Foveal visual acuity is worse and shows stronger contour interaction effects for contrast-modulated, than luminance-modulated Cs

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Abstract

Contrast-modulated (CM) stimuli are processed by spatial mechanisms that operate at larger spatial scales than those processing luminance-modulated (LM) stimuli and may be more prone to deficits in developing, amblyopic and aging visual systems. Understanding neural mechanisms of contour interaction or crowding will help in detecting disorders of spatial vision. In this study, contour interaction effects on visual acuity for luminance-modulated (LM) and contrast-modulated (CM) C and bar stimuli are assessed in normal foveal vision. In Experiment 1, visual acuity is measured for all-LM and all-CM stimuli, at ~3.5x above their respective modulation thresholds. In Experiment 2, visual acuity is measured for Cs and bars of different type (LM C with CM bars, and vice versa). Visual acuity is degraded for CM compared to LM Cs (0.46$\pm$0.04 logMAR versus 0.18$\pm$0.04 logMAR). With nearby bars, CM acuity is degraded further (0.23$\pm$0.01 logMAR or ~2 lines on an acuity chart), significantly more than LM acuity (0.11$\pm$0.01 logMAR, ~1 line). Contour interaction for CM stimuli extends over greater distances (arcmin) than it does for LM stimuli, but extents are similar with respect to acuities (~3.5x the C gap width). Contour interaction is evident when the C and bars are defined differently: it is stronger when a LM C is flanked by CM bars (0.17$\pm$0.03 logMAR) than when a CM C is flanked by LM bars (0.08$\pm$0.02 logMAR). Our results suggest that contour interaction for foveally viewed acuity stimuli involves feature integration, such that the outputs of receptive fields representing C and bars are combined. Contour interaction operates at LM and CM representational stages, can occur across stage, and is enhanced at the CM stage. Greater contour interaction for CM Cs and bars could hold value for visual acuity testing and earlier diagnosis of conditions for which crowding is important, such as in amblyopia.

Key Words: visual acuity; contour interaction; crowding; luminance-modulated; contrast-modulated; Landolt C

1. Introduction

The discriminability of a target localised in space is influenced by the presence of surrounding objects. Influence can be either facilitatory, where detectability is enhanced (e.g. Polat & Sagi, 1993, 1994), or inhibitory, where discriminability is degraded (e.g. Ehlers, 1936; Flom, Weymouth & Kahneman, 1963; see Levi, 2008 for review). Stationary targets may be differentiated from their backgrounds because of first-order cues such as luminance and colour, or second-order cues such as contrast, texture or depth. Whereas there are many studies investigating the nature of lateral facilitation (Polat & Sagi, 1993; Yu, Klein & Levi, 2002; Petrov, Verghese, & McKee, 2006) and crowding (e.g. Chung, Levi & Legge, 2001; Levi, Klein & Hariharan, 2002b; Pelli, Palomares & Majaj, 2004) for first-order, in particular, luminance-modulated (LM) stimuli, few have investigated facilitation and crowding using second-order stimuli, specifically contrast-modulated (CM) stimuli (Ellemberg, Allen & Hess, 2004; Wong, Levi & McGraw, 2005; Chung, Li & Levi, 2007; Hairol & Waugh, 2010a, b).

Visual detection responses to second-order stimuli such as contrast-modulated (or CM) stimuli are valuable to study because they are thought to be processed by separate streams from first-order or luminance-modulated (LM) stimuli (Schofield & Georgeson, 1999; Allard & Faubert, 2006, 2007), albeit with cross-links between them (Ellemberg et al, 2004; Chung et al, 2007; Hairol & Waugh, 2010a,b). Mechanisms that detect CM stimuli are thought to be based on larger underlying receptive fields with larger spatial summation areas than those that detect LM stimuli (Sukumar & Waugh, 2007), in line with lower high-frequency cut-off values from modulation sensitivity profiles for CM stimuli (Schofield & Georgeson, 1999). Objects defined by modulations of contrast require additional or later stages of processing to be detected, above early linear filtering required to detect objects defined by modulations of luminance (Chubb & Sperling, 1988; Derrington, Badcock & Henning, 1993). Since visual processes that involve higher levels of the visual pathway mature later in life than those at the lower levels (Daw, 1998), second- or higher-order processing mechanisms may take longer to develop and may, due to their additional complexity, be more susceptible to disease than those that process only first-order information. Indeed there is evidence to suggest that in amblyopia, where visual acuity is degraded due to discordant binocular input to the visual cortex during development, spatial detection of CM spatial stimuli is selectively affected (Wong et al, 2001,2005). Furthermore, sensitivity to resolving large CM letters (Bertone, Hanck, Guy & Cornish, 2010) appears to develop later in childhood; and with aging, sensitivity to detecting CM gratings deteriorates earlier (Tang & Zhou, 2009) and threshold elevation is greater for CM than for LM stimuli (Habak & Faubert, 2000). This potentially means that the use of second-order, for example, contrast-modulated (CM) stimuli in a well-designed clinical tool, may serve to more sensitively detect certain kinds of degraded spatial vision.

When the target stimulus is clearly visible, i.e., above detection threshold, spatial discrimination judgements about it are impaired by nearby objects, a phenomenon generally known as crowding. Crowding has been used to describe the interference effects of surrounding letters on letter identification under foveal and peripheral viewing conditions (e.g. Ehlers, 1936; Stuart & Burian, 1962; Levi et al, 2002b; Pelli et al, 2004) but is also used to describe effects on other spatial tasks, (e.g., Westheimer & Hauske, 1975; Levi, Klein & Aitsebaomo, 1985; Parkes, Lund, Angelucci, Solomon & Morgan, 2001). Clinically, crowding is a key feature to consider in visual acuity chart design, in part due to a longstanding belief that in amblyopia, crowding is greater than in normal vision (e.g. Hess, Dakin, Tewfik & Brown, 2001; Levi, Hariharan & Klein, 2002a; but see Stuart & Burian, 1962; Flom *et al*, 1963; Hess & Jacobs, 1979) and that if visual acuity is measured with a "crowded" visual acuity chart, it will show greater degradation, allowing for earlier or more sensitive diagnosis.

Contour interaction is a component of crowding and was first described by (Flom *et al.,* 1963; Flom, 1991). Specifically, Flom *et al.* (1963) found that the foveal resolution of the gap in a Landolt C is impaired when bars are placed near the four sides of it. When flanking elements are complex, e.g., letters, spatial impairment may be considered as crowding. Classical contour interaction is observed in both normal and amblyopic foveae (Flom *et al.*, 1963; Hess & Jacobs, 1979; Levi et al, 2002a, Hess et al, 2000, 2001), and at different retinal eccentricities where like crowding, the effect is greater than at the fovea (Jacobs, 1979; Wolford & Chambers, 1984; Hess, Dakin, Kapoor & Tewfik, 2000a). The underlying mechanisms of contour interaction and crowding in foveal vision have recently been debated (e.g. Chung et al, 2001; Levi et al, 2002b; Pelli et al, 2004; Ehrt & Hess, 2005; Levi & Carney, 2011), however our acuity data and those of others (Ehrt & Hess, 2005;

Danilova & Bondarko, 2007), suggest that foveal contour interaction involves more than simple masking.

Recent studies have investigated crowding for large luminance-modulated (LM) and contrast-modulated (CM) letters, by measuring threshold modulations for letter identification. These studies have been conducted foveally, in the periphery (Chung *et al*, 2007) and also in amblyopia (Chung, Li & Levi, 2008). For foveal viewing using large letters (about 1 deg in size or 1.1 logMAR), and a relatively short exposure duration (150ms), no significant crowding was measured for LM letters (which were about ~8x their visual acuity size), although previous visual acuity studies have found small but significant effects of contour interaction and crowding at the fovea (Stuart & Burian, 1962; Flom *et al*, 1963; Chung *et al*, 2001; Levi *et al*, 2002b). More crowding was measured for CM letters (which were about 1.3x their visual acuity size) or when LM letters were surrounded by CM letters (Chung *et al*, 2007, 2008). In peripheral and amblyopic viewing, greater magnitudes of crowding were found for both types of stimuli. Thus visual acuity for CM letters might reveal greater crowding, however under foveal conditions, large, near-visibility letters may not be best for revealing them. Crowding found with large letters near modulation detection threshold, and with small visual acuity letters, may well reveal different underlying limits of spatial vision (Ehrt & Hess, 2005; Danilova & Bondarko, 2007). Measurement of contour interaction using a C target and surrounding bars is attractive as it assesses a component of crowding (Flom *et al*, 1963), and uses more easily defined separations than when letters are surrounded by other letters, which is valuable when comparing spatial extents of interaction.

In this study we assess the magnitude and extent of contour interaction for foveally-viewed, luminance-modulated (LM) and contrast-modulated (CM) C visual acuity stimuli, placed at approximately equivalent visibility (3.5x modulation). The results will hold relevance to whether a visual acuity chart using contrast-modulated letters would show stronger contour interaction (or crowding) effects than one using luminance-modulated letters, as well as giving insight into the underlying mechanisms of contour interaction in spatial vision close to the resolution limit. If the effects of contour interaction (and therefore crowding) are greater for CM than LM visual acuity stimuli, the results may potentially prove valuable for the clinical assessment of vision, particularly in conditions such as amblyopia, where the sooner amblyopia is detected and treated, the better the potential visual outcome after treatment. Finally, the use of mixed stimuli (LM C surround by CM bars, and vice versa), provides us with information about whether or not for visual acuity, these processing streams are independent.

2. Methods

Apparatus

Stimuli were created using Matlab on a Pentium IV PC and loaded on to the frame-store memory of a Cambridge Research System graphics card (VSG 2/5), which allowed up to 15-bit luminance control, housed in the computer. They were then displayed on a Clinton Monoray CRT monitor with a 150 Hz framerate and a mean luminance of 53cd/m^2. The monitor was gamma corrected and the display was checked regularly to ensure that the desired luminance values were being presented.

