A normative framework for the study of second-order sensitivity in vision

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While the contrast sensitivity approach has been successful in evaluating the processing of first-order stimuli, there is a need to develop comparable ways of assessing second-order vision. Our purpose here is to establish normative data on second-order contrast-, orientation-, and motion-modulation sensitivity in humans. We propose a unified framework, applying the quick contrast sensitivity function (qCSF) method, which was recently developed for the rapid measurement of contrast sensitivity across the full spatial-frequency range (Lesmes, Lu, Baek, & Albright, 2010), to measure both first- and second-order sensitivity functions. We first show that the qCSF methodology can be successfully adapted to different kinds of first- and second-order measurements. We provide a normative dataset for both first- and second-order sensitivity, and we show that the sensitivity to all these stimuli is equal in the two eyes. Our results confirm some strong differences between first- and second-order processing, in accordance with the classical filter-rectify-filter model. They suggest a common contrast detection mechanism but different second-order mechanisms.

Introduction

Our assessment of visual function has always depended on our evolving understanding of retinocortical function at the single and multineuron level. Measuring the contrast sensitivity function using spatially localized band-pass Gabor patches of different spatial frequencies is useful because we know cells in striate cortex have localized receptive fields with spatial frequency band-pass responses that also depend on stimulus contrast (Campbell, Cooper, & Enroth-Cugell, 1969; De Valois & De Valois, 1990; Maffei & Fiorentini, 1973). This assessment was initially applied to quantify the optical quality of the eye (Campbell & Gubisch, 1966) and has had a long and successful history in quantifying overall striate function in health (Banks, Geisler, & Bennett, 1987; Campbell & Green, 1965; Campbell & Robson, 1968; Hess & Nordby, 1990) and disease (Bodis-Wollner, 1972; Hess & Howell, 1977; Kersten, Hess, & Plant, 1988; Legge & Rubin, 1986; Levi & Harwerth, 1977; Regan, Silver, & Murray, 1977).

This contrast sensitivity approach has been successful in evaluating the processing of first-order stimuli in striate cortex. Nevertheless, there is a need to develop comparable ways of assessing second-order vision in humans. There is evidence that this second-order sensitivity involves striate and extra-striate processing (Hallum, Landy, & Heeger, 2011; Kastner, Weerd, & Ungerleider, 2000; Larsson, Heeger, & Landy, 2010;...
Larsson, Landy, & Heeger, 2006; Reppas, Niyogi, Dale, Sereno, & Tootell, 1997). Second-order modulated stimuli are thought to be processed by the visual system in two serial stages: First the carrier is processed by localized, spatially band-pass neurons in striate cortex or even upstream to V1 (Demb, Zaghloul, & Sterling, 2001; Gharat & Baker, 2012; Rosenberg, Husson, & Issa, 2010), and then in a second stage the rectified first stage output is integrated by the larger receptive fields of cortical neurons (Baker, 1999; Morrone, Burr, & Vaina, 1995). Stimuli that involve modulations over large spatial extents would be ideally matched to the receptive field properties of cortical neurons. Such modulations could involve changes in contrast, orientation, or motion; with the latter two biasing the assessment to the ventral and dorsal extrastriate pathways, respectively.

In this study our purpose is to establish normative data on the sensitivity of three cardinal stimuli: contrast, orientation, and motion modulated, where each is measured with an optimal constant ratio between the carrier and envelope spatial frequencies (contrast: Dakin & Mareschal, 2000; Sutter, Sperling, & Chubb, 1995; Zhou & Baker, 1993; motion: Meso & Hess, 2010; and orientation: Landy & Oruc, 2002; Meso & Hess, 2011; Reynaud & Hess, 2012). We also include the measurement of the detectability of the carriers that were modulated to create these stimuli. Indeed, the contrast of the carrier was set to a constant suprathreshold value so that the upstream input can be equated, allowing a fair assessment of second order sensitivity.

We propose a unified framework in order to establish and compare these normative datasets using the same protocol for all the measurements. We use a common methodology, the quick contrast sensitivity function (qCSF) method, recently developed for the rapid measurement of contrast sensitivity across a range of spatial frequencies (Hou et al., 2010; Lesmes, Lu, Baek, & Albright, 2010). This method was originally designed to determine the first-order contrast sensitivity function (CSF). However, the second-order modulation sensitivity functions (MSF) present approximately the same bell-shape as their first-order counterpart (contrast-modulation: Hutchinson & Ledgeway, 2006; Schofield & Georgeosan, 2003; orientation-modulation: Landy & Oruc, 2002; and motion-modulation: Meso & Hess, 2010; Watson & Eckert, 1994). We show here that this method is accurate for the measurement of second-order sensitivity and then use it to establish normative data on both first and second-order sensitivities in humans.

