The Role of Transient Attention in the Radial-tangential Anisotropy of Crowding

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Research Article

Keywords: crowding, radial-tangential anisotropy, attention, critical spacing, spatial vision

DOI: https://doi.org/10.21203/rs.3.rs-822115/v1

Abstract

Crowding refers to the failure to identify a peripheral object due to its proximity to other objects (flankers). This phenomenon can lead to reading and object recognition impairments, and is associated with macular degeneration, amblyopia, and dyslexia. Crucially, the minimal target-flanker spacing required for the crowding interference (critical spacing) increases with eccentricity. This spacing is also larger when target and flankers appear along the horizontal meridian (radial arrangement) than when the flankers appear above and below the target (tangential arrangement). This phenomenon is known as radial–tangential anisotropy. Previous studies have demonstrated that transient attention can reduce crowding interference. However, it is still unclear whether and how attention interacts with the radial–tangential anisotropy. To address this issue, we manipulated transient attention by using a cue either at the target (valid) or fixation (neutral) location, in both radial and tangential target-flanker arrangements. Results showed that critical spacing was larger in the radial than in the tangential arrangement, and that cueing the target location improved performance and reduced the critical spacing for both radial and tangential arrangements, to the same extent. Together, our findings suggest that transient spatial attention plays an essential role in crowding but not in the radial-tangential anisotropy.

Introduction

Visual crowding describes the phenomenon where an object becomes harder to identify when it is surrounded by other objects (flankers) rather than when it is by itself [1,2]. While mostly unnoticeable, crowding can happen at any point in the visual field– including the fovea [3], but it is more predominant in peripheral vision [4]. Other phenomena hindering flankered object perception include masking, lateral interaction, and surround suppression. However, crowding is an important issue associated with slow and faulty reading [2], and common among clinical populations with macular degeneration, amblyopia, and dyslexia, making it particularly urgent to study [5].

The crowding window (the spatial extent of crowding) is often measured by the minimum spacing between target and flankers required for interference (critical spacing). The crowding window size scales with eccentricity. That is, as target eccentricity increases, the larger the critical spacing (Pelli et al., 2004; Bouma, 1970). Prior research has set this critical spacing at around 30–70% of the stimuli eccentricity [2,6–8].

A number of theories have attempted to explain and predict crowding. Most of these focus on pooling models – where individuals experiencing crowding process both target and flanker features together [9], or substitution models, in which observers confuse targets and flankers [10]. However, another possible explanation for crowding involves attention. This theory suggests that crowding happens due to limitations in the spatial resolution of attention, which is more limited in the visual periphery. Because the eye is unable to encode fine details in the large peripheral vision region, observers become unable to selectively attend to relevant targets without also attending to their irrelevant flankers, when these are close in proximity. Thus, observers struggle to distinguish targets from their flankers [11]. Paying attention to stimuli in the visual periphery becomes increasingly difficult as the stimulus eccentricity increases [12,13]. Accordingly, critical spacing can be used to measure degree of expected crowding [13].

An important characteristic of crowding is its contingencies on the spatial layout of the flankers, meaning that crowding is more or less likely to happen depending on the flankers' arrangement with respect to the target [14]. Two phenomena demonstrate this: (1) the radial tangential anisotropy and (2) the inner-outer asymmetry. The radial-tangential anisotropy refers to the phenomenon where crowding becomes 2-2.5 times more likely to happen when flankers are arranged radially (i.e. along the radius line drawn from the center of the visual field to the target), than tangentially (i.e., flankers are positioned above and below the target, perpendicular to the radius line) [15–17]. The inner-outer (or "in-out") asymmetry in the radial arrangement refers to the stronger interference created by the outer flanker than the inner one [18,19].