Stimuli

The stimuli for the main experiments consisted of luminance-modulated (LM) and contrast-modulated (CM) square Cs and bars. They were constructed by adding or multiplying square-wave modulating signals to dynamic binary noise. Binary noise has been used previously in several studies (e.g., Schofield & Georgeson, 1999, 2003; Manahilov, Calvert & Simpson, 2003; Chung, Levi & Li, 2006; Hairol & Waugh, 2010a, b), and is particularly suitable for creating square wave stimuli such as letters, which would then be reconstructed perfectly on rectification. The square C was constructed on a 5×5 template, where the gap of the C is 1/5 of the C's size. The bars were created in a similar way, where the length of the bars always matched the size of the C; the width of the bar always matched the size of the C's gap. The stimuli in this study can be mathematically expressed as:

$$I(x,y) = I_o[1 + nN(x,y) + lL(x,y) + mnM(x,y)N(x,y)] \quad \text{(Equation 1)}$$

where $I(x,y)$ is the luminance at position (x,y), I_0 is the mean luminance; n is the noise contrast, which was fixed at 0.2 for all experiments; $N(x,y)$ is the binary noise value at position (x,y) of -1 or 1; l is the luminance amplitude, which is zero for CM stimuli; m is the contrast amplitude, which is zero for LM stimuli; $L(x,y)$ is the luminance modulation function, a square wave; and *M(x,y)* is the contrast modulation, also a square wave. For generation of LM and CM stimuli, either *l* or *m* was adjusted, respectively, the other being set to zero. Ten images with randomly generated noise patterns were produced for each stimulus level (usually of seven C sizes) and for each of four C orientations, i.e., 280 images per experimental run. On each experimental trial, one of these 280 stored images of a particular size and orientation was selected and changed in random sequence, every three temporal frames, i.e., every 20 ms, for a stimulus duration of 800 ms. Prior to choosing an 800 ms duration, we did conduct a pilot experiment on 3 observers and found that the durations at which LM and CM visual acuity measures became stable were slightly different, i.e., 556 ± 188 ms and 603 ± 83 ms for LM and CM stimuli, respectively (see Figure 1).

[INSERT FIGURE 1 HERE]

Always of concern when using contrast-modulated stimuli in visual psychophysics is the presence of luminance cues that might drive responses. We took several steps to ensure that the thresholds and acuities we measured for contrast-modulated stimuli, depended on their contrast differences, rather than those of the higher frequency luminance noise, modulated to create them (reported in Hairol & Waugh, 2010a). These steps included detailed and regular monitor calibration and gamma correction, checking of experimentally created stimuli both photometrically and in MatLab using pixel-by-pixel luminance profiles; and limiting the luminance range of the monitor to avoid slight shifts in overall mean luminance, which might otherwise occur due to adjacent pixel nonlinearity.

Dynamic noise presentation was used to ensure that any statistical luminance clumping, did not provide useful luminance cues within a CM stimulus (e.g. see Smith & Ledgeway, 1997). It also helps to preclude the use of higher spatial frequency luminance cues, in determining visual responses (Manahilov et al, 2003). Each background noise check subtended 0.03 deg (1.8 arcmin) for both LM and CM stimuli (see also Hairol & Waugh, 2010a & b). Stimuli similar to those used in the experiments are shown in Figure 2. Note that we used a square, rather than a round C, which has the advantage of eliminating the jagged curve when a Landolt C is created. Although the jagged curve can be smoothed by applying anti-aliasing algorithms, this may introduce unwanted luminance artefacts across edges but not at the gap. This is a potential issue if we want observers to judge the position of the gap only using differences in contrast. Pilot experiments were conducted to check some aspects of the stimuli and experimental paradigms before the two main experiments. In brief, there were no significant differences in contour interaction functions obtained for round versus square Cs, or for incremental versus decremental luminance stimuli.

[INSERT FIGURE 2 HERE]

Experimental design

In the two main experiments, visual acuity was measured (as described in *Contour Interaction Experiments* section). In Experiment 1, the C was flanked by four bars that were similarly defined, i.e., a LM C is flanked by LM bars (denoted in Figures by 111), or a CM C was flanked by CM bars (denoted in Figures by 222). In Experiment 2, a C was flanked by four bars that were differently defined, i.e., a LM C was flanked by four CM bars (denoted in Figures by 212), or a CM C was flanked by four LM bars (denoted in Figures by 121). All stimuli were approximately equal in visibility for the two systems at 3.5× threshold modulation for gap position identification.

Determining visibility level

In order to more directly compare contour interaction functions between LM and CM systems in the main experiments, it is important to create approximately equally visible stimuli. These were created in the following way.

First, visual acuity thresholds for a high contrast LM C (l = 0.6) and CM C (m = 3.0) were measured using 80% of the monitor luminance range to ensure the absence of any potential luminance artefacts in our CM stimuli. Psychophysical procedures for measuring visual acuity are provided below. Under these conditions, the acuity for a CM C was about 2.75× the acuity for a LM C for our observers (LM: 0.0 ± 0.04 logMAR; CM: 0.44 ± 0.02 logMAR).

Because differently-defined stimuli were required for Experiment 2, same-sized equally-visible LM and CM stimuli were needed. Cs were therefore made to be twice the resolution size for the CM C, and threshold modulations for identifying the position of the C's gap were measured using a method of constant stimuli and 11 levels of modulation separated by 1.5dB, randomly presented for 125 trials in each run. Thresholds were calculated from psychometric functions fit to the modulation data using a Weibull function (Equation 2 below), which for a 4 alternative forced-choice paradigm produces a threshold equivalent to a 72.4% correct performance level. The modulations of the Cs and bars for both LM and CM stimuli were then set to the highest multiple possible on the monitor (limited by the CM range), which was at 3.5× threshold modulation (or 3.5× visibility).

Contour Interaction Experiments (Method of Constant Stimuli varying Size)

The main experiments used the pre-determined stimulus modulation levels just described, for both LM and CM acuity systems (at 3.5× visibility). Visual acuity thresholds to identify the position of the gap in a C were then measured for an isolated C and for a C with surrounding bars placed at 0 (or abutting), 1, 2, 3, 4, 5, 8 and 10 gap widths (2 letter widths), away.

Separation was defined as the distance from the edge of the bar closest to the C, to the outer edge of the C (as per Flom *et al*, 1963). In some studies of contour interaction and crowding, separation is defined as the distance between the centre of the target to the centre of the flanker (e.g. Chung *et al*, 2007; Levi & Carney, 2009). This method of defining separation might be more appropriate for more complex stimuli, such as letters flanked by other letters, or windowed narrow-band stimuli, where it becomes difficult to define edge-edge separation. The results will show that this definition holds little significance to the final outcome of our experiments.

Psychometric functions for visual acuity were generated using a method of constant stimuli for 7 levels of letter (and corresponding bar) size; each size level being separated by 0.1 logMAR. On each trial, the observer's task was to identify the position of the gap in the C. Each experimental run consisted of 100 trials and data from 4-6 runs were averaged. Psychometric function data were fit with a standard Weibull function from which threshold and slope parameters could be derived:

$$P_{correct}(s) = 1 - (1-g) \times \exp[-10^{\beta(s-th)}] \qquad \text{(Equation 2)}$$

where *th* is the estimated threshold, in logMAR, at 72.4% correct response for a 4 alternative forced-choice procedure; β is the slope of the psychometric function; *g* is the guess rate (25%); and *s* is a given target size in logMAR. To enable a full range of sizes to appear on the screen and to allow a perfect match in noise check size (0.03 deg), observers were seated at 9.5 metres away when LM C acuity was tested, or 4.77 metres away when CM C acuity was tested.

As mentioned, we attempted to use equally visible stimuli for both LM and CM systems. As size is varied when we measure visual acuity, it is possible that if visibility changes differently with size for LM and CM systems, the outcome may be slightly affected. We have analysed our psychometric function slopes to see how they impact on measured peak contour interaction. Slopes of our visual acuity functions for LM and CM Cs are slightly flatter for CM stimuli (slopes of 4.9±0.5 and 4.2±0.5 for LM and CM stimuli). These slightly flatter slopes fit with our Weibull function, do not lead to a difference in estimate of peak contour interaction at 72.4% performance, and would lead to a slight under-estimation of peak contour interaction for CM stimuli in our data if higher performance levels were chosen (Formankiewicz, Waugh & Hairol, 2012).

In each experimental run, the separation between the C and bars was fixed (in terms of C gap widths) and resolution thresholds were measured. For example, in the abutting condition, one of seven sizes of Cs was presented; the size of the bars varied too, but they always abutted the C. The nine levels of separation (including the unflanked C) were run in systematic and counterbalanced order. Within a standard experimental session, visual acuity thresholds were measured across the full range of separations, twice.

Participants indicated their responses using a Cambridge Research System CT3 4-way response box, without feedback. Testing was monocular using the observer's dominant eye and the non-tested eye was covered with a black patch.

Analysis

The magnitude of contour interaction at each target-bar separation is assessed by comparing the resolution threshold measured with surrounding bars to that obtained for an isolated C. As in studies conducted previously (Chung *et al.*, 2007, 2008; Hariharan, Levi & Klein, 2005; Levi *et al.*, 2002b), contour interaction in this experiment is characterised by the peak elevation, or the highest resolution threshold elevation in the presence of the bars relative to that measured for a C presented alone; and spatial extent, represented by the spatial separation between the target and bars at which the magnitude of threshold elevation drops to a criterion level. To objectively determine in particular, the extent of contour interaction, all data are fit with a Gaussian function in the form

$$F(sep) = A \times \exp(-(sep^2 / 2\sigma^2)) \qquad \text{(Equation 3)}$$

where *sep* is the separation between the C and bars, *A* is the peak amplitude of the threshold elevation at *sep* = 0 and σ is the standard deviation of the Gaussian. The extent of contour interaction is defined as two standard deviations of the Gaussian fit to the data (a definition previously used by others, e.g., Chung *et al.*, 2007, 2008; Hariharan, Levi & Klein, 2005; Levi *et al.*, 2002b). It is also possible to estimate the extent of contour interaction, as the furthest separation at which performance in the crowded condition is not significantly different from that for the isolated C (Danilova & Bondarko, 2007). We estimated extents in this same way using posthoc Tukey HSD pair-wise comparisons.

The availability of psychometric functions for each target-flanker separation, also allowed the data to be replotted as performance versus separation functions for a particular size, as per Flom *et al* (1963). Figure 3 reveals how this was done. This Figure also demonstrates how different psychometric function slopes obtained for abutting and separated bars, can influence the shape of the performance contour interaction function.

