1.5 octaves). The radial Log Gabors were even symmetric in the spatial domain (i.e., bright center, dark surround). To achieve this, a zero phase spectrum was used in the Fourier domain (Figures 1 and 2).

<table>
<thead>
<tr>
<th>Spatial frequency (c/d)</th>
<th>Central stimulus radius (deg)</th>
<th>Peripheral stimulus inner/outer radius (deg)</th>
<th>Velocities (deg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>12</td>
<td>12/24</td>
<td>4.2, 42, 84</td>
</tr>
<tr>
<td>1.0</td>
<td>6</td>
<td>6/12</td>
<td>2.1, 21, 42</td>
</tr>
<tr>
<td>5.0</td>
<td>1.2</td>
<td>1.2/2.4</td>
<td>4.2, 8.4</td>
</tr>
</tbody>
</table>

Table 1. Stimulus parameters for the RMKs.
Apparatus and calibrations

The stimuli were displayed on a Sony Trinitron monitor (E500) driven by a Bit++ device (Cambridge Research Systems) with 14-bit contrast resolution, connected to a Macintosh G4 computer running the PsychToolBox software under Matlab. The display resolution was 1024 × 768 pixels, pixel size was 0.375 mm, and frame rate was 60 Hz. The monitor was gamma corrected in software with lookup tables using luminance measurements obtained from an Eye-One Display 2 calibration device (Gretagmacbeth). The monitor was viewed in a dimly lit room. The mean luminance of the display was 50 cd/m². The stimuli were generated online, and a new RMK stimulus was generated for each presentation.

Protocol

A complete data set for two subjects (AZ, RH) is shown, AZ being naive to the purpose of the investigation.

Figure 1. The radial Log-Gabor micropatterns used had a spatial frequency band-pass spectrum with no DC. The spatial weighting function is shown at the top and the spatial frequency spectrum at the bottom.
Additional data (not shown) for all but the lowest velocities (2.1 deg/s and 4.2 deg/s) were collected for another subject (RD). All experiments were replicated on two subjects with the exception of the contrast response functions for central viewing for which subject AZ viewed a 1 c/d stimulus and RH, a 0.5 c/d stimulus. Owing to slight difference in the sensitivity of individual subjects, the mean luminance ranges tested may have differed slightly in some cases. Coherence thresholds were measured at multiples of contrast detection thresholds (i.e., $3^C$). Contrast detection thresholds were first measured for several element spatial frequencies and regional distributions using interleaved staircases, where subjects were required to judge the direction of homogeneous RMK stimuli presented at 40% coherence level (direction discrimination task). Coherence thresholds were then measured for RMK stimuli of preset contrast using a staircase procedure. In both staircase procedures, either the stimulus contrast or the coherence level was reduced after three correct responses (by 50% before the first reversal and 25% after the first reversal), and increased after one wrong response (by 25%). Each session stopped after 6 reversals, and the threshold corresponding to a criterion of about 80% correct was computed from the mean of the last four reversals. Subjects provided their responses by pressing keyboard keys associated with left and right motions, respectively.

Coherence thresholds were measured for different spatial frequencies ($f = [0.5, 1, 5]$ c/d), speed (2.1, 4.2, 21, 42, 84 deg/s), and regional distribution (central vs. peripheral) of microelements.

Auditory feedback was given after each trial. A white fixation mark was briefly presented at the beginning of each trial in the center of the display. Practice trials were run before the experiments commenced. The number of trials per run for each experiment varied between 50 and 100 for each subject, and thresholds were obtained from the average of 3–4 repetitions for each condition.

The mean luminance of the display was varied using Kodak gelatin neutral density filters fitted to light-tight goggles. The mean luminance was varied between 50 cd/m$^2$ and 0.016 cd/m$^2$ in 0.5 log unit steps and sufficient time was allowed for the eye to dark adapt.