Our comparison of the sensitivity to different second-order stimuli will provide a more comprehensive assessment of cortical function (Grill-Spector, Kushnir, Edelman, Itzchak, & Malach, 1998; Kastner et al., 2000; Hallum et al., 2011; Larsson et al., 2006; Orban et al., 1995; Zhou & Baker, 1994). It is our hope that this framework will provide the foundation on which data will be collected for a range of different conditions. In normals this could involve a more comprehensive assessment of the influence of age on cortical function. Clinical applications could include the assessment of the relative involvement of striate and extrastriate areas in conditions such as amblyopia, multiple sclerosis, traumatic brain injury, and cortical hypoxia.

Methods

Subjects

To establish this normative dataset, 52 subjects (27 males and 25 females, average age = 24.9 ± 0.3 years, range: 21–30 years) were recruited; four of them participated in the control experiment. They had normal or corrected-to-normal visual acuity (better than 20/25) and were free from ocular diseases. All subjects were students at the University of Science and Technology of China. Informed consent was obtained from all participants. This research has been approved by the ethics committee in University of Science and Technology of China and by the Ethics Review Board of the Montreal Neurological Institute. It was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus

All procedures and analyses were processed with Matlab (© the MathWorks), using the Psychophysics (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997), Palamedes (Prins & Kingdom, 2009), and qCSF (Lesmes et al., 2010) toolboxes. Stimuli were presented on a gamma-corrected Sony G220 CRT monitor. The area of the display was 32.5 × 24.4 cm, the mean luminance 40 cd/m², the refresh rate 75 Hz, and the resolution 1600 × 1200 pixels. Subjects viewed the display monocularly in a dimly lit room at a viewing distance of 60 cm. A chin-forehead rest was used to minimize head movements during the experiment.

Stimuli

The visual stimuli presented either a first-order luminance modulation or a second-order contrast-defined, orientation-defined, or motion-defined modulation. The first-order stimuli contained either an
orientation component or a motion component. They were then used as carriers for building the second-order stimuli. Previous studies have detailed the optimal relationship between the spatial properties of the first-order carrier and the second-order envelope for contrast- (Dakin & Mareschal, 2000; Sutter, Sperling, & Chubb, 1995; Zhou & Baker, 1993), motion- (Meso & Hess, 2010), and orientation- (Landy & Oruç, 2002; Meso & Hess, 2011; Reynaud & Hess, 2012) modulated stimuli. Hence, we set a constant four-to-one ratio between the first-order carrier frequency and second-order envelope frequency. The construction of the second-order stimuli was similar to the orientation-modulated stimuli in Reynaud and Hess (2012). For consistency, all contrasts are expressed as Michelson contrasts.

First-order, carriers

In the case of first-order oriented stimuli (subsequently denoted LM1d) or second-order orientation modulated stimuli (denoted OM), the carriers $\mathbf{c}_h$ and $\mathbf{c}_v$ (Figure 1a, first row) were functions of two-dimensional space ($x, y$), with a range of values between $-1$ and $1$. They were generated in the space domain by respectively filtering white noises $w_1, w_2$ by orthogonally oriented Gabor filters $G_h$ and $G_v$ (Equation 1). $G_h$ and $G_v$ were respectively horizontally ($0^\circ$) and vertically ($90^\circ$) oriented. Their frequency and contrast were determined by the method (see Procedures), their bandwidth was 3 octaves.

\[
\mathbf{c}_h(x, y) = w_1(x, y) \ast G_h(x, y)
\]
\[
\mathbf{c}_v(x, y) = w_2(x, y) \ast G_v(x, y).
\]  

(1)

In the case of first-order moving stimuli (denoted LM2d) or second-order motion modulated stimuli (denoted MM), the carriers $\mathbf{c}'_h$ and $\mathbf{c}'_v$ (Figure 1b, first row) were functions of two-dimensional space and time ($x, y, t$) with a range of values between $-1$ and $1$. They were generated by successively filtering white noises $w_1, w_2$ by both the orthogonally oriented Gabor filters $G_h$ and $G_v$ (Equation 2). The carriers were moving in

\[
\mathbf{c}'_h(x, y, t) = w_1(x, y, t) \ast G_h(x, y, t)
\]
\[
\mathbf{c}'_v(x, y, t) = w_2(x, y, t) \ast G_v(x, y, t).
\]  

(2)

