Interference in visual crowding stimuli with small separations between target and flanking stimuli

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Short title: Crowding stimuli

ABSTRACT

Visual crowding occurs when flanking stimuli reduce the visibility of a target stimulus. This effect is typically stronger the closer the flanking stimuli are to the target. However, it has been observed that this trend may be reversed causing an upturn at the very smallest separations. It has been shown previously that crowding may be consistent with interference in the stimuli. Interference takes place in the stimuli and does not depend on vision or the visual system. The present analyses examine interference between stimuli at very small separations. It is found that when the analyses are confined to very low spatial frequency components interference may result in reduced interference at the very smallest separations. This is consistent with the upturn observed in some psychophysical experiments,

Key words: phase; vision; amplitude; spatial frequency.

INTRODUCTION

The term "visual crowding" refers to phenomenon that adjacent flanking stimuli reduce the visibility of a target stimulus (Levi, 2008). Crowding has generally been interpreted in terms of mechanisms or elements in the visual system (Bacigalupo & Luck, 2019; Battaglini et al., 2019; Bi et al., 2009; Chaney et al., 2014; Clarke et al., 2014; Coates et al., 2018; Crutch & Warrington, 2007, 2009; Doron et al., 2015; Fang & He, 2008; Freeman & Simoncelli, 2011; Han & Luo, 2019; He et al., 2019; Leaf et al., 1999; Lev & Polat, 2015; Levi, 2008, 2011; Liu et al., 2019; Manassi et al., 2012, 2016; Manassi & Whitney, 2018; Motter, 2018; Ogata et al., 2019; Parkes et al., 2001; Patro, & Huckauf, 2019; Pelli et al., 2004; Reddy & VanRullen, 2007; Sacchi et al., 2018; Siderov et al., 2020; Soo et al., 2018; Whitney & Levi, 2011; Yashar et al., 2019). However, analyses have demonstrated that effects similar to crowding may be generated by interference in the stimuli (Skottun, 2018a, b).

Interference can be best understood by considering Fourier spectra. Each element in a Fourier spectrum consists of a complex number of the form $z = (a + bi)$ where $i = \sqrt{-1}$ and a and b are real numbers. When adding two elements, z_1 and z_2 , we get $z_1 + z_2 = (a_1 + b_1i) + (a_2 + b_2i) = a_1 + a_2 + (b_1 + b_2)i$. The amplitude, i.e. the absolute, of this sum is $|z_1 + z_2| = \sqrt{(a_1 + a_2)^2 + (b_1 + b_2)^2}$. Were we instead to take the sum of the amplitudes, i.e. sum of the absolutes, we would get $|z_1| + |z_2| = \sqrt{a_1^2 + b_1^2} + \sqrt{a_2^2 + b_2^2}$. Thus, $|z_1 + z_2| \neq |z_1| + |z_2|$ when $a_1/b_1 \neq a_2/b_2$. Given that a/b expresses the phase we have that the amplitude of a sum is not equal to the sum of amplitudes unless the phases are identical. More specifically, $|z_1 + z_2| < |z_1| + |z_2|$ when the phases differ. Put simply, the amplitude of the sum is smaller than the sum of amplitudes when the phases differ.

Given that flanking stimuli and target stimuli for all practical purposes differ in their phase spectra we have that when adding flanking stimuli to a target stimulus the sum of amplitudes in the combined stimulus will be smaller than the sum of amplitudes in the stimuli determined separately. The fact that the amplitude of the sum is smaller than the sum of amplitudes entails that the amplitudes of the target, of the flanking stimuli, or both will be reduced in the combined stimulus. In other words, one cannot count on a stimulus having the same stimulus power when presented in combination with other stimuli as when presented by itself (Skottun, 2018a, b). (For a discussion of "stimulus power" see Skottun, 2018c.) This occurs irrespective of whether or not the stimuli are seen or activate any visual system. (For further discussions of interference in visual stimuli see Skottun, 2018a, b, c, d.)