[INSERT FIGURE 3 HERE]

Observers

Five observers with normal vision participated in this study. They all had best corrected visual acuity of 6/5 or better in each eye and stereopsis of at least 30 arcsec (using the TNO stereotest). As amblyopes have a binocular vision disorder and show selective deficits to detecting CM stimuli (Wong et al, 2001) as well as possibly enhanced crowding (Hess et al, 2001; Levi et al, 2002a), it was important for the purposes of the current study that “normal” observers be binocularly normal.

All observers were well practised on both types of stimulus, before data collection commenced. Observers AD, JC and HMY were unaware of the purposes of the study. The Anglia Ruskin University Research Ethics Committee approved the conduct of this research, which complied with the tenets of the declaration of Helsinki. Written informed consent was obtained from all observers before the start of experiment.

3. Results

3.1 Experiment 1: Contour interaction for luminance-modulated (LM) and contrast-modulated (CM) square Cs with similarly-defined bars (111 and 222)

Absolute LM and CM gap resolution thresholds for Cs at 3.5× visibility threshold are plotted against separation in multiples of gap width for each observer in Figure 4. Averaged across observers, the resolution threshold for an unflanked LM C is 0.18±0.04 logMAR (at 3.5x modulation threshold), which is higher than the 0.0 logMAR that might be expected for a maximum modulation LM C. The threshold for an unflanked CM C (at 3.5x modulation threshold) is 0.46±0.04 logMAR, i.e., 0.28±0.04 logMAR worse than that for the LM target. For all observers, thresholds are highest when the bars abut the C and decrease as the bars are moved further away from the C. The Gaussian fits (shown in grey) adequately describe the fall-off in contour interaction function with increasing bar separation, although it slightly underestimates the peak effect. It also provides an objective way to estimate extent, allowing interpolation of data between sampled points.

Averaged threshold elevations (across the four observers of Figure 4) are shown in Figure 5 a (top panel) along with the best fit Gaussians. For both LM and CM Cs, the effect of the bars on resolution threshold is greatest when the bars abut the C (separation of zero). Contour interaction reduces as the bars are placed further away from the C.

A repeated measures ANOVA performed with Greenhouse-Geisser correction on the actual LM and CM threshold elevation data for the four observers reveals that there is a significant effect of stimulus type on threshold elevation [$F(1, 3) = 11.22$, $p < 0.05$]; and a highly significant effect of separation on threshold elevation [$F(2.68, 8.02) = 53.71$, $p < 0.001$]. The interaction between target type and separation is significant [F (2.25, 6.74) = 6.75, $p < 0.05$]. That is, changes in threshold elevation across separation are dependent on the stimulus type used; the CM effects are greater.

Table 1 reveals averaged actual peak elevation data and spatial extent values (interpolated from the Gaussian fit of Equation 3) of contour interaction for LM and CM stimuli. Peak threshold elevation is larger for the abutting CM C (0.23 ± 0.01 logMAR) than for the LM C (0.11 ± 0.01 logMAR) and this difference is significant [$F(1,3) = 24.79$, $p < 0.05$]. The spatial extent of contour interaction, when expressed in multiples of gap width is 3.82 ± 1.00 gap widths for CM stimuli and 3.37 ± 0.54 gap widths for LM stimuli, which are not significantly different [$F(1,3) = 0.24$, $p > 0.05$].

As mentioned in the Methods section, an alternative way to estimate the extent of contour interaction, is to statistically compare visual acuities for the isolated and surrounded C conditions. The aforementioned main finding about extent (in gap widths) is confirmed statistically using Tukey HSD posthoc tests performed on the actual data (not interpolated from the Gaussian). That is, there is no difference in extent for LM and CM stimuli, (i.e., for both types, isolated and surrounded visual acuities are significantly different for 0, 1 and 2 gap widths).

The same threshold elevation data are shown in Figure 5 b (middle panel), but now separation is expressed in minutes of arc. Using these units of extent, contour interaction is larger for CM stimuli; LM extent of 4.97 ± 0.44 arcmin and CM extent of 11.00 ± 1.83 arcmin [t test; $p<0.05$]. If separation is expressed as centre-to-centre spacing, the extents become 9.51 ± 0.61 (LM) and 19.65 ± 2.00 (CM) arcmin, which are also statistically different (at $p<0.05$).

The results using the same data but plotted as change in percent correct performance as a function of separation in multiples of gap width are shown in Figure 5 c (bottom panel). As was the case for logMAR acuity contour interaction functions in Figure 5 a, the peak change in percent correct performance is larger for CM than LM stimuli, and the extent estimates in gap widths are similar for the two types. Other than a small improvement in performance (%correct) for abutting stimuli found for LM stimuli, similar to that sometimes found by Flom et al (1963), performance overall is reduced by the presence of the bars and improves as they move away. Figures 3 b and c show that differences in shape can occur between the two ways of assessing contour interaction, including the presence or absence of a “dip” for closely separated bars, which depend at least in part, on the underlying psychometric function slopes (Formankiewicz, Waugh & Hairol, 2012).

[INSERT FIGURE 4 HERE]

[INSERT FIGURE 5 HERE]

[INSERT TABLE 1 HERE]

3.2 Experiment 2: Contour interaction for luminance-modulated (LM) and contrast-modulated (CM) square Cs with differently-defined bars

Gap resolution thresholds were measured for LM square Cs surrounded by CM bars (212) and CM square Cs surrounded by LM bars (121) for observers IH, HMY, MF and AD. Both Cs and bars were equated in visibility for each type (according to LM or CM C modulation thresholds) at 3.5× threshold modulation. Gap resolution thresholds for isolated LM and CM Cs and for LM and CM Cs surrounded by differently-defined bars for each of four observers are plotted as a function of separation in Figure 6. Note that even though the isolated Cs were the same as those used in Experiment 1, thresholds were re-measured within this new experiment (and so the exact values vary). Resolution thresholds are elevated when a LM C is surrounded by CM bars (212), reducing to the isolated C level by 5 gap widths. However when CM Cs are surrounded by LM bars (121), in three of the four observers, threshold is only elevated at the abutting condition, often reaching the no-bar threshold level by 1 gap width.

A repeated measures ANOVA performed on individual 121 and 212 threshold elevation data reveals that there is a significant overall effect of separation [$F(2.01, 6.03) = 9.90$, $p < 0.05$]. The interaction between stimulus type and separation does not reach statistical significance with Geisser-Greenhouse correction [$F(2.22, 6.67) = 4.32$, $p = 0.06$]; and the overall effect of stimulus type on threshold elevation does not reach statistical significance either [$F(1, 3) = 8.603$, $p = 0.06$], reflecting the large individual variability in contour interaction patterns. A Tukey’s posthoc pairwise comparison analysis, reveals significant differences in threshold elevation for the 121 and 212 conditions ($p<0.05$) at the abutting and 1 gapwidth separation conditions, i.e., for these separations, threshold elevation is greater for the 212 condition ($p<0.05$).

The Gaussian function described in Equation 3 did not fit individual data well (see Figure 6) and in some cases, extent estimates fell within the smallest sampled separation of 1 gap width. Averaged data provided better fits. Thus to enable comparison with extent estimates from Experiment 1, we only report the extent parameters estimated from fits to the averaged data in Table 2 (versus Table 1, asterisked data).

Figure 7 shows threshold elevation and performance data averaged across the four observers. For a LM C surrounded by CM bars (212), elevation of resolution threshold is greatest when the bars abut the C (0.17 ± 0.03 logMAR), the effect reducing as the bars are moved away. When the CM C is surrounded by LM bars (121), a peak elevation of 0.08 ± 0.02 logMAR is found with the effect reducing by 2 gap widths. As noted above, these peak elevations are statistically different ($p<0.05$).

Table 2 reveals average peak magnitude and objectively determined spatial extents of contour interaction for 121 and 212 based on the averaged data shown in Figures 7 a and b. The spatial extent of contour interaction as estimated from the averaged data for the 212 arrangement is 3.96 ± 0.78 gap widths. For the 121 arrangement, it is 0.99 ± 0.46. Extents in arcmin, (i.e., extents in gap widths multiplied by the unflanked threshold) are 2.79 ± 1.28 and 5.96 ± 1.18 arcmin for 121 and 212 conditions, respectively. With a t-test difference comparison, these extents are significantly different [$p<0.05$] with both being significantly smaller (in arcmin) than those found in response to all-CM stimuli of 11.00 ± 1.83 arcmin in Experiment 1. Tukey's HSD posthoc testing on discrete data also showed a difference in extents in gap widths between 121 and 212 arrangements; for 121 only the abutting condition is different from the isolated condition, whereas for 212 the abutting and the 1 gap width condition are both significantly different from the isolated condition ($p<0.05$).

The change in performance versus separation functions (Figure 7 c) show similar patterns to the threshold elevation plots (Figure 7 a). The extents determined from discrete performance data (using Tukey HSD posthoc tests) are confirmed to be larger for 212 than for 121 ($p<0.05$).

[INSERT FIGURE 6 HERE]

[INSERT FIGURE 7 HERE]

[INSERT TABLE 2 HERE]

A summary of all averaged raw data for 4 observers (3 who took part in both Experiments) is shown in Figure 8. As described earlier, visual acuity for equally visible LM and CM stimuli is significantly different; CM acuity being about 0.3 logMAR (or ~3 lines on a clinical visual acuity chart) worse. When the LM C is surrounded by either LM bars (111) or CM bars (212), the contour interaction effects on visual acuity look similar. However, when the CM C is surrounded by LM bars (121 condition), contour interaction effects appear to be much weaker, than when the CM C is surrounded by CM bars (222). These findings are not consistent with any slight differences in visibility that may exist between the bars and the Cs in the mixed condition (with differently defined Cs and bars), for the different sizes presented. If this were the case, one would expect greater contour interaction for the 121 than the 222 condition, as the bars may be slightly more visible; and 212 should show a weaker effect than the 111 condition as the bars may be slightly less visible here.

The general impressions described above hold up statistically, both when comparing peak elevation and extent means provided in Tables 1 and 2; contour interaction for 222 is significantly stronger in peak and extent than 121 ($p<0.05$) whilst these parameters for 111 and 212 are not statistically different ($p>0.10$). When the actual data for 3 observers who participated in both experiments undergo repeated measures ANOVA with Greenhouse-Geisser correction the same results are found. Using the alternative extent analysis with posthoc Tukey pairwise comparisons, the isolated acuity is significantly different from the abutting and 1 gap width condition for the 222 condition. However in the 121 condition, the isolated condition was not significantly different from any other. In psychophysical studies like this one, where data from large numbers of trials are collected on a small group of observers, it is wise not to place too much weight on statistical analysis, particularly when significance is not achieved. Rather we use them here to provide some objectivity to our graphical results, which generally match the statistical outcomes. In summary, a CM C surrounded by CM bars appears to produce significantly more contour interaction (in magnitude and extent) than a CM C surrounded by LM bars.