The carrier is constituted of nonoriented two-dimensional-filtered noise moving horizontally or vertically (first-order motion case, noted LM2d). Two carriers moving in random orthogonal directions are respectively modulated by out-of-phase sine-wave gratings and summed to generate the second-order motion-modulated stimulus (noted MM). (c) Contrast modulation. The carrier is constituted of nonoriented two-dimensional filtered noise, its contrast is modulated by a sine-wave grating to generate the second-order contrast-modulated stimulus (noted CM). Stimuli are rendered here at 100% Michelson contrast.
random orthogonal directions, one vertical, one horizontal, at a drifting temporal frequency of 2 Hz. Note that the illustration Figure 1b indicates leftward and downward arrows but the actual carriers could move randomly leftward or rightward for the horizontal one and upward or downward for the vertical one.

\[
c_h'(x, t) = w_1(x + t, y)G_h(x, y)G_v(x, y)
\]

\[
c_v'(x, t) = w_2(x, y + t)G_h(x, y)G_v(x, y).
\]  

(2)

In the case of second-order contrast modulated stimuli (denoted CM) the carrier \(c_0\) (Figure 1c, first row) was a function of two-dimensional space \((x, y)\), with a range of values between \(-1\) and 1. It was generated by successively filtering white noise \(w_1\) by both orthogonally oriented Gabor filters \(G_h\) and \(G_v\) (Equation 3).

\[
c_0(x, y) = w_1(x, y)G_h(x, y)G_v(x, y).
\]

(3)

**Second-order, modulation**

As we wanted here to explore a wide range of frequencies, including high and low frequencies for which the thresholds would actually be quite high, we did not use any square-root rectification of the envelope because it is known that such a rectification might create a visual artefact at high modulation levels (Landy & Oruç, 2002). Also, at low modulation levels, the contrast energy change between square-root and non-square-root correction is very small (Watson & Eckert, 1994). Thus, to build the second-order stimuli, the carriers were modulated by two half-cycle phase-shifted grating envelopes of a frequency 1/4 that of the carrier, \(m_1\) and \(m_2\), respectively (Equation 4). These took values between zero and one, and were weighted by a modulation parameter \(m\) (0 < \(m\) < 1) characterizing the blending applied between the two textures (Figure 1a and b, second rows).

\[
m_1(x) = 1/2\left(1 + m \sin(2\pi m x)\right)
\]

\[
m_2(x) = 1/2\left(1 - m \sin(2\pi m x)\right).
\]

(4)

For the orientation-modulation stimulus, the final stimulus \(I_o\) consisted of the sum of the modulated oriented carriers \(c_h\) and \(c_v\) (Equation 5, Figure 1a third row). The second-order motion-modulated stimulus \(I_m\) consisted of the sum of the modulated moving carriers \(c'_h\) and \(c'_v\) (Equation 6, Figure 1b third row). In the case of second-order contrast-modulation, only one carrier and envelope were used, and the final stimulus \(I_c\) only corresponds to the modulated carrier (Equation 7, Figure 1c). These operations were done via the OpenGL blending functions of the Psychophysics toolbox.

\[
I_o(x, y) = \left(c_h(x, y) \times m_1(x)\right) + \left(c_v(x, y) \times m_2(x)\right)
\]

(5)

\[
I_m(x, y, t) = \left(c_h'(x, y, t) \times m_1(x)\right) + \left(c_v'(x, y, t) \times m_2(x)\right)
\]

(6)

\[
I_c(x, y) = c_0(x, y) \times m_1(x).
\]

(7)

In all of the second-order stimuli, the carriers did not provide any information about the envelope orientation. In particular, for the motion-modulation case, the two carriers were moving in random orthogonal directions (one horizontally and one vertically). Thus the direction of motion never provided any cue on the envelope orientation. The final stimulus was presented on a grey background in a Gaussian aperture of 10° standard deviation (see Reynaud & Hess, 2012). The filtered noise carrier has an RMS contrast of approximately 0.2 times that of the Michelson contrast. The application of the Gaussian mask also has the effect of reducing the apparent contrast of the stimulus.

**Procedures**

**Trial proceedings**

A single-interval identification task was employed to estimate the detection sensitivity. The subjects’ task was to identify the orientation of the carrier for the first-order measurements or the orientation of the envelope for the second-order measurements, horizontal or vertical. The trial time course was as follows: (a) a green fixation dot appeared on the screen, (b) the dot disappeared and the stimulus was presented for 1 s with an auditory cue, (c) a red dot appeared to indicate to the subject that a response was needed, (d) when the subject answered, the dot disappeared and audio feedback about the correctness of the response was provided. Dot luminance was matched to that of the background.