Although crowding most typically increases with decreasing separation between target and flanking stim-

uli some investigators have observed a reversal of this tendency at the very smallest separations (Flom et al., 1963; Coates et al., 2018; Siderov et al., 2020). This is illustrated in Fig. 1. Like crowding in general the upturn of the function at small separations has been interpreted in terms of neural mechanisms. In the words of Siderov et al. (2020): "We interpret our results to indicate that neural interactions between nearby contours reduce performance when the target and flanking bars form discrete neural images. At sufficiently small separations, the images of the target and flanking bars can not be distinguished and performance is governed by the contrast of the target in the blended neural image."

Fig. 1

Fig. 1. Percent correct responses as a function of separation between target and flanking stimuli re-plotted from Fig. 1 of Siderov et al. (2020; data are for a "20 % Flank"). As can be seen, while the percentage of correct responses generally increases with separation there is an "upturn" at the very smallest separation where the percentage of correct responses decreases with increasing separation.

It has been shown that such an upturn at the every smallest separations may be consistent with interference between stimulus elements (Skottun, 2018a; see particularly Figs. 3 and 6 of that paper). However, the stimuli simulated in those analyses were Gabor patches (i.e., sine gratings or sine waves multiplied by Gaussians). The present report explores this issue with stimuli that are more representative of those used to assess visual crowding.

METHODS

Computer simulations were carried out in *Mathematica* (Wolfram Research). Two stimulus configurations were examined: (1) A central X flanked by vertical bars, and (2) a central X flanked on both sides with an identical X. In the first case the flanking and target stimuli have substantial amplitudes at different orientations. In the second case the target and each of the flanking stimuli have identical amplitude spectra. The stimuli are shown in Fig. 2.

We denote the target and flanking stimuli by $\mathbf{t}$ and $\mathbf{f}$, respectively, and their Fourier spectra by $\mathbf{T}$ and $\mathbf{F}$. We further denote the amplitude operator (i.e., the absolute operator) by $|\cdot|$ (i.e., $|z| = \sqrt{a^2 + b^2}$). We then get that the amplitude spectra of the target and flanking stimuli may be written as $|\mathbf{T}|$ and $|\mathbf{F}|$ and the amplitude spectrum of the two stimuli combined can be denoted by $|\mathbf{T} + \mathbf{F}|$. The *Relative Amplitude Sum* was defined as $\sum |\mathbf{T} + \mathbf{F}| / (\sum |\mathbf{T}| + \sum |\mathbf{F}|)$. (For details see Skottun, 2018a, b, c.) Expressed in words, the *Relative Amplitude Sum* is the ratio of the sum of amplitudes in the combined stimulus relative to the sum of amplitudes in the target plus the sum of amplitudes in the flanking stimuli. Note that $\sum |\mathbf{T} + \mathbf{F}| < \sum |\mathbf{T}| + \sum |\mathbf{F}|$ when $\mathbf{F}$ and $\mathbf{T}$ have different phase spectra (see *Introduction*). Thus, interference manifests itself in a *Relative Amplitude Sum* of less than 1.0 and the amount of interference may be quantified as the amount the *Relative Amplitude Sum* falls below 1.0.

RESULTS

A focus of the present investigation was to examine the effect of spatial frequency upon the *Relative Amplitude Sum*. In order to do so amplitudes were included from below some particular cut-off frequency. (Cut-off frequencies of 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, or 20 cycles/image were examined even though only data for cut-off frequencies of 4, 9 and 20 cycles/image are shown). This was achieved by creating a circle centered upon the d.c. component with radius corresponding to the cut-off value and to compute the *Relative Amplitude Sum* only for amplitudes of components within the circle.

In Fig. 3 is shown *Relative Amplitude Sum* as a function of separation between target and flanking stimuli. (Separation is the distance between the outer edges of the target stimulus and the inner edges of the flanking stimuli.) In Fig. 3A are shown data for a central X flanked by bars (as shown in Fig. 2A) for integration of amplitudes below 4 (solid line) and 20 (dashed line) cycles/image. In Fig. 3B are shown results for a central X flanked by identical Xes (as shown in Fig. 2B) for integration of amplitudes below 4 (solid line) and 9 (dashed line) cycles/image.