[INSERT FIGURE 8 HERE]

4. Discussion

The present study is the first to reveal in visual acuity terms, that contour interaction for foveally viewed stimuli occurs more strongly for contrast-modulated (CM) Cs and bars, than for approximately equally visible, luminance-modulated (LM) Cs and bars. In summary, the peak contour interaction effect reduces acuity by about 2 lines (0.23 ± 0.01 logMAR) for CM C targets surrounded by CM bars, whereas it reduces acuity by about 1 line (0.11 ± 0.01 logMAR) for LM C targets. The extent of contour interaction in gap widths (or proportions of letter size) is similar for LM (3.37 ± 0.54) and CM (3.82 ± 1.00) stimuli, however it is more extensive in minutes of arc for CM (11.00 ± 1.83) than for LM (4.97 ± 0.44) stimuli. These findings hold potential significance for clinical application, as well as providing new information about foveal spatial vision at the acuity limit. From the results of Experiment 1 we have characterised peak elevation and spatial extent parameters for 3.5× visibility LM and CM stimuli. In Experiment 2, we show that contour interaction can also affect visual acuity when Cs and bars are defined differently, i.e., one by luminance, the other by contrast.

The finding that contour interaction effects are greater for CM than LM Cs, and that interactions occur between CM Cs and LM bars and vice versa, agree with results of previous work in which modulation thresholds for identifying letters flanked by other letters at the fovea were measured (Chung et al, 2007, 2008). In these earlier studies, Chung and colleagues measured modulation thresholds at the fovea for identifying a large letter surrounded by low visibility flankers (1.6×). They found stronger crowding effects for CM (a change in modulation threshold of 1.34× from the unflanked condition) than LM letters of (1.05×), which was described as “absent or weak”. Very small magnitude effects were found with mixed stimuli, e.g., for the 121 condition, insignificant crowding (of 1.01×) and for the 212 condition, small but significant crowding (of 1.06×) was found. Although these studies and ours examine contour interaction and crowding under different circumstances, the results agree, although our effects are measurably stronger: for 111 a change in resolution threshold of 1.29× (or 0.11 logMAR), for 222 of 1.70× (or 0.23 logMAR), for 121 of 1.20× (or 0.07 logMAR) and for 212 of 1.48× (or 0.17 logMAR). Chung *et al*, did not find differences in extents for the LM and CM or mixed stimuli in degrees, however they used fixed-size large letters (about 1 deg in size) that generated large crowding extents (of 2.21 deg); whereas our visual acuity paradigm used letters close to the resolution limit of vision (unflanked letter sizes of ~0.1 to 0.25 deg). Contour interaction is known to show different effects for large and small luminance letters viewed foveally (Ehrt & Hess, 2005; Danilova & Bondarko, 2007).

CM and LM Visual Acuity

As seen in Figure 4 (and Table 1), visual acuity for discriminating the orientation of a C is almost twice as large for CM (0.46 logMAR or 2.88 arcmin) compared to LM (0.18 logMAR or 1.51 arcmin) targets for all observers. The worse acuity for CM Cs suggests that they are processed at a larger spatial scale, compared to LM Cs, a finding that is similar to both high-frequency cut-off (resolution) differences in LM and CM modulation transfer functions (Schofield & Georgeson, 1999) and spatial summation estimates for LM and CM blobs (Sukumar & Waugh, 2007). Using blob stimuli with similar noise characteristics to those used in the current study, Sukumar & Waugh (2007) found that spatial summation estimates for CM stimuli were 2-3 times larger than those for LM stimuli, similar to visual acuity differences reported here (of 1.9× to 2.8×). Chung *et al* (2007) reported that the size threshold for high modulation CM letters can be approximately 6× larger than that for LM letters. Differences between studies could be due to differences in noise, affecting stimulus visibility and in exposure durations used. Chung *et al* (2007) used an exposure duration of 150 ms, whereas in the current study it was 800 ms, a time more akin to clinical visual acuity measurement. Pilot results in Figure 1 show that if 150 ms exposure duration was used for our stimuli, CM acuity would be 4.0× worse than LM acuity, closer to the ~6× value reported by Chung *et al* (2006, 2007).

Does spatial extent of contour interaction scale with target size?

In Figure 5 a, the extent of contour interaction for equally visible LM and CM square Cs scales with separation when expressed in multiples of gap width, suggesting a similar mechanism for contour interaction for both stimulus types, which scales with receptive field size. When separation is expressed in minutes of arc as in Figure 5 b, the physical extent of contour interaction is smaller for LM than for CM stimuli. The results of this experiment support the suggestion that differently-sized mechanisms with similar behaviour are involved in spatial processing LM and CM targets (Sukumar & Waugh, 2007; Hairol & Waugh, 2010a).

The scaling of target size and extent of contour interaction is one of the key indicators (Levi *et al.*, 2002b; Pelli *et al*, 2004) to suggest that the deleterious effect of contour interaction or crowding for foveal stimuli engages a masking mechanism, similar to simultaneous masking (e.g., Legge & Foley, 1980; Levi *et al*, 2002b) or remote masking (Chung *et al.*, 2001, Levi *et al.*, 2002b). The current paper results show that the extent of contour interaction measured for foveal visual acuity targets does scale with stimulus size *across* LM and CM systems, (i.e., their extents are similar when measured in C gap widths). However *within* the LM and CM systems, the extent may not necessary scale with target size. Using standard luminance acuity targets, Danilova & Bondarko (2007) did not find a systematic change in contour interaction extent with a small variation of letter size (1.1-2.2× change in size).

Our acuity paradigm involved a range of stimulus sizes to generate full psychometric functions, so we can investigate whether or not, size and extent scale over a small range of sizes (1.3-1.7× change in size). This involved selecting a fixed size, rather than a fixed performance level and determining (from psychometric functions) the performance level associated with it, for a range of separations. Extents were objectively estimated using Gaussian functions fit to the performance-separation data (see Figure 3 for a schematic to illustrate this). Results of this analysis are shown in Figure 9. Moving between systems produces a scaling effect with size, however within the LM or CM system, direct scaling does not hold. One attractive notion is that size-extent scaling for visual acuity *only* holds when the visual system is forced to move from one channel to another, such as from the LM to the CM system, or from one spatial scale to another, such as for different narrow-band stimuli (Levi et al, 2002b). When visual acuity can be processed within a spatial channel (perhaps an “acuity” channel), direct size-extent scaling no longer holds (in agreement with the findings of Danilova & Bondarko, 2007). In Figure 9 we compare our suprathreshold visual acuity data with reanalysed simultaneous masking results (see Figure 10 of Hairol & Waugh, 2010a) for three different LM and CM blob sizes (sd = 30, 15 and 7.5 arcmin). Two notable differences are seen. First, the masking results show direct scaling of stimulus size and extent of masking, both for LM and CM blobs (slope of 0.91±0.15), whereas the visual acuity results do not. Second, the lateral extents of LM and CM masking are similar in arcmin, whereas for visual acuity they are not. Thus, the direct scaling of size and lateral extent results are characteristic of masking (Polat & Sagi, 1993; Levi et al, 2002b; Pelli & Majaj, 2004); but are not like our C acuity data.

[INSERT FIGURE 9 HERE]

The issue of whether foveal contour interaction (and possibly crowding) is more complicated than masking is an important issue to address, both from the theoretical and clinical perspective. It would be therefore be of interest in a future study to assess the size-extent relationship for visual acuity over a larger range of sizes, e.g., by varying target visibility or by blurring stimuli.

Physics of the stimulus cannot explain contour interaction

Hess, Dakin & Kapoor (2000b) proposed that contour interaction effects of neighbouring bars on the resolution of a C, could be created by changes in the physics of the stimulus, specifically differences in amplitude spectra taken aligned and orthogonal to the gap in a Landolt C, with and without bars, rather than any underlying neural processing within the visual system. For well-constructed contrast-modulated stimuli, no consistent energy should exist at any particular spatial frequency and contour interaction obtained for these stimuli, should not be able to be explained on the basis of differences in spectral energy (we show that this is the case for our stimuli in the Appendix). Thus for our CM stimuli, observers cannot use first-order spectral energy to resolve the C, and the effects of contour interaction that we measure, which are even greater than found for LM stimuli, cannot be explained by them.

Are LM and CM stimuli processed by independent pathways?

As shown in Experiment 1, there appear to be mechanisms operating at different spatial scales underlying resolution as well as contour interaction for LM and CM stimuli. Are spatial processing streams for LM and CM stimuli totally independent? Experiment 2 was conducted to address this question for visual acuity, where the C was surrounded by bars of different type to it. If two completely independent channels exist for LM and CM contour interaction processing, then the ability to discriminate the direction of the gap in the C should be independent from influence by surrounding bars that are of different type from the C.

As shown in Figures 6 and 7, contour interaction does occur when the C and bars are differently-defined. When both target and bars are equally visible, contour interaction for a LM C occurs when it is flanked by CM bars (212) with a peak magnitude of 0.17 ± 0.03 logMAR, which remains significantly different from the isolated C condition when the bars abut the C or are at a separation of 1 gap width away. Contour interaction also occurs for a CM C flanked by LM bars (121), with a peak magnitude of 0.08 ± 0.02 logMAR, although the effect is significant only when the bars abut the C. This asymmetrical effect suggests that contour interaction does occur between LM and CM spatial stimuli, but not necessarily in equal measure. It is possible that the direction of asymmetry of contour interaction measured may depend on how C and bar visibilities are scaled, although we think it unlikely that visibility of the two shapes for LM and CM systems is affected differently. Asymmetry of lateral interactions has also been revealed for detection and modulation matching tasks (Ellemberg et al, 2004; Hairol & Waugh, 2010a) as well as in a letter detection crowding task (Chung *et al.*, 2007; Chung *et al.*, 2008), although not always in a consistent direction.

A framework for contour interaction for LM and CM stimuli

The results of these contour interaction studies using LM and CM visual acuity stimuli can be explained if one speculates that 1) LM stimuli are processed, (i.e., representations extracted) using receptive fields at an early stage, such as in V1; 2) CM stimuli are processed at a later stage, in V1, or in a higher visual area such as V2, using larger receptive fields, and 3) contour interaction may occur at multiple stages of combination.