Petrov & Meleshkevich (2011a) and Kewan-Khalayly & Yashar (2021) provided evidence for the theory stating that the inner-outer asymmetry of crowding, in a flanker-target radial arrangement, is dependent on the locus of spatial attention. Kewan-Khalayly and Yashar (2021) showed that transient attention - fast covert (without eye movements) spatial attention, manipulated by a peripheral cue [21] – interacts with the inner-outer asymmetry. Specifically, spatially cueing the inner flanker reduced the inner-outer asymmetry, whereas spatially cueing the outer flanker increased the asymmetry. Moreover, in a flanker-target tangential arrangement, transient attention reduced the critical spacing necessary for crowding [22]. Together, crowding and transient attention appear to be closely related, which might be useful in the study and possibly as a mean to elevate crowding. However, the nature of these mechanisms, the different stages of attention, and the levels of processing at which they may modulate visual activity are not yet well understood.

Accordingly, the present study aims to provide quantitate characterization of the effect of attention on crowding and improve our understanding of the processes involved in this phenomenon. In particular, we offer an investigation of the role of covert attention on the radial-tangential anisotropy in crowding. Using two different cue conditions, we compared cue influence on target orientation recognition, as well as interaction between target-flanker critical spacing and flanker arrangement (radial or tangential). We hypothesized that cueing attention would facilitate target identification, hence performance should improve in the cued conditions. Assuming that the radial-tangential anisotropy is due to the locus of covert attention, we predicted that attention would improve target identification in the radial arrangement more so than in the tangential flanker arrangement.

Methods

Participants. Sixteen students (9 males; age range = 19–35 years, *M* = 27.75, SD = 4.81) from the University of Haifa participated in this study, either in exchange of course credit or payment of 50 shekels (around 14$) per hour. Based on previous literature, we estimated that a sample size of 12 participants was required to detect a crowding effect with 95% power, given a .05 alpha [23]. However, we collected data from four additional participants to account for possible dropouts or technical difficulties. All participants ignored the research question and reported normal or corrected to normal vision, and no attention deficits. An informed written consent was obtained from all observers before starting the study. All methods, practices, and procedures were performed in accordance with the Declaration of Helsinki and were approved by the University Committee on Activities Involving Human Subjects at the University of Haifa (No. 226/20).

Apparatus. Stimuli were presented using Matlab software (The MathWorks, Inc., Natick, MA) and the Psychophysics Toolbox, and displayed on a gamma-corrected 21 inch CRT monitor (with 1280 × 960 resolution and 85-Hz refresh rate). Eyelink 1000 (SR Research), an infrared eye tracker, was used to monitor and record eye movement, and a SpectroCAL MKII spectroradiometer (Cambridge Research Systems, UK) was utilized to calibrate brightness and color. Participants were individually tested in a dimly lit room and prompted to use a keyboard to generate responses. Finally, a chin-rest was used to ensure all participant were 57 cm away from the computer monitor.

Stimuli and procedure. Figure 1 illustrates the present experiment's paradigm. All stimuli were colored black (luminance 0.0073 cd/m^2) and presented on a gray background (53 cd/m^2). Firstly, participants were asked to fixate their gaze on the location of the fixation mark. This fixation mark was a centered black dot (subtending 0.24° of visual angle), which appeared on the screen for 500ms and continued to appear until the observer maintain fixation for 300 ms. Following observer fixation a cue appeared on the screen for 50ms. The cue was a black ring (1 px pen width) subtending 1º of diameter. In the neutral cue condition, the cue circle appeared at the center of the screen. In the valid cued condition, the cue appeared 5.9º away from the center of the screen, on the horizontal meridian, in the same hemisphere as the target. An interstimulus interval (ISI) of 50 ms followed the cue, and the target display appeared next, for 100ms. In crowded display trials, three letter shapes (each subtended 0.75° of visual angle) appeared on the screen: one target and two flankers.