**Main experiment—Quick contrast sensitivity function**

In the main experiment, the sensitivity functions were determined using the quick contrast sensitivity function (qCSF) method (Hou et al., 2010; Lesmes et al., 2010). This method is a Bayesian adaptive procedure that estimates multiple parameters of the psychometric function. The qCSF jointly estimates thresholds across the whole spatial frequency range. For each trial, the method finds the optimal stimulus in order to maximize the expected information gain about
Figure 2. Sensitivity function characterization (adapted from Lesmes et al., 2010). The sensitivity is described by the truncated log-parabola model as a function of the spatial frequency. Four parameters are represented: the peak gain \( \gamma_{\text{max}} \), the peak frequency \( f_{\text{max}} \), the bandwidth \( \beta \), and the cutoff frequency \( f_c \).

The parameters of the sensitivity function under study (Lesmes et al., 2010). The method estimates the sensitivity function with the truncated log-parabola model (Ahumada & Peterson, 1992, Watson & Ahumada, 2005). The log-parabola function in Equation 8 can be described by three parameters: the peak gain \( \gamma_{\text{max}} \), the peak frequency \( f_{\text{max}} \), and the bandwidth \( \beta \) (full-width at half-maximum, Figure 2).

\[
S'(f) = \log_{10}(\gamma_{\text{max}}) - \kappa \left( \log_{10}(f) - \log_{10}(f_{\text{max}}) \right)^2, \tag{8}
\]

with \( \kappa = \log_{10}(2) \) and \( \beta' = \log_{10}(2\beta) \).

The truncated log-parabola comes from the truncation imposed for low frequencies and described by the parameter \( \delta \). The log-sensitivity \( S \) is then expressed in Equation 9:

\[
S(f) = \log_{10}(\gamma_{\text{max}}) - \delta \quad \text{if} \quad f < f_{\text{max}} \quad \text{and} \quad S'(f) < \log_{10}(\gamma_{\text{max}}) - \delta \quad \text{else}.
\tag{9}
\]

Unlike Lesmes et al. (2010), we discarded the truncation parameter from our analyses because it was often out of the range of our measurements. The cutoff frequency \( f_c \) was calculated in function of the other parameters, as the frequency for which the sensitivity is minimal \( S = 0 \) (Equation 10).

\[
f_c = f_{\text{max}} \cdot 10^{-\frac{\log_{10}(\gamma_{\text{max}})}{2}} \tag{10}
\]

For the qCSF measurements, the possible range for the modulation was 0.001 to 1. The frequency range in which the sensitivities were measured was truncated compared to that in the original methodology; here it was 1 to 14.16 c/d for first-order luminance and 0.25 to 3.54 c/d for second-order modulation frequency. The initial priors of the qCSF were set manually: The gain prior was set to 100 for the first order and to 10 for second order; the peak frequency prior was set to 8 c/d for the first-order and to 2 c/d for the second-order; and the bandwidth prior was set to 3 octaves in both cases.

Sensitivity was measured monocularly with the dominant eye measured first. The first-order sensitivities were measured just before their second-order counterparts because, for each subject individually, the contrast of the carrier for the OM and MM conditions was set to 10 times their contrast threshold for detecting the respective carrier (LM1d and LM2d conditions). For the CM, the mean contrast was fixed at 0.5 to ensure that the full range of modulation was always available. Then, for half of the subjects the order of the measurements was LM1d - OM - LM2d - MM - CM. For the other half the order was CM - LM2d - MM - LM1d - OM. Each run consisted of 100 trials preceded by five training trials. Each run took approximately 7 min and was repeated two times. An extra run was performed in case these two repetitions showed a notable difference.

### Control experiment—Constant stimuli

In a control experiment, the second-order thresholds were measured with the constant stimuli method separately for each spatial frequency: 0.25, 0.35, 0.49, 0.68, 0.94, 1.31, 1.83, 2.54, and 3.54 c/d. The levels of modulations were 0.02, 0.04, 0.08, 0.16, 0.32, 0.64, with 40 repetitions per level. The detection thresholds were determined by fitting a Weibull function (least-square estimation method) to the psychometric datasets. Their standard deviations were estimated by a bootstrap procedure. The order of the control measurements was OM - CM - MM The dominant eye was always measured first, as in the main experiment. Each measurement took approximately 15 min.

### Results

#### Suitability of the truncated log-parabola model

An important step in our study was to show that the qCSF method can be adapted to second-order vision. It is known that the second-order modulation sensitivity function presents a bell shape (contrast modulation: Hutchinson & Ledgeway, 2006; Schofield & Georgeson, 2003; orientation-modulation: Landy & Oruç, 2002; and motion-modulation: Meso & Hess, 2010; Watson & Eckert, 1994). However, the accuracy of the truncated log-parabola model to second-order sensitivity functions still needs to be assessed. Thus, we tested this model on...
the second-order sensitivity measured using the method of constant stimuli. The measured sensitivities from four subjects for both their dominant and nondominant eyes are reported as a function of spatial frequency in Figure 3. The contrast-, orientation-, and motion-modulation data are presented in Panels a, b, and c, respectively.