The results of Figure 8 may provide a clue to how contour interaction could operate. Equally-visible LM stimuli and CM stimuli are detected by mechanisms with differently-sized underlying receptive fields. Spatial extents of contour interaction, in terms of target gap size are equivalent but in minutes of arc, extents for CM stimuli are larger (see Table 1). When approximately equally visible LM and CM C and bars are placed close together, (i.e., 121 and 212 conditions) outputs from underlying receptive fields of different scale must be combined. If the target C engages a smaller LM receptive field, and surrounding CM bars stimulate larger neighbouring receptive fields (212 case), for the same separation with respect to the target size, greater magnitudes of contour interaction might be expected due to encroachment. The magnitude of contour interaction (see Figure 8) is higher for the 212 than the 111 condition (0.17±0.03 logMAR versus 0.11±0.01 logMAR). A loss of efficiency when combining information across differently-sized receptive fields, or channels, may also reduce the effect of combination. When the target C engages a larger CM receptive field, and the LM bars stimulate smaller neighbouring receptive fields (121 case), lower amounts of contour interaction might be expected. Again our results indicate a significant reduction in the peak contour interaction effect for the 121 (0.08±0.02 logMAR), versus the 222 case (0.23±0.01 logMAR). Differences in combined effects of the target C and bars could possibly be explained by a single spatial channel at a second stage, e.g., Danilova & Bondarko (2007), however it is difficult to understand how spatial extents in the mixed conditions do not fall between those found for all-LM and all-CM stimuli.

The greatest magnitude of contour interaction is found when both the C and the bars are contrast-modulated (the 222 condition). It is difficult to explain a larger relative effect of contour interaction with these than with equally visible LM stimuli without suggesting a different stage of combination with enhanced effects. The extent of interaction in minutes of arc is also larger only for these stimuli (11.00 ± 1.83 arcmin). Losses of efficiency in combining information could occur both across spatial scale, or across different levels of representation (via feed-back and feed-forward processes). The extent of interaction in minutes of arc for all-LM (the 111 condition) and both mixed conditions (121 and 212) are more similar at 4.97 ± 0.44, 2.79 ± 1.28 and 5.96 ± 1.18 arcmin, respectively. If extents are calculated from centre-to-centre of the C and the bars, as is done in studies that employ more complex letters or blurred edge stimuli, extents are 9.51 ± 0.61, 11.25 ± 1.34 and 10.50 ± 1.25 arcmin for the 111, 121 and 212 conditions suggesting a similar stage of combination. The extent for the all-CM stimuli would be 19.65 ± 2.00 arcmin, again perhaps reflecting a different neural substrate and supporting a multi-stage framework for contour interaction. A recent review of the literature also suggests that more than a single stage of crowding is likely (Whitney & Levi, 2011).

5. Conclusions

Isolated C visual acuity for 3.5× visibility Cs is reduced for CM stimuli by about a factor of two when compared to LM stimuli. The deleterious effect of nearby contours on foveal C visual acuity is also greater for contrast-modulated (CM) stimuli than for approximately equally visible, luminance-modulated (LM) stimuli. Contour interaction does occur between CM and LM stimuli, indicating that the systems are not independent; both contribute to contour interaction processes occurring across stages of representation. Our results are in agreement with the suggestion that contour interaction occurs at more than one locus in the visual system, with larger effects found at the CM than the LM locus, possibly at a higher stage within V1, V2, or in another extrastriate region. The extent of foveal contour interaction for LM and CM acuity stimuli is similar in gap widths. Due to poorer visual acuity for CM stimuli, contour interaction therefore occurs over correspondingly longer distances in minutes of arc. Clinical studies of crowding may benefit by using CM stimuli, due to their larger magnitude contour interaction effects, as well as their potentially increased sensitivity to changes with development or aging, or in visual conditions such as amblyopia.

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Appendix

To investigate whether consistent luminance cues were available to use in making judgements about our CM Cs, the amplitude difference spectrum (ADS) between two directions, the direction containing the gap and the direction perpendicular to it, was calculated for our LM and CM square Cs using MatLab.

First, experimental LM and CM square C images were created and then Fourier transforms on whole images were calculated. The difference in Fourier spectra, or ADS was calculated in two directions from an average of a high number of images. Averaging was required to find identifiable peaks in the ADS for the LM (noise) stimuli. The peak of the ADS is the critical spatial frequency that is potentially available for the observer to use to detect the orientation of the C's gap (Bondarko & Danilova, 1997). Hess *et al.* (2000b) reported that flanking bars at one gap width away displace the spatial frequency energy band relevant to detecting the orientation of a luminance-based C to a frequency that the fovea is less sensitive to. For the LM noisy C (Figure I a), the ADS pattern for an average of 500 images (Figure I b) shows the peak frequency occurring at about 1.15 cycles per letter for an unflanked C (Figure I c), within the range of peaks found for a noiseless, first-order square C by Liu (2001) and a rounded Landolt C (Bondarko & Danilova, 1997; Hess et al, 2000b). For a LM C flanked by LM bars placed at one gap width away (Figure I d and I e), there is a shift in the peak frequency, where it now occurs at about 1.65 cycles per letter (Figure I f), similar to the findings of Hess *et al.* (2000b).

For an unflanked CM square C (Figure II a), averaging 500 images greatly reduces the visibility of the CM C (Figure II c) and the resultant ADS contains no consistent peak frequency (Figure II e). For a CM square C with surrounding bars at one gap width away (Figure II b), again there are no consistent peak frequencies available to the observers (Figure II f). In fact, the ADS for CM stimuli, both for an isolated C and one surrounded by bars, show only random peaks and troughs, similar to the ADS obtained for images containing unmodulated background random noise only (Figures II g, h). In the current study there are many similarities between contour interaction for LM and CM stimuli, suggesting similar underlying mechanisms (though contour interaction is stronger for CM stimuli), but clearly, this cannot be by using consistent linearities as revealed by the ADS for Cs with and without bars.

[INSERT FIGURE I HERE]

[INSERT FIGURE II HERE]

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Table 1

Peak magnitude and extent of contour interaction for LM and CM square Cs with similarly-defined bars

Stimuli	Target visibility (multiples of threshold)	Bar visibility (multiples of threshold)	Unflanked threshold (logMAR) ±1SEM	Peak elevation (logMAR) ±1SEM	Extent (multiples of gap width) ±1SEM	Extent (arcmin) ± 1SEM
111 (LM)	3.5×	3.5×	0.18 ± 0.04	0.11 ± 0.01	3.37 ± 0.54 3.21 ± 0.28*	5.34 ± 1.24 4.97 ± 0.44*
222 (CM)	3.5×	3.5×	0.46 ± 0.04	0.23 ± 0.01	3.82 ± 1.00 3.81 ± 0.63*	11.17 ± 2.88 11.00 ± 1.83*

Table 2

Peak elevation and extent of contour interaction for LM and CM square Cs with differently-defined bars

Stimuli	Target visibility (multiples of threshold)	Bar visibility (multiples of threshold)	Unflanked threshold (logMAR) ±1SEM	Peak elevation (logMAR) ±1SEM	Extent (multiples of gap width) ±1SEM	Extent (arcmin) ±1SEM
121	3.5×	3.5×	0.45 ± 0.02	0.08 ± 0.02	0.99 ± 0.46	2.79 ± 1.28
212	3.5×	3.5×	0.18 ± 0.04	0.17 ± 0.03	3.96 ± 0.78	5.96 ± 1.18

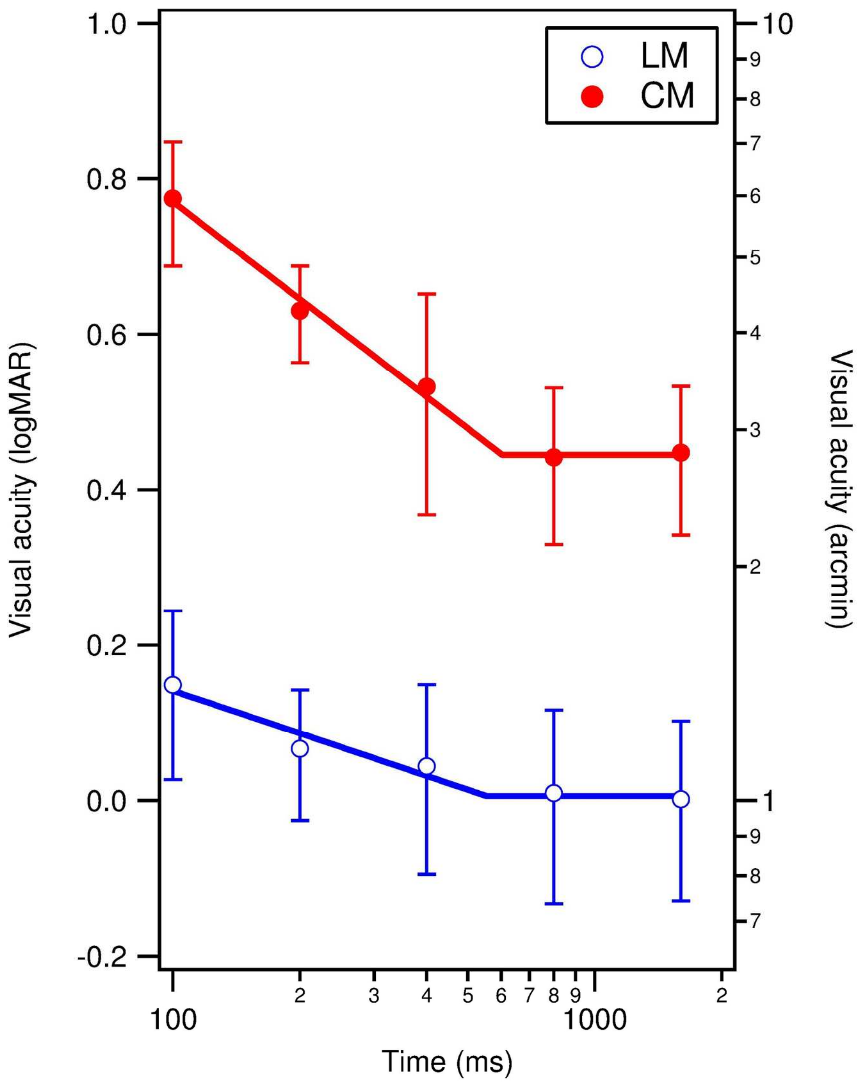

Figure 1
Visual acuity in logMAR (left ordinate) and MAR (right ordinate), plotted as a function of stimulus duration (ms), for LM and CM stimuli. Error bars represent ±1se (across 3 observers). Data are fit with a double power function (the continuous blue and red lines) on log-log co-ordinates to estimate the duration, after which visual acuity becomes stable (see text for values).
142x194mm (300 x 300 DPI)