The target was a "T" shape, oriented either upright (0º), inverted (180º), or tilted to the left (270º) or the right (90º), and it was presented at an eccentricity of 7º on the horizontal meridian either to the right or to the left of the fixation mark. Note that on valid trials the cue was inner to the target and at 1.1º center to center distance from the target. Flankers were two "H" shapes, either upright or tilted 90º. On half of the crowded display trials, the flankers were positioned *radially*: one to the right and one to the left of the target. On the other half of the trials, the flankers were positioned *tangentially*: one above and one below the target. In each crowded display trial, both flankers were equally spaced from the target. Target-flanker center-to-center spacing was either: 1.1°, 2°, 3°,4°, 5°, 6°, 8° or uncrowded (target alone). Target and flankers were always black. After 500 ms, the response period began, and the monitor displayed a blank screen.

Participants were instructed to report the target's orientation by pressing on one of four designated keys on the keyboard (each key representing one of the 4 possible target orientations). Subjects could take as long as needed to respond. The orientation of both target and flankers, as well as display hemifield, were randomly selected in each trial, There were 40 trial for each combination of cue condition (neutral vs. valid), target-flanker spacing (1.1º ,2º ,3º ,4º ,5º ,6º ,8º and uncrowded), and display arrangement (tangential vs radial). Trial order was unpredictable (quasi-randomized). In total, the experiment consisted of 1280 trials, which were divided into two sessions of 640 trials each. Participants rested for half an hour between the two sessions. Each session was further divided into ten blocks. Following each response, a high or low-pitched tone played to indicate a correct or incorrect response, respectively. Note that participants completed 40 practice trials prior to starting the actual experiment.

Analysis. A three-way analysis of variance (ANOVA: cue condition × target-flanker spacing × stimuli arrangement (radial vs. tangential)) with repeated measures was performed on the accuracy data, excluding the trials where the target appeared without flankers (uncrowded). Additionally, individual data was fitted to an exponential curve using the Weibull function [24] with the goal to compute critical spacing thresholds, per condition (cue and neutral cue). Critical spacing thresholds were defined as the Weibull function coordinate corresponding to 75% of correct trials. Next, using the critical spacing data, we conducted a 2x2 repeated measures ANOVA to explore the relation between cue condition, display arrangement, and critical spacing. Follow-up repeated measures t-tests were performed to further parse out condition differences in critical spacing.

Results

Accuracy. Figure 2 plots accuracy rate as a function of cue condition, display arrangement and target-flanker spacing. As expected, we found a significant main effect for cue condition [$F(1,15) = 25.31$, $p < 0.001$, $\eta^2_p = 0.63$], showing that participant accuracy was higher during valid cue trials than neutral cue trials. We also found a significant main effect for the target-flanker spacing [$F(6,90) = 267.95$, $p < 0.001$, $\eta^2_p = 0.95$], which, in accordance to previous research, showed that accuracy increased as target-flanker spacing increased. Additionally, there was a significant main effect for stimuli layout (radial vs. tangential) [$F(1,15) = 104.12$, $p < 0.001$, $\eta^2_p = 0.87$], showing that accuracy was higher in tangential display trails than in radial display trials. Next, a significant interaction was found between cue condition and target-flanker spacing [$F(6,90) = 3.36$, $p < 0.005$, $\eta^2_p = 0.183$], which revealed that the impact of spacing on accuracy varied across cue conditions. Another significant interaction effect was found between stimuli layout (radial vs. tangential) and target-flanker spacing [$F(6,90) = 32.28$, $p < 0.001$, $\eta^2_p = 0.7$], which revealed that the impact of spacing on accuracy varied across stimuli layout. We further explored these effects by fitting the data to an exponential curve and calculating each condition's critical spacing.

Critical spacing. Two participants had to be removed from further analysis because their data did not reach asymptote (i.e., the estimated critical spacing was exceptionally large). Figure 3 plots critical spacing for the radial and tangential arrangements in the form of their horizontal and vertical extent of crowding (crowing window) for neutral and valid trials. As expected, there was a main effect of cue condition on critical spacing, [$F(1, 13) = 16.81$, $p = 0.001$, $\eta^2_p = 0.56$, where we saw smaller critical spacing in valid trials than in neutral trials. As expected, there was a main effect of display arrangement on the critical spacing, [$F(1, 13) = 110.1.28$, $p < 0.0001$, $\eta^2_p = 0.89$], where we found smaller critical spacing in the tangential rather than in the radial arrangements. Importantly, here was no interaction between cue condition and display arrangement, $F < 1$.