Data points were then fitted a posteriori with the truncated log-parabola model (Equation 8, least-squares estimation method). The function faithfully fits the data (solid lines in Figure 3, coefficient of determination \( r^2 = 0.73 \)), therefore we can affirm that the truncated log-parabola is an accurate model to describe second-order sensitivity functions.

We then compared the truncated log-parabola a posteriori estimates (Figure 3 solid lines) to the qCSF estimates (Figure 3 dotted lines). Visually, both estimates are coherent with the data points. More precisely, the four studied parameters of the model: the peak gain \( c_{\text{max}} \), the peak frequency, \( f_{\text{max}} \), the cutoff frequency, \( f_c \), and the bandwidth, \( \beta \), are compared in the scatter plots shown in Figures 4a–d. On the horizontal axis are reported the values estimated with the qCSF and on the vertical axis, the values for the fit a posteriori. The estimates for gain, peak frequency, and cutoff frequency fall close to the identity line and are not significantly different (paired Wilcoxon signed rank test, \( \alpha = 0.05 \)). The bandwidth estimates show larger values for the fit a posteriori compared to the qCSF. Indeed, the qCSF forces a band-pass result and therefore might not capture low-pass sensitivity functions well. However these differences are not significant either (paired Wilcoxon signed rank test, \( \alpha = 0.05 \)). As a result, we can say that the truncated log-parabola model accurately describe the second-order sensitivity and that the sensitivity function parameters estimated with the two methods are not significantly different. Thus, the qCSF method is an appropriate tool to measure the sensitivity to second-order modulations.

**Normative dataset**

The average sensitivity functions over the 52 subjects for first- and second-order modulations are shown in Figure 5a for the dominant eye (DE) and in 5b for the nondominant eye (NDE). The individual functions for each subject are shown in the Appendix. The first observation is that the ensemble of the sensitivity functions is qualitatively similar for the two eyes. We can observe that the sensitivity functions are clustered in two groups corresponding to the first-order and the second-order sensitivity. The first-order sensitivities are an order of magnitude in amplitude and frequency above the second-order ones. This agrees with previous
work (e.g., Hutchinson & Ledgeway, 2006) finding that first-order vision exhibits better sensitivity and extends to higher spatial frequencies than second-order vision.

The two first-order contrast-sensitivity functions for oriented and moving carriers are similar in both amplitude, peak position, and shape. They peak at a frequency of approximately 2 c/d and have a sensitivity of 40 (based on Michelson contrast, equivalent to 190 in RMS contrast, see Method and Kukkonen, Rovamo, Tiippana, & Näätänen, 1993). This result with filtered noise stimuli is consistent with well-known previous results using single sinusoids (Campbell & Robson, 1968).

The second-order contrast-modulation sensitivity function peaks at a frequency of approximately 1.2 c/d with a sensitivity of 40 (based on Michelson contrast, equivalent to 190 in RMS contrast, see Method and Kukkonen, Rovamo, Tiippana, & Näätänen, 1993). This result with filtered noise stimuli is consistent with well-known previous results using single sinusoids (Campbell & Robson, 1968).

The second-order contrast-modulation sensitivity function peaks at a frequency of approximately 1.2 c/d with a sensitivity of approximately six. The orientation-modulation sensitivity function peaks at a frequency of 1 c/d with a sensitivity of approximately five. Finally, the motion-modulation sensitivity function peaks at a frequency of 0.7 c/d with a sensitivity of approximately four. Here again, these observations are consistent with previous results (contrast-modulation: Hutchinson & Ledgeway, 2006; Schofield & Georgeson, 2003; orientation-modulation: Kingdom & Keeble, 1999; Landy & Oruç, 2002; and motion-modulation: Meso & Hess, 2010; Watson & Eckert, 1994).

The Figure 5c and d shows the sensitivity functions reconstructed from the log-parabola model (Ahumada & Peterson, 1992; Watson & Ahumada, 2005) with the parameters estimated by the qCSF method for the dominant and nondominant eye, respectively. They accurately represent the data and allow further study of the parameters of the sensitivity function. The model representation of the data has been truncated to the delta threshold level of the qCSF (Lesmes et al., 2010) because this parameter is not studied here, and the sensitivity curve has been extended to show the cutoff frequency (see Method). The cutoff frequency for the first-order functions is approximately 25 c/d. It is around 8, 5, and 3.5 c/d for second-order contrast, orientation, and motion modulation, respectively.