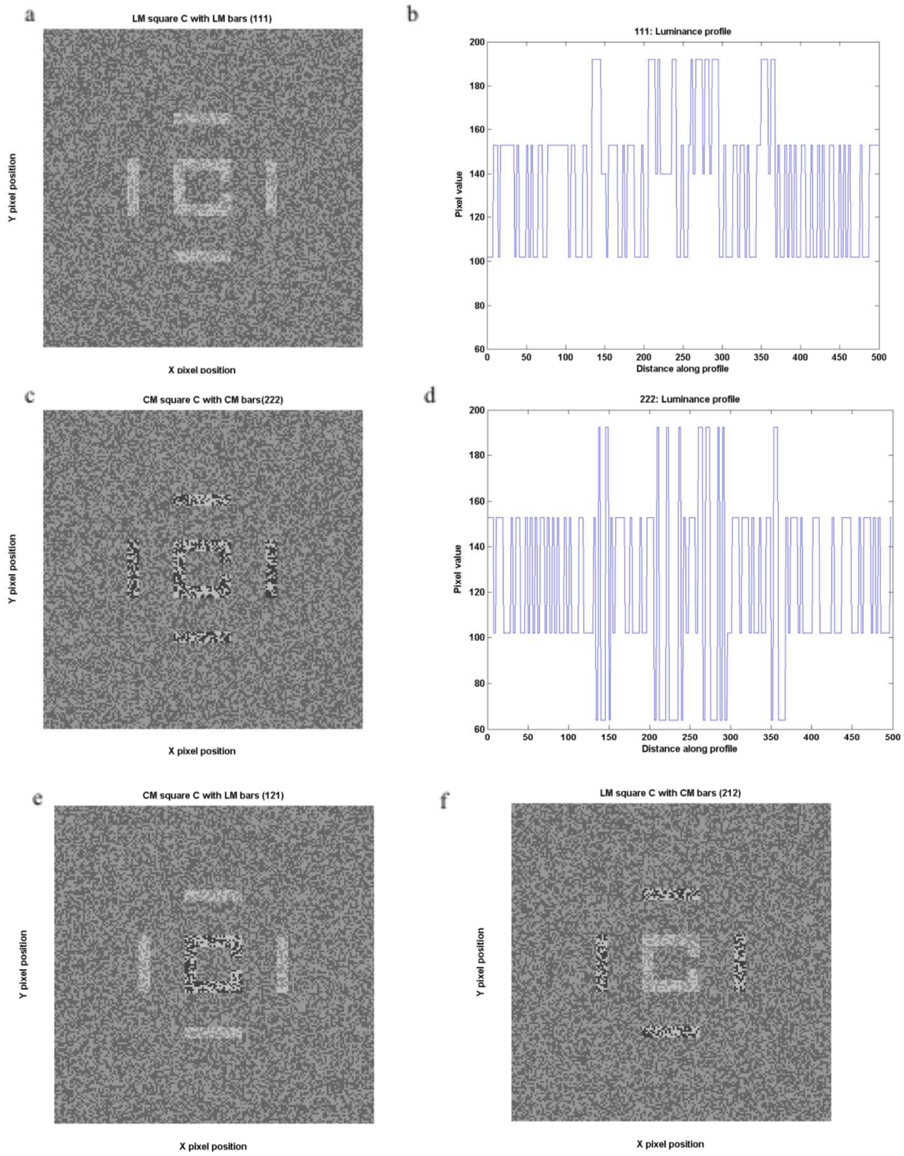

Figure 2
Greyscale figures a, c, e and f are similar stimuli to those used in experiments. In these figures, the separation between the square Cs and bars is 3 gap widths (0.6× letter size). Figures b and d are luminance profiles for the stimuli in a and c, generated using MatLab. Profiles were taken across the gap from the top to the bottom of the figures in the left column. The left and right luminance shifts represent the bars; the central shifts represent two limbs of the square C with the gap at the centre. a) LM square C surrounded by LM bars (111) with luminance amplitude l set at 0.3. b) Luminance profile for LM stimuli. c) CM square C surrounded by four CM bars (222) with contrast amplitude m set at 1.5. d) Luminance profile for CM stimuli. e) CM square C surrounded by four LM bars (121). f) LM square C surrounded by four CM bars (212).
214x251mm (300 x 300 DPI)

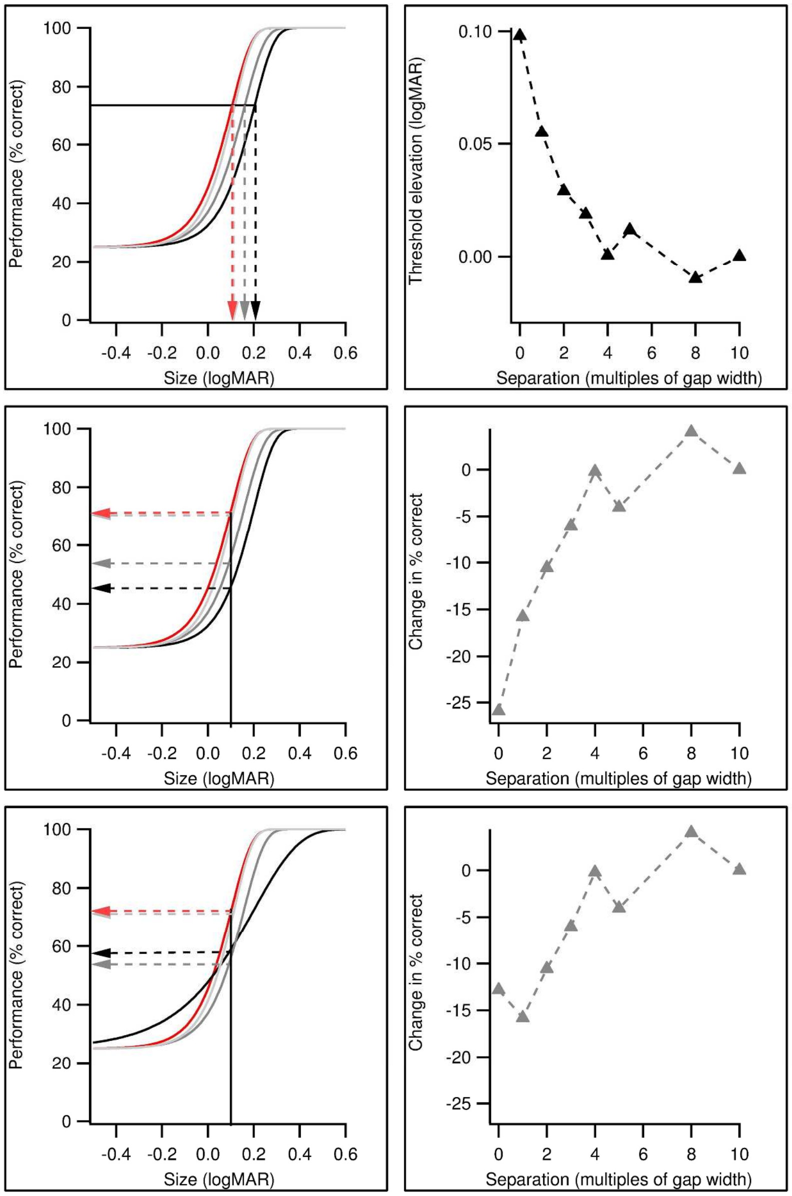

Figure 3
A schematic showing how logMAR and performance contour interaction functions across C-bar separation (right panels) can be obtained from the same set of psychometric functions generated by our experimental data (left panels). Data for the isolated C are shown in red, from which other data are compared to find the magnitude of contour interaction. Top row: Visual acuity thresholds (in logMAR) are taken from the appropriate psychometric function for the isolated letter and each separation at a fixed performance level of 72.4 % correct (left). Threshold elevations are then calculated as the difference between the logMAR threshold at each separation and that obtained without the surrounding bars, and plotted as a function of separation (right). Middle row: The size that corresponds to 72.4% correct response for the isolated letter is taken from the psychometric function (left). For this fixed size, performance (% correct response) is then derived for each separation from the appropriate psychometric function. The change in percent correct (i.e. that change in percent correct with and without surrounding bars) for each separation is then calculated and plotted as a function of separation (right). Bottom row: As for middle row, however the slopes of

psychometric functions are flatter for the abutting condition (black curve). This results in a different contour interaction performance function shape (more like Flom et al, 1963).
218x328mm (300 x 300 DPI)

