One universal critical spacing of crowding on the brain

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Abstract
In perception, “crowding” is the improper mixing of objects that are closer to each other than the critical spacing. The critical spacing is negligible in central vision, but, in peripheral vision, grows in proportion to eccentricity. To measure the critical spacing, flanking letters are placed near a target letter and moved apart until the target is identifiable. Current methods place the flankers equidistant from the target. Consider a target in the right visual field. It has long been accepted that when flanking letters are placed above and below the target letter, the critical spacing is smaller than when the flankers are placed to the left and right. However, those experiments used flankers that were not equally effective. To be equally effective, flankers should be spaced so that they are mapped symmetrically on the visual cortex, rather than symmetrically at the visual field. Using equally effective flankers, I find that the critical spacing is the same in all directions tested. This builds on the known fact that critical spacing at the cortex is independent of eccentricity and kind of object, to show that there is one universal critical spacing at the cortex [1, 2]. This is a significant step toward modeling and explaining crowding, and thus how people recognize objects.

Introduction

When identifying a letter in your peripheral vision, the presence of letters flanking the target letter causes interference that obscures the identity of the target letter. This phenomenon is known as crowding. The effects of crowding are decreased when the eccentricity, the distance from the point of fixation to the target letter, is decreased and when the spacing, the distance from the flanking letters to the target letter, is increased. The *critical spacing* is the spacing at which the observer can identify the target letter with an accuracy of 75%. Consider a target letter in the right visual field. Typically, the flanking letters are placed at equal distances from the target letter radially, such that the virtual line connecting the three letters would be horizontal, or tangentially, such that the virtual line would be vertical (*Figures 1 and 2*). It is a longstanding fact in the literature that the critical spacing of crowding is greater radially than tangentially [3]. However, Toet and Levi found that, when spaced radially, the interactions on the peripheral side of the target letter (the side furthest from the point of fixation) are stronger than on the foveal side [4]. Thus equally spaced radial flankers are unequally effective. If the critical spacing is measured with unequally effective flankers, then the results will overestimate the critical spacing. Toet and Levi measured the shape of the zone where crowding occurs in the periphery using symmetric (unequally effective) flankers, and, by doing so, they systematically overestimated the radial critical spacing. Because the crowding is stronger on one side, the peripheral side, for radial spacing, the critical spacing on the foveal side is overestimated. It might seem that this problem could be avoided by measuring the critical spacing using only one flanker. This would allow you to measure the crowding on each side of the target letter separately. However, this does not produce consistent results, perhaps because the observers can learn to use a combining field that is centered away from the target, extending to include the target letter but not the single flanker.

I propose that to measure the radial critical spacing accurately, the letters should be spaced symmetrically on the visual cortex rather than spaced symmetrically on the retina and on paper. Letters spaced tangentially do not cause asymmetric crowding because when they are symmetric on paper, they are also symmetric on the cortex. Only letters spaced radially need to be spaced asymmetrically on paper to achieve symmetric spacing on the cortex. Position on the cortical surface of the neural representation of the visual field is logarithmic [1]. That is, position on the cortex is the logarithm of the position on the retina, relative to the point of fixation in the fovea. Symmetric cortical spacing is achieved by the following equation, which has the cortical spacing of the inner (left) flanker on the left, and that for the outer (right) flanker on the right

$$\log t - \log f = \log f' - \log t \qquad (1)$$

where t is the retinal distance (in deg) from the point of fixation to the target letter, f is the retinal distance from the point of fixation to the flanker on the foveal side, and f' is the retinal distance from the point of fixation to the flanker on the peripheral side. This is easily be solved for the retinal position of the far flanker,

$$f' = t^2/f. \qquad (2)$$

The target position t is kept constant. f' is larger than f, so, decreasing f, increases f' more so. This produces equal crowding on both sides of the target.