Discussion

The present study examined the combined effects of transient attention and flanker arrangement on the crowding window. Specifically, we measured the effect of a cue on the critical spacing for both tangential and radial flanker arrangements. The results showed that both a peripheral cue and a tangential arrangement reduced the critical spacing. Importantly, our findings also showed that attention affected the critical spacing for both arrangements to the same extent.

The locus of attention and crowding asymmetries. Previous explorations of spatial attention on crowding have yielded inconsistent results. While some studies have failed to show an attentional effect on crowding errors beyond the overall effect of attention on performance [11,22, 25–27], other studies have demonstrated an attentional effect on crowding interference [11,22, 25–27]. A key difference between studies that showed an attentional cueing effect and studies that did not was the cue's location with respect to the target. For example, in a study that used a tangentially arranged target-flanker display, Scolari et al. (2007) failed to show critical spacing reduction by a peripheral cue that appeared at the target's location. In contrast, Yeshurun and Rashel (2011) – who, also used a tangential target-flanker arrangement, demonstrated a critical spacing reduction of about 0.5º-0.75º by a valid cue that appeared at an inner location than the target, i.e., a location between the center of the screen and a peripheral target.

Recently, Kewan-Khalayly & Yashar (2021) resolved the aforementioned inconsistency, as they showed that the peripheral cue effect in crowding is contingent on the cue’s eccentricity with respect to the target location. For instance, cueing the target location did not alter crowding errors in radial crowding, whereas cueing the outer flanker location (a more eccentric location than the target) increased crowding errors. Importantly, cueing the inner flanker location in a radial arrangement (a less eccentric location than the target) decreased crowding errors. In the present study, we used an inner cue in radial and tangential arrangements, and showed a critical spacing reduction in both arrangements. Thus, the results here extend previous findings on tangential and radial target-flanker arrangements, and suggest that the locus of attention plays the same role in both.

The present study's findings support the view that spatial attention is not involved in radial-tangential anisotropy. Spatial attention, however, does appear to play a role in the inner-outer asymmetry (Kewan-Khalayly & Yashar, 2021). Thus, the present study's results, together with Kewan-Khalayly & Yashar's (2021) results, propose that different processes may be involved in the inner-outer asymmetry versus the radial-tangential anisotropy.

Models of attention and crowding. Our findings are consistent with recent models of attention. Spatial attention enhances various aspects of stimulus representation, such as contrast, signal to noise ratio, and visual acuity [28–32]. This signal enhancement can explain the overall increase in correct valid cue trials but not the reduction in critical spacing. Therefore, a possible explanation for our finding could be that attention increases spatial resolution in the periphery [33]. Support for this interpretation comes from neurophysiological studies showing that attention contracts the receptive field of cells around the attended location (see, e.g., Desimone & Duncan (1995), Luck et al. (1997), Moran & Desimone (1985); reviewed by Anton-Erxleben & Carrasco (2013). Hence, reducing the receptive field size over the target area may reduce the pooling area or 'integration field' of crowding [6]. In this way, target and flankers would no longer fall within the same integration field. Our results show that this reduction is uniform across the radial and tangential axes.

Limitations. Our study did not directly explore the differences between the role of attention in the radial-tangential anisotropy and its role in the inner-outer asymmetry. Accordingly, further investigation is required to more concretely disassociate these two phenomena. First, the distance between the inner and outer flankers and the target was kept equal throughout the task, which did not take into account the inner-outer asymmetry found in crowding [18]. Given that the outer flanker tends to increase crowding more than the inner flanker, future studies should explore how attention affects crowding when the distance between the inner flanker and the target, and the outer flanker and the target differ. Additionally, we kept the stimuli's eccentricity constant. However, in a tangential arrangement, the magnitude of the cueing effect varies with target eccentricity [22]. Thus, future studies should explore how peripheral cues influence crowding at different eccentricities, for both radial and tangential arrangements.