By replicating previous results, we confirm that the qCSF methodology can be well adapted to different kinds of first- and second-order measurements and can provide a powerful tool with which to investigate the sensitivity of the human visual system. By providing a
unified framework with the same protocol for all the measurements, we can precisely compare these different modulation sensitivity functions. We conclude that the two first-order sensitivity functions are very similar and are an order of magnitude in amplitude and frequency above the second order ones. The three second-order modulation sensitivity functions are relatively similar to one another too, but not as much as the two first-order ones. These differences will be analyzed and discussed further below.

Differences between the two eyes

The similarities between the two eyes led us to test if they are significantly different by comparing all parameters in these two conditions. The sensitivity function parameters’ means and standard deviations across all subjects for each stimulus and eye conditions are shown in Figure 6. These bar graphs represent quantitatively the observations previously made regarding the differences in max gain (Figure 6a), peak frequency (Figure 6b), and cutoff frequency (Figure 6c) between the first- and second-order conditions.

In all conditions, the parameter values are very similar in the two eyes. Only two parameters/conditions show a significant difference (paired two-tailed Wilcoxon signed rank test, \( p = 0.05 \)): the gain in MM (Figure 6a) and the bandwidth in LM1d (Figure 6d). Therefore, individually, the performance in the two eyes is not different and we can collapse the data from both eyes into one population of 104 eyes for further analysis.

Analysis of the sensitivity function parameters

The resulting sensitivity functions averaged over the 104 eyes are shown in Figure 7a. The sensitivity functions estimated from the log-parabola model (Ahumada & Peterson, 1992; Watson & Ahumada, 2005) with the parameters averaged over the two eyes are illustrated in Figure 7b. They show the exact same pattern as the functions measured for the individual eyes (Figure 5).

The distributions of all the parameters for each condition, with the two eyes’ data merged, are shown in Figure 8. Their means and standard deviations are listed in Table 1. A paired two-tailed Wilcoxon signed rank test (\( p = 0.001 \)) was used to test if the parameters differed from condition to condition. Only nonsignificant differences are indicated; all other pair-wise comparisons from condition to condition were significantly different.

As suggested by the observation of the sensitivity functions in Figure 7, the parameter distributions for the two luminance-contrast conditions (orientation and motion detection) are identical (Figure 8 first row). However, when we compare the first and second-order sensitivities, the maximum gain, the peak frequency, and the cutoff frequency distributions are significantly
lower for the second-order than the first-order (Figure 8a, b, & c first vs. second row). The distributions of these parameters are also different between each second-order conditions, except the peak frequency between contrast- and orientation-modulation conditions, which is not significantly different (Figure 8a, b, & c second row). For the bandwidth, we can observe that second-order orientation and motion modulation distributions are not significantly different from one another but are narrower than the contrast-modulation (Figure 8d second row). In turn, the bandwidth of the contrast-modulation sensitivity is not different from any of the first-order conditions (Figure 8d first vs. second row). We confirm here that the two first-order conditions represent the same results, whereas second-order conditions are dramatically different from first-order ones. Also the second-order conditions are reasonably different from one another.

Relationship between first and second order

To investigate the relationship between first and second-order sensitivity, we calculated the ratio $q = \frac{MSF}{CSF}$ between different second-order modulation sensitivities and first-order carrier contrast sensitivity functions (averaged between LM1d and LM2d for homogeneity), assuming a spatial frequency ratio of...
four between the carrier and the envelope (Figure 9a). The ratios for OM, MM, and CM conditions follow a power function of the spatial frequency \( f \) of the envelope (Equation 11):

\[
q = a f^k.
\]  

(11)

This function can be derived from the ratio of two truncated log-parabola functions (Equation 8), assuming that \( f_{\text{max}} \) and \( \beta \) can be approximated in the numerator and denominator, where \( a \) and \( k \) are two free parameters of amplitude and gain, respectively. The estimated values of the parameters \( a \) and \( k \) and the coefficients of determination of the regressions \( r^2 \) for the different conditions are displayed in Table 2. The contrast modulation presents the largest gain, then the orientation modulation and the motion modulation. Below 0.5 c/d, the ratio is minimized by a plateau of approximately 0.1, 0.09, and 0.08 c/d for the three conditions, respectively.

This regression model is only descriptive. It shows that a nonlinear modulation of the first-order sensitivity, following a continuous monotonic power function of the spatial frequency, can reasonably account for the different tuning observed in the second-order MSFs above approximately 0.5 c/d. Below this frequency, the relationship looks to be constant.