Fig. 2

Fig. 2. The stimuli employed in the present analyses. Panel A shows a central X flanked by vertical bars and Panel B shows a central X flanked by an identical X on both sides. In both of the shown examples the overall size of the image was 255 x 255 elements and the separation between target and flanking stimuli were 5 elements. The separation is the distance between the outer edge of the target and the inner edge of the flanking stimuli.

Fig. 3

Fig. 3. *Relative Amplitude Sum* as a function of separation between target and flanking stimuli. Panel A shows data for a central X flanked by vertical bars (as shown in Fig. 2A) and Panel B gives data for a central X flanked by Xes (as shown in Fig. 2B). In Panel A the solid and dashed lines show data for summing of amplitudes below 4 and 20 cycles/image, respectively. In Panel B the solid and dashed lines show results for amplitudes below 4 and 9 cycles/image, respectively.

As can be seen from Fig. 3A there is clear evidence for *Relative Amplitude Sum* to decrease with decreasing separation when only the amplitudes of spatial frequency components below 4 cycles/image are included (solid line). In other words, the amount of interference increases with separation for an X flanked by bars when only very low spatial frequencies are taken into account. However, when all amplitudes below 20 cycles/image are included (dashed line) we obtain an essentially flat curve.

In the case of a target flanked by Xes (Fig. 3B) there is clear evidence for interference since all the values fall well below 1.0 but there is no clear effect of separation in that the data form essentially horizontal

lines. This applies to both data for amplitudes below 4 cycles/image (solid line) and for amplitudes below 9 cycles/image (dashed line).

These observations have been made based simply on the stimuli. That is, no assumptions about the visual system have been made. As a consequence, there has been no limit to the distance (in space-domain) over which the stimulation is integrated. In other words, stimuli far apart have been assumed to have the same ability to interfere with each other as stimuli that are close together in space. Given that receptive fields of visual neurons have finite sizes it would seem reasonable to assume that a given stimulus would be

Fig. 4

Fig. 4. Same as Fig. 3 with the exception that the stimuli were multiplied (in space-domain) with a 2-D gaussian having a $\sigma = 20$ image elements prior to computing the *Relative Amplitude Sums*.

more affected by other stimuli that are close by than those that are farther away. In order to simulate limited spatial integration the stimuli were multiplied (in space-domain) with a 2-D Gaussian having a $\sigma = 20$ elements centered upon the target stimulus.

The results are shown in Fig. 4. In Fig. 4A are shown results for the case where the central X was flanked by bars (as shown in Fig. 2A) and Fig. 4B shows results for when the central X was flanked by Xes (as in Fig. 2B). The analysis behind these plots is the same as the one behind those in Fig. 3 with the exception that the stimuli have been multiplied with a 2-D Gaussian in the space domain prior to computing the *Relative Amplitude Sums*. As can be seen, there is a general trend for the *Relative Amplitude Sum* to increase with separation so as to become close to 1.0 at the larger separations. That is, interference tends to decrease with separation. The reason for this is obviously that when the stimuli are weighed with a Gaussian centered upon the target stimulus (i.e., upon the central X) flanking stimuli will decrease in contrast as they are moved further away from the target. However, in the case of *Relative Amplitude Sum* calculated from only frequency components below 4 cycles/image there is evidence for a modest decrease with separation at the very lowest separations. This is apparent in both the data obtained with vertical bars as flanking stimuli (solid line in Fig. 4A) and in the results obtained with Xes as flanking stimuli (solid line in Fig. 4B).

There has been some discussion of the possible role of optical factors in relation to crowding (Flom, 1991; Coates et al., 2018). For instance, Coates et al. (2018) sought to make use of adaptive optics to counteract optical imperfections. Given the main effect of imperfect optics is blurring of the retinal image the effect of blur was investigated. This was carried out for an X flanked by bars (as in Fig. 2A) by convolving them with a 2D gaussian having a $\sigma = 8$ picture elements. The stimuli blurred in this manner are shown in Fig. 5A. In Fig. 5B is shown *Relative Amplitude Sum* as a function of separation for amplitudes of components below 4 cycles/image. The dashed line shows the results for the blurred stimuli (as shown in Fig. 5A). For comparison are shown with a solid line the results for un-blurred stimuli (this curve is a re-plot of the solid line in Fig. 3A). As can be seen, (and as was to be expected) blurring had little effect upon the interference including little effect upon the upturn at small separations.