**Results**

Figure 3 shows the contrast thresholds of coherent motion stimuli (fixed 40% coherence) for two subjects for three spatial frequencies (0.5, 1, and 5 c/d) and 5 image velocities (4.2 deg/s, 8.4 deg/s, 21 deg/s, 42 deg/s, 84 deg/s) for central vision (see Table 1). The error bars represent ±1 SE. Similar results are displayed in Figure 4 for two subjects, for two spatial frequencies (0.5 and 1 c/d), and 3 image velocities (21 deg/s, 42 deg/s, 84 deg/s) for the peripheral stimuli (see Table 1). In both cases, the dashed lines are not meant to provide optimal fits to the data but are constrained to have a slope of $-0.5$ so that the extent to which these global motion contrast thresholds conform to the prediction for static and flickering stimuli (van Nes & Bouman, 1967; van Nes et al., 1967) in the low luminance regions can be ascertained. In all cases, but for the first two photopic levels, there is a strong dependence of contrast threshold on luminance. The falloff with reducing luminance conforms reasonably well to the square-root prediction (van Nes & Bouman, 1967; van Nes et al., 1967).

Similar contrast threshold data were obtained for two subjects (AZ and RH) for lower image velocities (2.1 and 4.2 deg/s) for both central and peripheral vision (20 deg...
Figure 3. Contrast thresholds for 40% global motion RMKs for two subjects as a function of element contrast for central stimulation. Results are shown for RMKs composed of radial Log Gabor's of different spatial frequencies (colors) and different micropattern velocities (bottom row data vs. top row data; same spatial frequency but a factor of 2 different in velocity).

Figure 4. Same as for Figure 3 but for peripheral stimulation.
Having the relevant information on the contrast detection threshold for central and peripheral global motion stimuli of different spatial frequencies and speeds allows one to compare global motion coherence thresholds for stimuli of comparable contrast relative to threshold. We used the contrast threshold data displayed in Figures 3 and 4 to set the stimulus contrast at 3 times the threshold so we could measure motion coherence thresholds as a function of mean luminance factoring out any visibility effects relevant to these motion stimuli. These global motion coherence thresholds are displayed in Figures 5–8 for central and peripheral visions. For illustrative purposes, only the central data for the two velocity ranges for AZ and the comparable peripheral data for RH are shown in Figure 5. A similar conclusion was obtained from the peripheral data from AZ and the central data from RH (data not displayed).

The results show that global motion sensitivity is invariant with mean luminance over the whole luminance range for which measurements could be made for these stimuli of fixed suprathreshold contrast. This is true for stimuli of different spatial frequency, image velocity, and retinal position.

So far we have demonstrated invariant motion sensitivity for global stimuli when they are at 3 times their contrast threshold. One presumes that a similar result would be obtained at other fixed suprathreshold values; in other words, the contrast response function for global motion detection for stimuli with different parameters is simply displaced laterally for different luminances (along the contrast axis) by an amount that corresponds to the contrast threshold (Simmers, Ledgeway, Hess, & McGraw, 2003). If this were the case, then contrast response functions for motion coherence measured at different luminances should be identical when plotted as a function of the contrast normalized to threshold (contrast as fixed multiples above threshold). Contrast response functions for global motion detection plotted as a function of contrast relative to threshold for different luminances are shown in Figures 7 and 8. Figure 7 shows data for medium–high image velocities and Figure 8 for stimuli of low image velocities.

Figure 5. Motion coherence thresholds are displayed as a function of the mean luminance for RMK stimuli composed of arrays of radial Log-Gabor elements set at 3 motion contrast thresholds. Results are shown for three spatial frequencies (0.5 c/d, 1 c/d, 5 c/d) and 5 medium to high micropattern velocities (4.2 deg/s to 84 deg/s). The error bars represent ±1 SE.
The results describing the relationship between coherence threshold and micropattern contrast are fitted (dashed curve) by a power function:

\[ Y = ax^b + c \]  

where a, b, and c are constants.

The derived parameters (see Supplementary Table 1) describe a two-stage model used previously to describe results for RMK stimuli (Hess, Hutchinson, Ledgeway, & Mansouri, 2007; Simmers et al., 2003). In all cases, motion contrast response functions at different luminances superimpose (have similar fitted functions) when plotted in terms of contrast relative to threshold confirming the prediction based on the results previously shown in Figures 5 and 6. This is the case for all stimulus spatial frequencies, micropattern velocities, and retinal regions investigated.