We then repeated the calculation of \( q \) with different envelope/carrier spatial frequency ratios \( f_m/f_c \): 2, 4, 8, and 16 (note that in the visual stimulus the carrier spatial frequency was always four times the envelope frequency). The power function model (Equation 11) still fits the data very well for all these conditions (mean \( r^2 = 0.88 \)), however it gives a poor fit for a 1:1 ratio. The gain parameter \( k \) of the regression follows a logarithmic increment as a function of the \( f_m/f_c \) ratio (Figure 9b). This increment is identical, with just an offset difference, for the three conditions. It shows that the relationship between the first and second order functions is consistent for a full range of \( f_m/f_c \) ratios, just scaling as a function of the ratio. Moreover, it shows that the log-parabola model (Ahumada & Peterson, 1992; Watson & Ahumada, 2005) and the qCSF method (Lesmes et al., 2010) can be applied to a wide range of second-order modulation sensitivity.

### Discussion

#### Accuracy of the qCSF method for the measurement of second-order sensitivity

In this study, our aim was to provide a normative dataset on second-order modulation sensitivity using the qCSF methodology. The use of the qCSF to

\[
\begin{align*}
\alpha & = 0.17 \\
\beta & = 0.78 \\
\gamma & = 0.92
\end{align*}
\]  

Table 2. Estimates of the amplitude \( a \) and gain \( k \) parameters and coefficient of determination \( r^2 \) of the power function regression of the ratio \( q \) between the OM, MM, and CM sensitivity functions and the first-order contrast sensitivity (Equation 11).
A normative dataset to study visual sensitivity

The dataset we provide here is specific to a certain type of carrier and carrier/envelope relationship too. This relationship has been already assessed in several articles, in the case of contrast (Dakin & Mareschal, 2000; Schofield & Georgeson, 1999, 2003; Smith & Ledgeway, 1997), orientation (Reynaud & Hess, 2012), and motion modulation (Meso & Hess, 2010). To cover the most common cases and avoid artifacts as much as was possible, we chose here to use filtered noise as carrier and a constant ratio between carrier and envelope spatial frequencies of four. We also chose to use orthogonal cardinal carriers in the OM condition, nonoriented carriers in the CM condition, and non-oriented carriers moving in random orthogonal cardinal directions in the MM condition.

Our population of subjects was quite young and presented a very narrow range of ages (average age = 24.9 ± 0.3 years, see Method). Widespread deficits are known to accompany normal aging (Weale, 1982), and previous studies, while not reporting strong effects of age on the tuning of the CSF, did show that age affects its magnitude (Habak & Faubert, 2000; Owsley, Sekuler, & Siemsen, 1983; Tang & Zhou, 2009).

On the other hand, older individuals have been shown to exhibit a larger decline in the detectability of second-order stimuli than for first-order stimuli (Habak & Faubert, 2000; Tang & Zhou, 2009). Furthermore, for second-order stimuli, this change in the gain was also accompanied by a slight change in the tuning of the MSF (Tang & Zhou, 2009). These studies suggest a dissociation between the mechanisms underlying the perception of first- and second-order stimuli and that the age dependent decline observed in the detectability of second-order stimuli may reflect a greater complexity for second-order processing. The narrow age range of our subjects has the advantage of providing a very good normative dataset for subsequent studies on the effects of age. The large number of subjects and the reproducibility of the results between the two eyes makes us very confident about the validity and the relevance of our results.

Mechanisms of second-order processing

In this study, we provide a unified analysis framework by using the same protocol for all the first- and second-order measurements, allowing precise comparison of these different modulation sensitivity functions. We observe remarkable similarities in the first-order contrast sensitivity functions, in both the oriented and moving carrier conditions. The observed functions are in accordance with previous studies (Ledgeway & Hutchinson, 2005). This argues in favor of a common detection mechanism, one based purely on luminance contrast arising in striate cortex (Smith, Greenlee, Singh, Kraemer, & Hennig, 1998).

The three second-order modulation sensitivity functions are relatively similar to one another too. They are characterized by a lower frequency tuning, and a lower sensitivity than the first-order sensitivity functions. This is consistent with a different processing scheme (Allard & Faubert, 2007), one that has its origin downstream from first-order processing, as reflected in a classical filter-rectify-filter model (Chubb & Landy, 1991; Landy & Graham, 2004; Zavit & Baker, 2013).

In our data the second-order MSFs were not identical. Their gain, frequency peak, and bandwidth showed small but significant differences from each other. For contrast-defined form, we observe that the bandwidth of the sensitivity functions is comparable between the contrast-modulation and the first-order conditions (Figure 6, see also Schofield & Georgeson, 2000; Schofield & Georgeson, 1999, 2003; Smith & Ledgeway, 1997), orientation (Reynaud & Hess, 2012), and motion modulation (Meso & Hess, 2010). To cover the most common cases and avoid artifacts as much as was possible, we chose here to use filtered noise as carrier and a constant ratio between carrier and envelope spatial frequencies of four. We also chose to use orthogonal cardinal carriers in the OM condition, nonoriented carriers in the CM condition, and non-oriented carriers moving in random orthogonal cardinal directions in the MM condition.