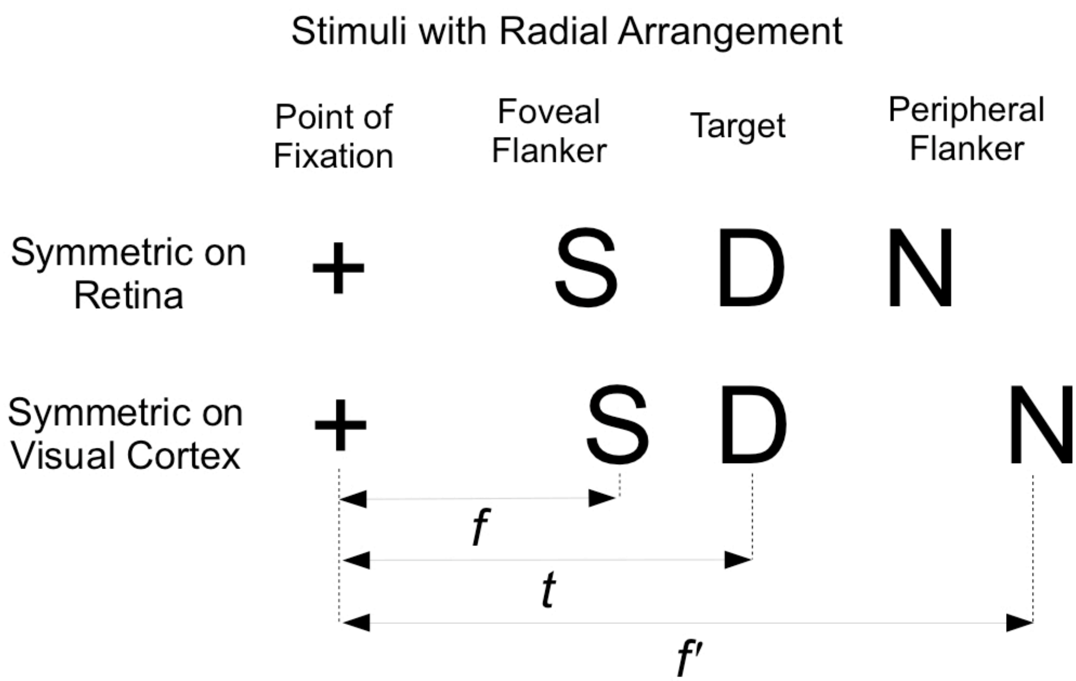

Figure 1: Toet and Levi measured radial crowding with the letters arranged symmetrically on the retina. When I use the logs of the distances t, f, *and* f' *to calculate the spacing, the letters will be mapped symmetrically on the visual cortex. This produces equal crowding on the foveal and peripheral sides of the target letter.*

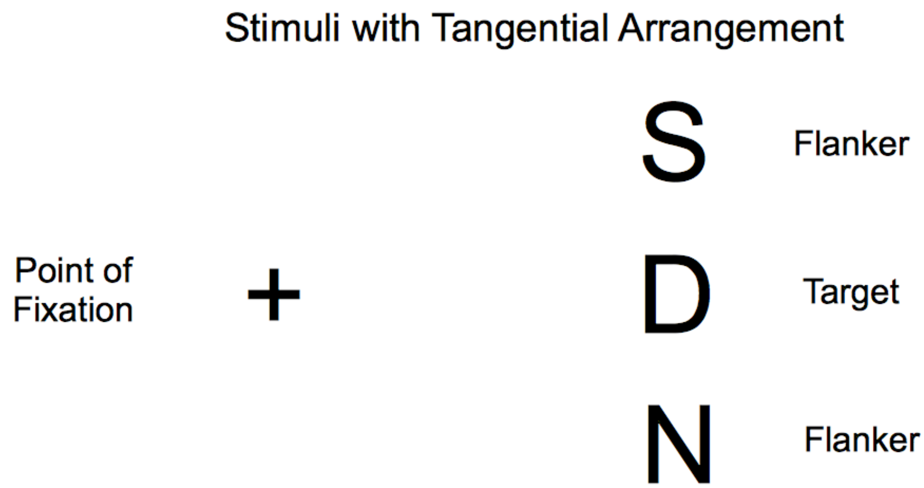

Figure 2: When letters are arranged tangentially, flankers that are symmetric on the retina are also symmetric on the visual cortex.