In Fig. 5C are shown corresponding results obtained with stimuli that were multiplied in the space domain with a 2D gaussian having a $\sigma = 20$ image elements. The dashed line gives *Relative Amplitude Sum* as a function of separation for blurred stimuli and the solid line gives results for un-blurred stimuli. In this case there is somewhat more of an effect of blurring but the upturn of the function at the very smallest separation is clearly apparent in the results obtained with blurred images. These results show, therefore, that blurring may influence the effect of interference to a small degree but does not affect the upturn of the curve at the smallest separations that can be observed under some conditions. The obvious reason for this is that the upturn is observed predominantly when only (or mainly) amplitudes at very low spatial frequencies

Fig. 5

Fig. 5. The effect of blur, (A) A central X flanked by bars blurred by convolution with a 2D gaussian having a $\sigma = 8$. The separation between the central X and each of the bars is 33 picture elements in this image. (B) *Relative Amplitude Sum* as a function of separation for an un-blurred stimulus and a stimulus blurred by convolution with a 2D gaussian. (C) *Relative Amplitude Sum* for a blurred and un-blurred image when the stimuli in the space domain had been weighed with a gaussian having a $\sigma = 20$ image elements. The results in both Panels B and C are for integrating amplitudes below 4 cycles/image. In both panels solid lines give results without blur and dashed lines give result for stimuli that have been blurred by convolution with a 2D gaussian having a $\sigma = 8$ image elements. (The curve for the un-blurred stimuli shown with solid line in Panel B is the same as the one shown with solid line in Fig. 3A and the solid line in Panel C is the same as the solid line in Fig. 4A.)

are considered. These are the components least affected by blurring.

DISCUSSION

It has previously been pointed out that interference in the stimuli has the potential to generate effects comparable to those seen in visual crowding (Skottun, 2018a, b). The present analyses serve to emphasize the relevance of interference to crowding by showing that interference in the stimuli can also cause reduced crowding at very small separations as has been observed in some psychophysical experiments (Flom et al., 1963; Coates et al., 2018; Siderov et al., 2020). The analyses also show that the effect of interference may depend profoundly upon which parts of the amplitude spectra are included in the analyses.

The reason for the reduced interference at small separations is presumably that small separations involve small differences in spatial phase. Interference is the result of combining signals which differ in their phase spectra. When the phases are similar there will be little interference but when they are different the amount of interference will be larger. If smaller spatial separations involve smaller differences in spatial phase this would cause interference to be smaller when the separation is small. In the case of crowding this would mean that the crowding might be reduced at the smallest separations. As was seen above, the upturn was observed only, or mainly, when only low spatial frequency components were taken into account. The reason for this is presumably that a given spatial displacement represents a smaller change in phase for low spatial frequency components than for high ones. This, however, should not be taken to mean that other factors may not have an influence.

Some may perhaps think that reduced interference only found when the analysis is confined to low spatial frequencies would not be of significance. In relations to this it should be pointed out that images tend to have their largest amplitudes at the very lowest spatial frequencies (Tolhurst et al., 1992). Thus, the lowest frequencies may be particularly important.

Interference, it should be re-emphasized, takes place in the stimuli and is independent of seeing and of the visual system. However, the visual system may influence how interference manifests itself. This, it needs to be pointed out, should not be taken to mean that the interference takes place in the visual system. In the present analyses the influence of the visual system was simulated by multiplying the stimuli with a space-domain 2D gaussian in order to model limited spatial extent of integration (Fig. 4 and Fig. 5C). This was the only assumption about the visual system incorporated in the present analyses.

As was pointed out above, crowding has commonly been interpreted within a framework of neural mech-

anisms. The present work along with previous investigations (Skottun, 2018a, b, c) demonstrate that interference in the stimuli needs to be taken into account.

Yeshurun et al. (2015) have reported crowding effects not only along the space dimension but also along the time dimension. In this connection should be noted that interference may also take place along the time dimension (Skottun, 2018e).

It would seem that in order to understand responses to visual stimuli one must first understand the stimuli. The present analyses represent an attempt at such an understanding. (In this connection see also Skottun et al. 1994.)

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