Conclusions

The present study shows that the effect of spatial attention on the crowding window is isotropy. Namely, attention reduced the critical spacing for both radial and tangential arrangements to the same extent. Our results extend previous attentional findings on tangential and radial target-flanker arrangements, and suggest that the locus of attention plays the same role in both. Furthermore, we provide evidence in support of the view that attention enhances spatial resolution by contracting receptive (or integration) field size, and suggest that this contraction is uniform across the radial and tangential axes.

Declarations

Data availability

The data and analysis codes are available from the corresponding author upon request.

Author Contributions

AY conceptualized this study. BKK collected the data. BKK and AY contributed to the research design. BKK, MM and AY contributed to the statistical analysis, interpretation of the data and writing.

Funding

This work was supported by The Israel Science Foundation Grant Nos. 1980/18 (to A. Yashar).

Competing interests

The authors declare no competing interests.

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Figures

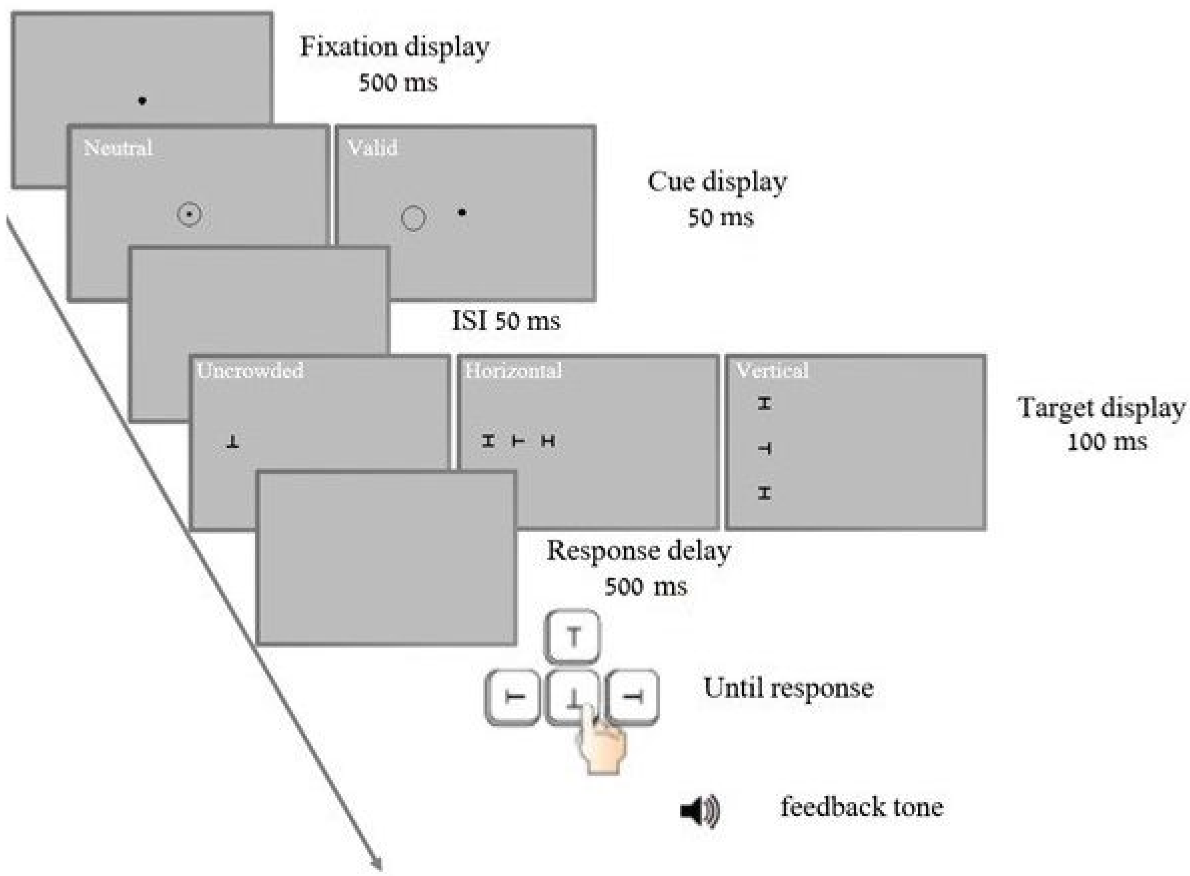

Figure 1

Illustration of the sequence of events within a trial. After a fixation point is displayed, a valid or neutral cue appears briefly before the stimuli. The participant is asked to maintain eye fixation for the entire duration of the trial and report the orientation of the target. An eye tracker was used to monitor eye fixation.