Materials and Methods

4 male and 2 female subjects, between the ages of 16 and 52, participated in the experiment. All participants gave informed written consent. For participants who were minors, parental consent was obtained as well. All subjects had normal, or corrected to normal, vision. The test was written in MATLAB, and run on a laptop with a 30 cm wide screen. The distance from the screen to the observer was kept constant at 50 cm.

The stimulus, a target letter and two flanking letters, had five variations, in which the separation of the flankers and the target letter increased by increments of 25 degrees of visual angle. The experiment used the method of constant stimuli [6]. The stimuli were presented in a quasi-random order that ensured each variation was shown 40 times for a total of 200 trials. The letters were chosen at random from the list “D, H, K, O, R, S, U, V, and Z,” which was presented to the observers after every trial. Before each experiment, the observers were given the following instructions: “After each presentation, please type the target letter, ignoring the flankers to the left and right. It is very important that you always fixate on the + while the letters are presented.

Once you are fixating on the + click to begin." A tone was played during the 200 milliseconds that the stimulus was presented. The observers were watched during this time to ensure that they did not move their eyes to see the stimulus foveally. After the stimulus was flashed, the observers were presented with a list of the possible letters. The observers reported which letter they believed was the target letter. After the observers typed a letter, they were given auditory feedback—a high tone if correct and a low tone if incorrect. The observers performed the experiment twice, once with the letters arranged tangentially, and once with the letters arranged radially. After the observer completed each set of 200 trials, the program reported their percent accuracy for the five spacings. I averaged the accuracy of the observers at each of the spacings, and graphed the averages for both tangential and radial letter arrangements on the same graph.

In the radial condition the symmetric cortical spacing implies unequal retinal spacing of the two flankers. To plot the radial results we take effective radial spacing to be the geometric mean of the two spacings.

Results

Figure 3 depicts the average proportion of trials that that the observers answered correctly, as a function of the spacing of the letters, measured in degrees of visual angle. As the spacing of the letters increases, i.e. the flanker move further from the target letter, the observers are able to identify the target letter correctly more often. The observers are able to reach almost complete accuracy at the widest spacing. This is true for both tangential and radial orientation of the letters, and is a well known fact of psychophysics. The interesting part is in the near superimposition of the two graphs. The proportion correct is not significantly different at any spacing. The curves for tangential and radial orientation of the letters match amazingly well, refuting the prior belief that radial critical spacing is twice the tangential one. Testing with equally effective flankers, the critical spacing of crowding is found to be the same, radially and tangentially.