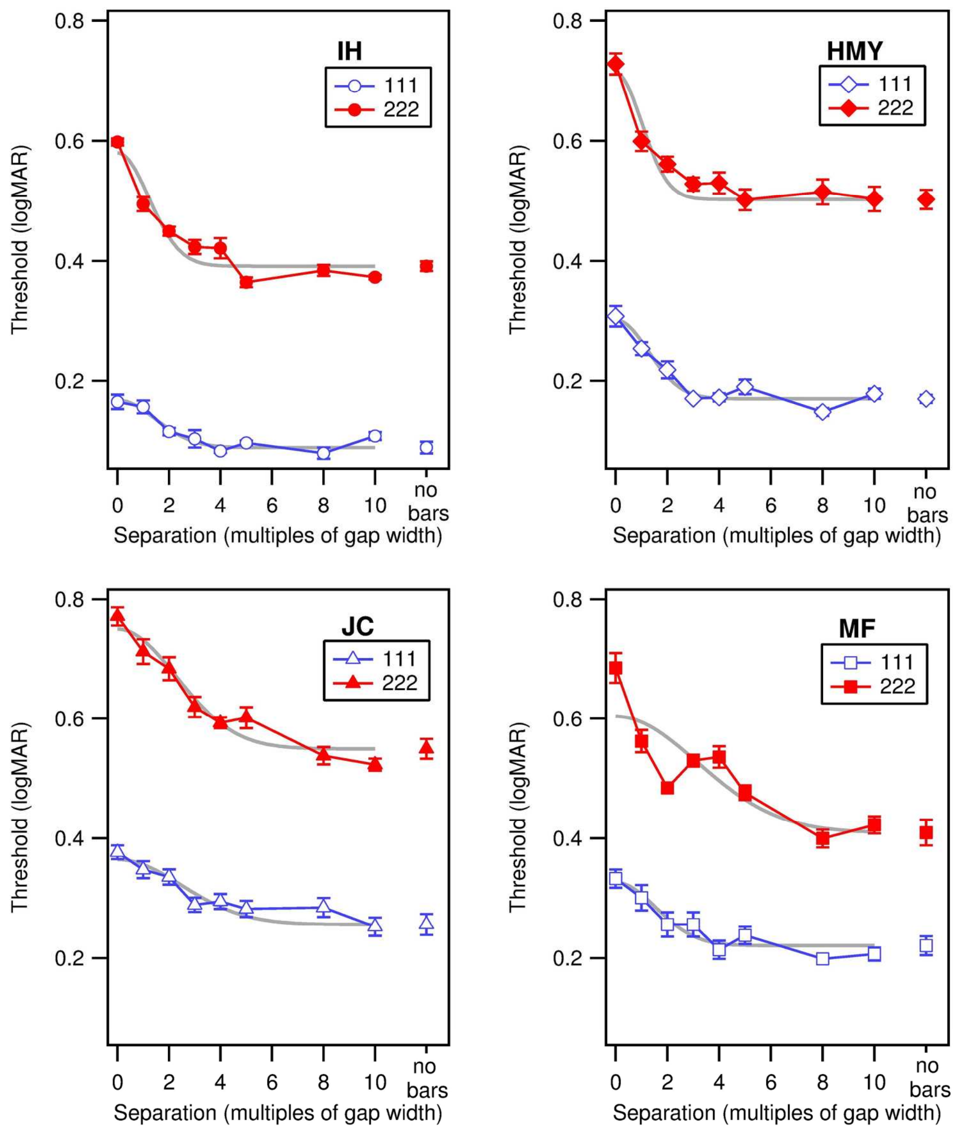

Figure 4
Gap resolution threshold in logMAR plotted as a function of separation between C and bars in multiples of gap width for observers IH, HMY, JC and MF. The open symbols are data for LM target flanked by LM bars (111), filled symbols are for CM target flanked by CM bars (222) and the error bars represent ±1 SEM (between run intra-observer variance). Gaussians used to estimate contour interaction extents are fit to the data.
187x215mm (300 x 300 DPI)

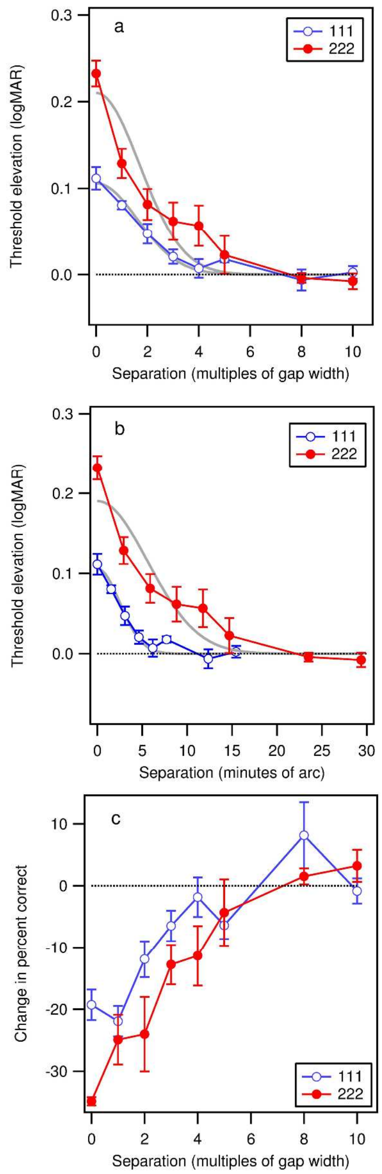

Figure 5
(a) Averaged resolution threshold elevations (resolution threshold in the presence of bars relative to threshold without bars) as a function of C-bar separation expressed in multiples of gap width for 111 (open symbols) and 222 (filled symbols) stimuli. Values above zero at any given separation indicate where thresholds are higher than the isolated C (or no bars) condition. (b) Averaged threshold elevation as a function of separation expressed in minutes of arc, for 111 and 222 stimuli. (c) Data re-plotted, as change in percent correct as a function of target bar separation for 111 and 222 stimuli. The dotted line represents no change in performance, (i.e., no contour interaction). All error bars represent ±1 SEM (inter-observer variance). The curves in (a) and (b) are Gaussian fits to the averaged data.
271x787mm (300 x 300 DPI)

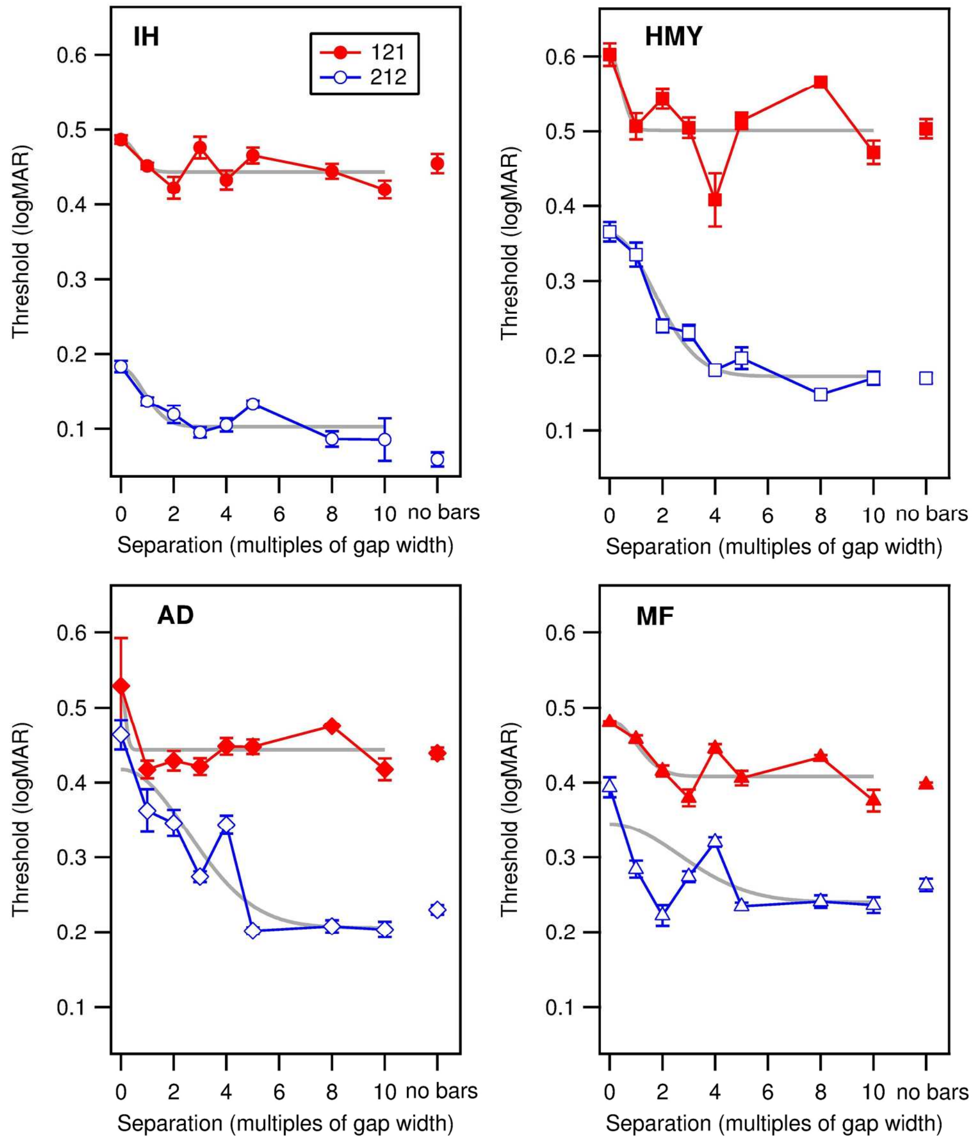

Figure 6
Gap resolution thresholds in logMAR plotted as a function of separation in multiples of gap width between C and bars for observers IH, HMY MF and AD. The open symbols are data for LM target flanked by CM bars (212) and filled symbols are for CM target flanked by LM bars (121). Gaussians often did not fit individual data well. AD showed large variability for the abutting 212 stimulus.
185x215mm (300 x 300 DPI)

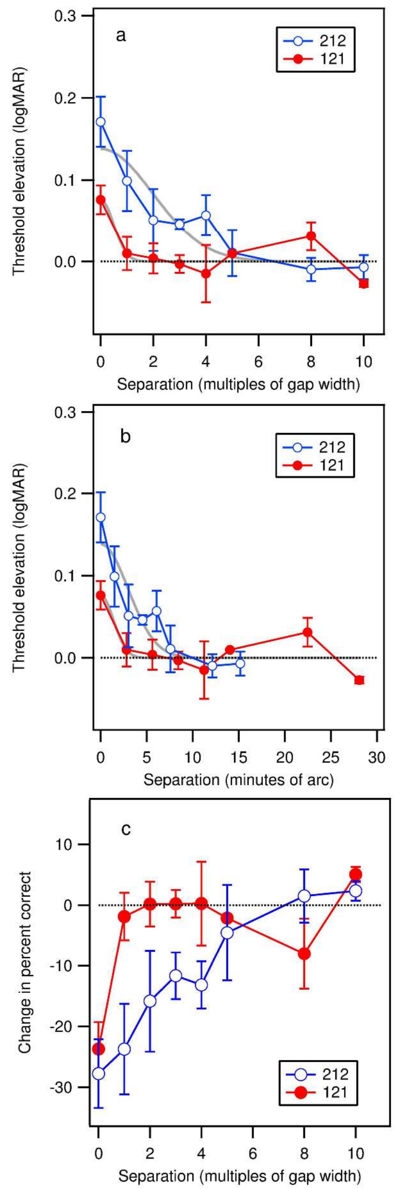

Figure 7
(a) Averaged gap resolution threshold elevation (resolution threshold in the presence of bars relative to resolution threshold without bars) as a function of target-bar separation for 212 (open symbols) and 121 (filled symbols). (b) Averaged threshold elevation as a function of separation expressed in minutes of arc, for 212 and 121. (c) Data are re-plotted as change in percent correct versus separation functions for the 212 and 121 arrangements. The dotted line represents no change in performance for an isolated C. Error bars represent ±1 SEM (inter-observer variance).
264x748mm (300 x 300 DPI)