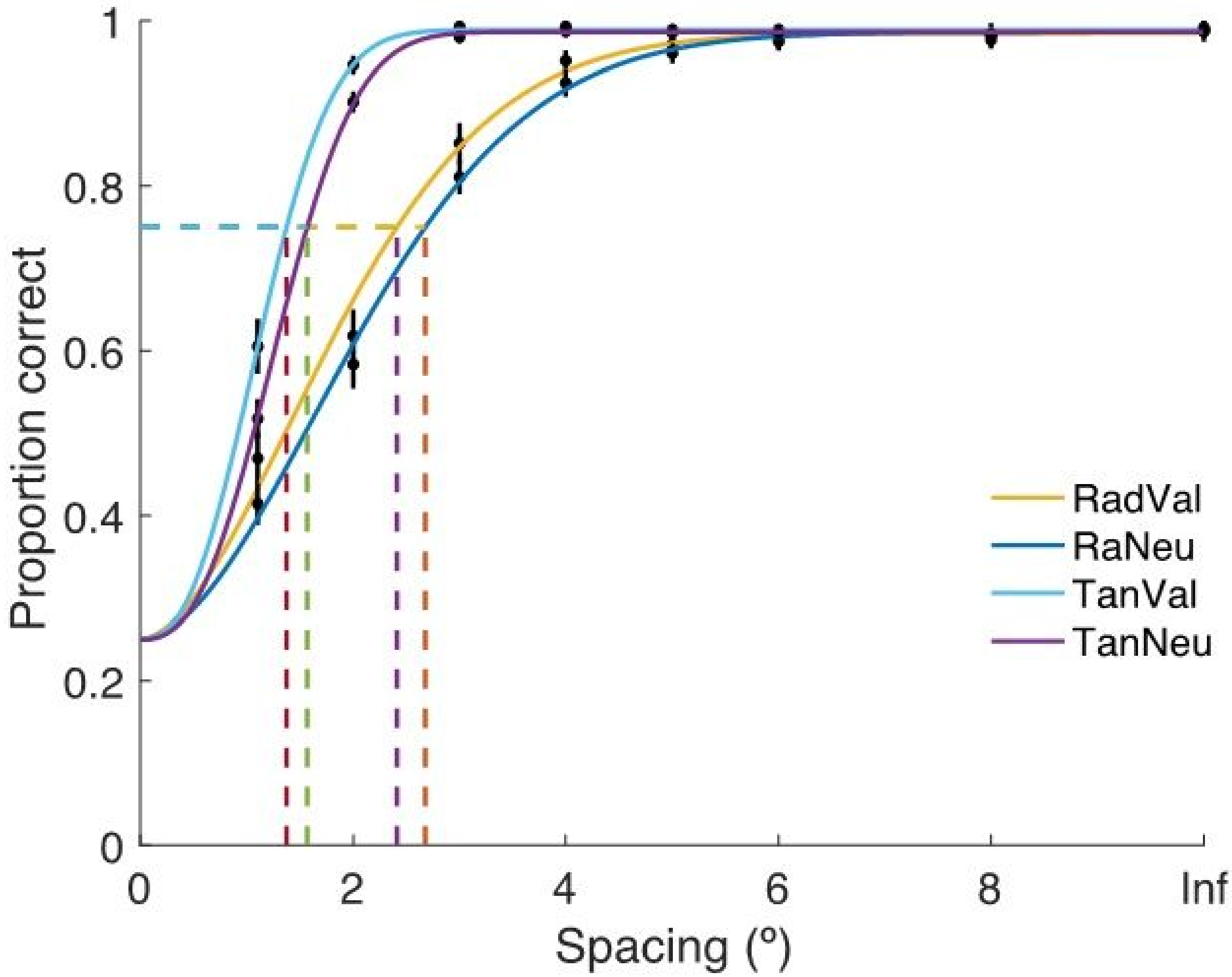

Figure 2

Group average fitted curves, using the Weibull function. This model was used to estimate each condition’s critical spacing. Dotted vertical lines indicate the critical spacing for both cued and neutral conditions, and radial and tangential layouts. Inf: infinite