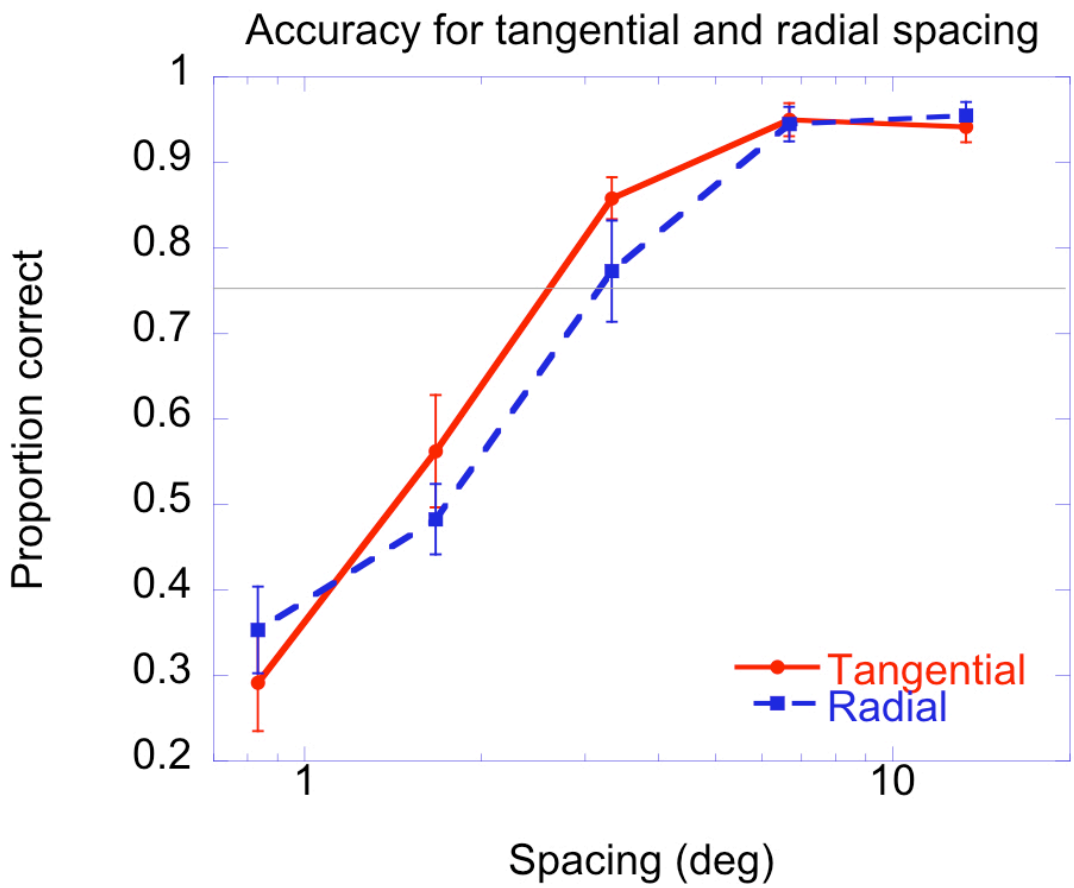

Figure 3: Observers were asked to identify a target letter between flankers. The flankers were arranged radially or tangentially. The curves, averaged across all 6 observers, show the proportion of correctly identified target letters as a function of the spacing between target and flanking letters. The error bars, ± .037 averaged across the 6 observers, are displayed. As the spacing increases, the proportion correct increases because crowding is relieved as the flankers move beyond the critical spacing. The critical spacing (75% correct) is 2.6 deg tangentially and 3.2 deg radially. That's a ratio of 1.2, nearly 1, and much less than the ratio of roughly 2 reported by Toet and Levi. The curves for radial and tangential arrangements are very similar. This indicates that when the flankers are equally effective, as in my experiment, the critical spacing is the same in all directions.

Discussion and Conclusion

The eccentricity dependence of crowding was first reported by Bouma in 1970 [4].

Although it has continued to be studied since then, not much is known about its underlying causes and processes. It is agreed that "the size of the crowding zone scales linearly with eccentricity. ... flankers have an asymmetric crowding effect," which is called "inward-outward asymmetry," and that the crowding zone is elliptical because the radial crowding effects are stronger than the tangential crowding effects, which is called "radial-tangential anisotropy" [5]. The purpose of this experiment was to test the hypothesis that the old result is an artifact. For flankers to have equal crowding effects in a radial arrangement of letters, they have to be mapped symmetrically on the visual cortex. We measured the critical spacing using the standard tangential arrangement and using this new radial arrangement. We found that the crowding was equal in both directions. Using equally effective flankers, we find that crowding has the same critical spacing, radially and tangentially. Combined with the known fact that critical spacing at the cortex is independent of eccentricity and kind of object, we conclude that there is one universal critical spacing at the cortex [2]. This is a significant step toward modeling and explaining crowding, and thus how people recognize objects.

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