**Discussion**

The results of the present investigation show that global motion thresholds are invariant with mean luminance. This is the case for a wide range of spatiotemporal frequencies and for the central and peripheral parts of the visual field. It is, however, contingent on the visibility of the stimuli being equated across mean luminance for the task in hand, in this case, motion direction discrimination of RMK stimuli. Since the main effect of reducing the mean luminance is to reduce the visibility (i.e., elevate the contrast thresholds) in a spatial frequency-dependent manner, it is important to be able to compensate for these effects in a scale-dependent way. Our use of spatial frequency band-pass elements allowed such a compensation and, in turn, reveal the dependence of visibility, but not global motion, on variations in mean luminance. In a similar manner, we have shown previously that global motion sensitivity for both first- and second-order stimuli is invariant across the visual field, once the local visibility of the stimuli are equated (Hess & Aaen-Stockdale, 2008).

All previous studies have used spatial frequency broadband elements to investigate this issue and unsurprisingly, for the reasons listed above, have come to conflicting conclusions. For example, one such study (Billino et al., 2008) reported invariant behavior at low but not high velocities. Since visibility was not controlled for (they used stimuli of fixed high contrast), this may have been
due to either a greater reliance on the higher spatial scale information contained within their stimulus or to an interaction across spatial scale. Our results show that spatially band-pass stimuli with high image velocity, much higher than used in this previous study (Billino et al., 2008), display invariant behavior with mean luminance.

Another study (Lankheet et al., 2000) used a random pixel array that was scaled in size with acuity at different light levels. This method scales the visibility of the high spatial frequency components of the broadband stimulus, and given the octave bandwidth of visual filters, it is the high spatial frequencies of a random pixel array that will underlie detection. They found that the detection (as quantified by a static noise mask) for such a scaled stimulus was invariant with mean luminance. This conclusion is consistent with what we find, but the contribution of different spatial scales remains indeterminate with such a broadband stimulus. In a latter paper, the authors (Lankheet et al., 2002) attempt to measure “spatial and temporal tuning functions” as a function of mean luminance for their random pixel arrays. They found large shifts in the spatial parameter and smaller shifts in the temporal parameter. However, the interpretation of such results is far from simple for such a spatiotemporal broadband stimulus.

In the present study, we show that for individual spatial scales and for individual velocities, coherence thresholds are invariant with reductions in mean luminance. A similar comment can be made concerning a study by

Figure 7. Coherence thresholds for two observers are shown as a function of the contrast above motion detection threshold for two luminance levels for central vision. The contrast response functions are similar when compared for stimuli of equivalent suprathreshold contrast. Results are shown for different spatial frequencies and micropattern velocities. The error bars represent ±1 SE.
McCollum et al. (2000) in which spatial and temporal determinants of global motion were studied in monkeys as a function of mean luminance limited to the photopic range. They found that global motion sensitivity did increase as luminance was increased but only for low contrasts. Their stimulus, unlike the one used here, was composed of sharp-edged dots (spatial frequency broadband) that were not modulated about the mean level (smearing the distinction between contrast and mean luminance). Our results emphasize the important spatial scale/contrast dependence as light level is reduced (van Nes & Bouman, 1967), a dependence that is hard to appreciate when spatial frequency broadband stimulus elements are used because different motion contributions are carried by different spatial scales. The effectiveness of these different scale contributions will depend on mean luminance as well as absolute contrast.

These results suggest that reducing the luminance affects the detectability of stimuli in motion rather than their motion processing per se, suggesting that both the processing of local motion in different parts of the field and its subsequent integration at a global stage must be unaffected by changes in mean luminance as vision changes from cone-dominated photopic levels to rod-dominated scotopic levels. What little neurophysiology there is on this issue suggests an explanation. Both the

![Figure 8](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933482/)

Figure 8. Coherence thresholds for two observers are shown as a function of the contrast above motion detection threshold for two luminance levels for central and peripheral visions. Results for a spatial frequency of 0.5 c/d and image velocity of 4.2 deg/s are shown. The error bars are ±1 SE.
spatial and temporal tuning of cortical cells (Bisti, Clement, Maffei, & Mecacci, 1977; Hess, 1990) are invariant with reductions in mean luminance (though this is far from the case in the retina, see Enroth-Cugell & Robson, 1966). It is just the contrast sensitivity that changes with reducing mean luminance and this occurs in a spatial frequency-dependent manner. The invariant spatiotemporal tuning properties of cells in the early part of the cortical pathway as the light level is reduced enables the local motion properties of cells to maintain their invariance across luminance.

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References