spacing represents uncrowded display trials. Error bars = ±1 within subject standard error.

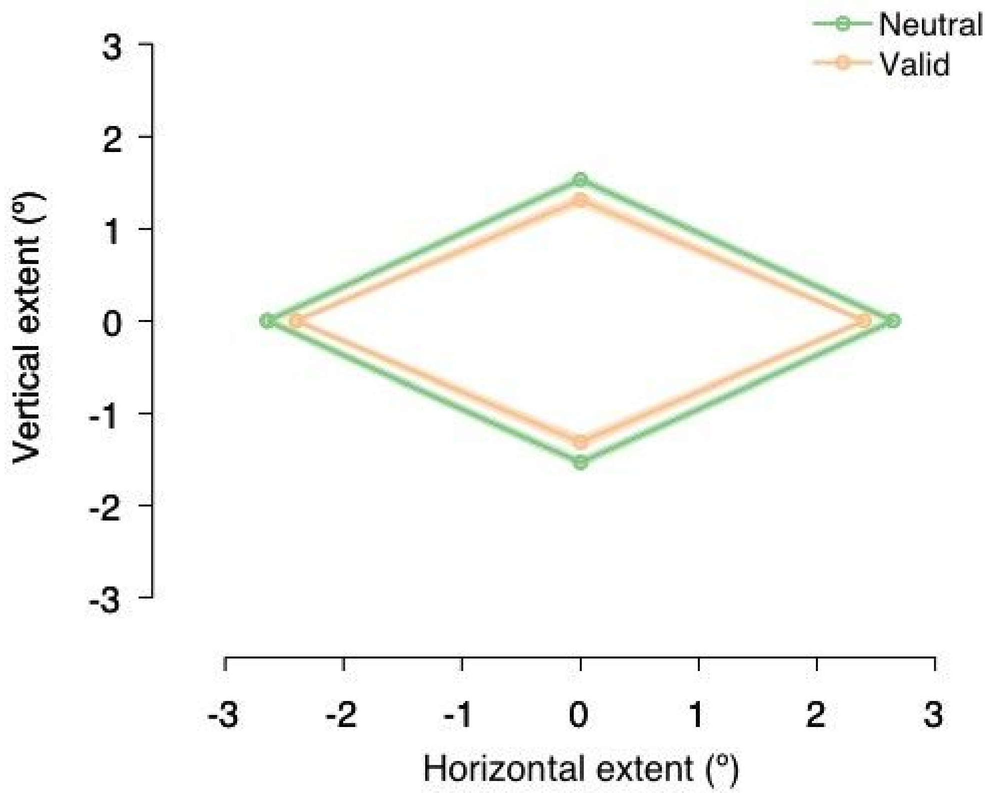

Figure 3

Crowding window. Mean critical spacing values in degrees (°) as a function of cue condition and flanker arrangement. Shaded area = ±1 within subject standard error.