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These observations suggest that not all second-order conditions are processed by a common mechanism (see Motoyoshi & Kingdom, 2007 for orientation vs. contrast; and Ledgeway & Hutchinson, 2005 for orientation vs. motion).

Site of second-order processing

We show comparable results from the dominant and the nondominant eye for all the first and second-order stimuli tested here. This would indicate that the main determinants of detectability for these stimuli are likely to be cortical. There is no general consensus as to which areas of the cortex are used to analyze each of the three second-order stimuli used here. There are two conflicting views; first, all three stimuli could be processed in the same extrastriate, cue-invariant area that is sensitive to the orientation of stimuli, such as V3A (Zeki, Perry, & Bartels, 2003; Zeki & Shipp, 1988). The other view is that different areas are used to process motion-defined form, orientation-defined form, and contrast-defined form.

For motion-defined form, some evidence supports the involvement of areas V1, V2, V3A/B, LO1, LO2, and V7 (Larsson et al., 2010; Reppas et al., 1997) possibly involving feedback from MT (Marcar & Cowey, 1992; Regan, Giaschi, Sharpe, & Hong, 1992; Wang et al., 1999). For orientation-defined form, single cell data suggests areas downstream from V2 (El-Shamayleh & Movshon, 2011) while human fMRI studies (Hallum et al., 2011; Kastner et al., 2000; Larsson et al., 2006) suggest the involvement of V1, V2, V3, V3A/B, LO1, hV4, and VO1. Lesion studies implicate V4 involvement (Merigan, 2000). For contrast-defined form, there is evidence of a strong involvement of V1 and V2 (Hallum & Movshon, 2012), which is consistent with the similarities observed in this condition and first-order stimuli. There is also some evidence that the first stage of second-order processing could originate upstream to V1 and that first and second-order processing might be processed in parallel (Demb et al., 2001; Gharat & Baker, 2012; Rosenberg et al., 2010). The present results show that while the sensitivity functions for the three different types of second-order stimuli used here are similar, they are not identical, this is inconsistent with the involvement of a uniquely tuned mechanism.

Conclusions

We show that the qCSF methodology is adaptable to different kinds of first- and second-order measurements. This method is fast and convenient and might be further adapted to other measurements such as disparity. It has the potential to become a powerful tool to investigate the sensitivity of the human visual system. We provide a normative dataset for first- and second-order sensitivity in subjects of a narrow age range and we show that the sensitivity to all these stimuli is equal in the dominant and non-dominant eye. Altogether this constitutes a comprehensive framework for future fundamental and clinical studies.

Finally, our results, like others before, suggest some strong differences between first- and second-order processing. In particular, second-order stimuli might require more processing steps than first-order stimuli, in accordance with the classical filter-rectify-filter model. The different first and second-order sensitivities studied suggest a common first-order contrast detection stage, whereas the second order modulations might be processed by different mechanisms.

Keywords: second-order, first-order, luminance, contrast, orientation, motion, sensitivity function, qCSF

Acknowledgments

The authors wish to thank Dr. Jiawei Zhou and Ms. Yi Gao for the help in setting the experiments and Dr. Curtis L. Baker and Dr. Alex S. Baldwin for helpful comments and discussion on the manuscript. The authors also want to acknowledge the two anonymous reviewers for their suggestions about control experiments. This work was supported by National Natural Science Foundation of China grants (NSFC 31300913) to YT and (NSFC 81261120562) to YZ and a Natural Sciences and Engineering Research Council of Canada grant (NSERC #46528) to RFH.

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Commercial relationships: none.

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References


**Appendix**

**Individual subjects data**

The Figure A1 presents the individual sensitivity functions for the two eyes of the 52 subjects for each condition. The data are very comparable between subjects and between eyes and qualitatively confirm our analysis. The first- and second-order sensitivity functions are respectively clustered in two groups. Among the second-order functions, the motion-, orientation-, and contrast-modulated sensitivity functions increase in range and sensitivity in this order.
Figure A1. Individual sensitivity functions for each condition, for the two eyes of the 52 subjects. For the dominant eye, the sensitivity functions are shown for the first-order oriented carrier (light blue, LM1d), the first-order moving carrier (light red, LM2d), the contrast-modulation (green, CM), the orientation-modulation (dark blue, OM), and the motion-modulation (dark red, MM). For the nondominant eye, the functions represented are the same as for the dominant eye, coded with darker shades of the same colors.