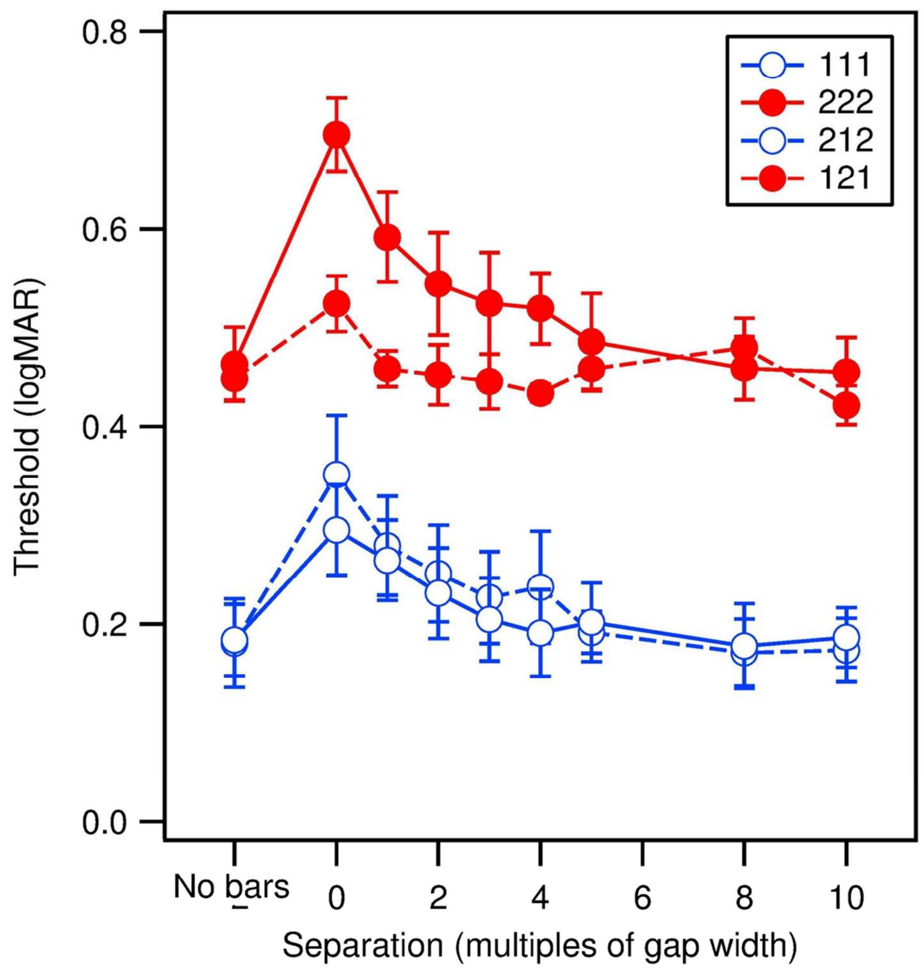

Figure 8
Averaged C acuity thresholds for the isolated C (no bars) condition and for Cs surrounded by bars of same and different type (111, 212, 222, 121 – see text for details) placed at different separations from the C. The data have been averaged across 4 observers. Three of the four observers participated in both Experiments 1 and 2. Error bars represent ±1 SEM (inter-observer variance).
104x104mm (300 x 300 DPI)

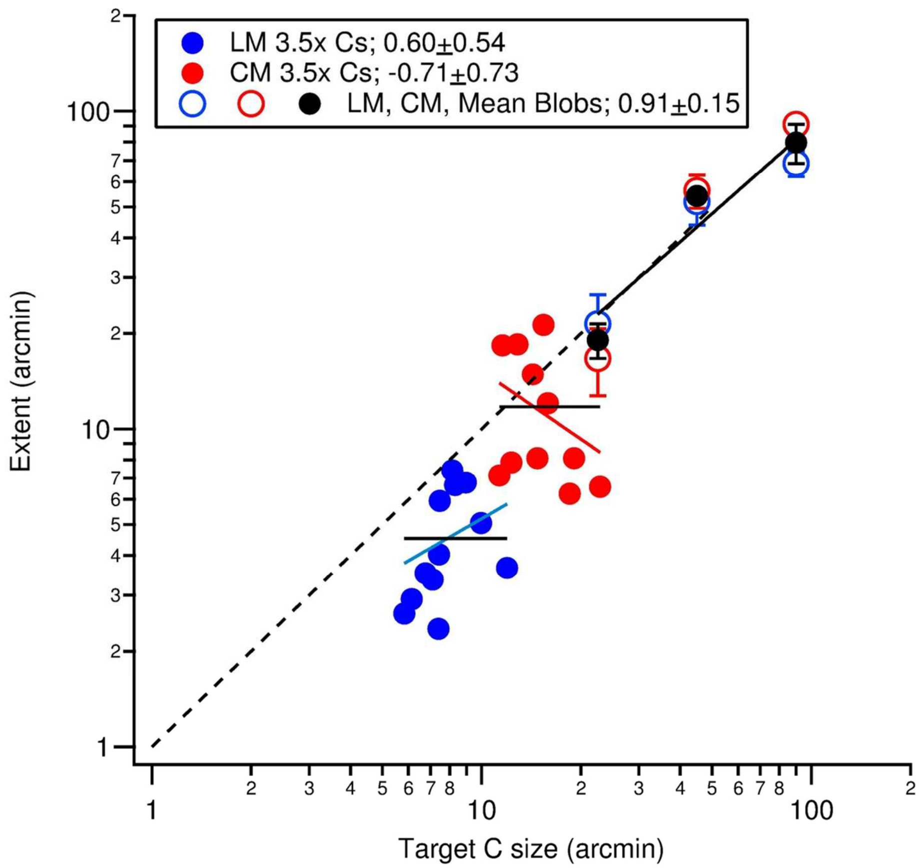

Figure 9
Extents (arcmin) for fixed sizes of LM and CM Cs (arcmin) for 3 observers are shown by solid blue (LM) and red (CM) symbols, respectively. The relationship between extent and size within LM and CM data is not directly proportional (as shown by 1:1 black dotted line). Solid black lines represent fixed extents for LM and CM systems. Going between LM and CM data, increasing size is associated with increased extent in arcmin. The open blue and red symbols represent extents (armin) of lateral masking functions for LM and CM blob stimuli (Hairol & Waugh, 2010a; Figure 10). The sd of the blob stimuli were 30, 15 and 7.5 arcmin. They are plotted here at sizes of +1.5xsd (or 90, 45 and 22.5 arcmin) for ease of comparison with C data. LM and CM extents in arcmin are not statistically different and scale directly with target size. Solid black symbols represent the mean of LM and CM masking data.
117x105mm (300 x 300 DPI)

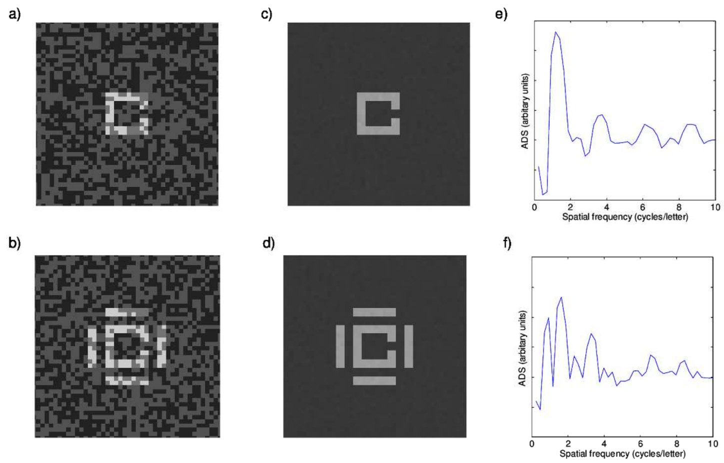

Figure I
a) Unflanked LM C stimulus. b) Flanked LM stimulus with LM bars at one gap width. c) Average of 500 unflanked LM stimuli. d) Average of 500 LM flanked stimuli. e) ADS for the average of 500 unflanked LM stimuli. f) ADS for the average of 500 LM flanked stimuli.
297x209mm (200 x 200 DPI)

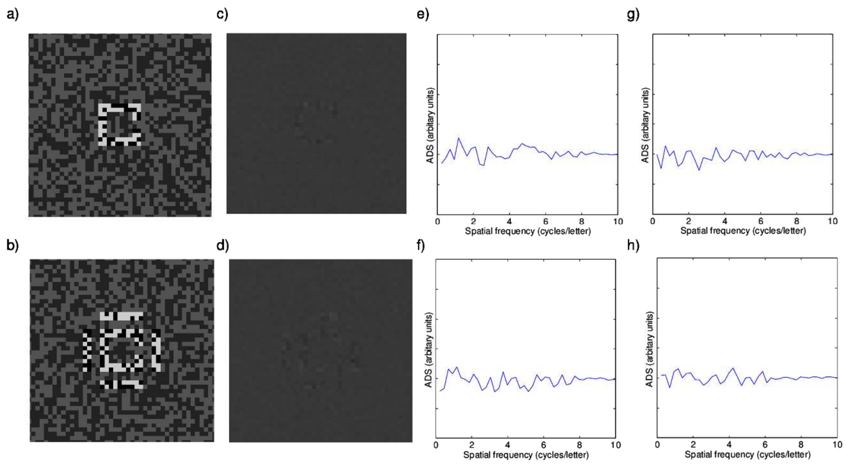

Figure II
a) Unflanked CM C stimulus. b) Flanked CM C stimulus with CM bars at one gap width away. c) Average of 500 unflanked CM stimuli. d) Average of 500 CM flanked stimuli. e) ADS for the average of 500 unflanked CM stimuli. f) ADS for the average of 500 CM flanked stimuli. g) ADS for the average of 500 unmodulated random noise images. h) ADS for a second average of 500 unmodulated random noise images.
297x209mm (200 x 200 DPI)