Spatial attention alleviates temporal crowding, but neither temporal nor spatial uncertainty are necessary for the emergence of temporal crowding

Shira Tkacz-Domb Department of Psychology, University of Haifa, Haifa, Israel

Yaffa Yeshurun Department of Psychology, University of Haifa, Haifa, Israel

Recently, we demonstrated temporal crowding with normal observers: Target identification was impaired when it was surrounded by other stimuli in time, even when the interstimuli intervals (ISIs) were relatively long. Here, we examined whether temporal and spatial uncertainties play a critical role in the emergence of temporal crowding. We presented a sequence of three letters to the same peripheral location, right or left of fixation, separated by varying ISI (106–459 ms). One of these letters was the target, and the observers indicated its orientation. To eliminate temporal uncertainty, the position of the target within the sequence was fixed for an entire block (Experiment 1). To eliminate spatial uncertainty, we employed spatial attentional precues that indicated the letters' location. The precue was either auditory (Experiment 2) or visual (Experiment 3). We found temporal crowding to result in worse performance with shorter ISIs, even when there was no temporal or spatial uncertainty. Unlike the auditory cue, the visual cue affected performance. Specifically, when there was uncertainty regarding the target location (i.e., when the target appeared in the first display), precueing the target location improved overall performance and reduced the ISI effect, although it was not completely eliminated. These results suggest that temporal and spatial uncertainties are not necessary for the emergence of temporal crowding and that spatial attention can reduce temporal crowding.

Introduction

When a peripheral target is surrounded by other elements (i.e., flankers), the ability to identify the target is impaired. However, this target can be identified easily when it appears in isolation. This phenomenon is known as *spatial crowding*, and it has been studied extensively (see Whitney & Levi, 2011, for a review). There are many factors that influence the degree of spatial crowding. For instance, spatial crowding decreases as the distance between the target and flankers increases (e.g., Bouma, 1970; Pelli, Palomares, & Majaj, 2004), and the minimum distance between the target and flankers at which the flankers no longer affect performance scales with target eccentricity (e.g., Bouma, 1970; Toet & Levi, 1992; Yeshurun & Rashal, 2010). More recently, crowding was also demonstrated in the time domain (Bonneh, Sagi, & Polat, 2007; Yeshurun, Rashal, & Tkacz-Domb, 2015). Specifically, when a peripheral target is surrounded in time by other stimuli (i.e., stimuli that appear before and after the target at the same spatial location), the ability to identify the target is lower than when it appears in isolation, and performance deteriorates as the stimulus-onset-asynchrony (SOA) between the target and the nontarget stimuli decreases. Hence, *spatial crowding* typically refers to cases in which the flankers appear at the same time as the target but in different spatial locations, whereas *temporal crowding* refers to cases in which the nontarget stimuli appear at the same spatial location but at different points of time.

A previous study that examined temporal crowding compared amblyopic with normal vision observers using foveal presentation (Bonneh et al., 2007). In this study, temporal crowding was measured by presenting a rapid sequence of digits to the center of the screen, and the task was to identify the smaller digit that appeared amidst the other digits in the sequence. The speed of the sequence could be either fast in the crowded condition (200 ms SOA) or slow in the uncrowded condition (400 ms SOA). Critically, the SOA in the crowded condition was longer than the 100–150 ms limit of classical masking (e.g., Breitmeyer, 1984; Breitmeyer & Ogmen,

Citation: Tkacz-Domb, S., & Yeshurun, Y. (2017). Spatial attention alleviates temporal crowding, but neither temporal nor spatial uncertainty are necessary for the emergence of temporal crowding. *Journal of Vision*, *17*(3):9, 1–12, doi:10.1167/17.3.9.

doi: 10.1167/17.3.9 Received July 15, 2016; published March 10, 2017 ISSN 1534-7362

2000; Enns, 2004; Enns & Di Lollo, 2000; Gorea, 1987; Michaels & Turvey, 1979). The authors found performance impairment in the crowded condition in comparison with the uncrowded condition with strabismic amblyopes but not with observers with normal vision.

In a recent study, we investigated whether temporal crowding can be found for observers with normal vision when the stimuli are presented at the periphery of the visual field (Yeshurun et al., 2015). In this study, a sequence of three letter displays was presented. In each letter display, a single letter appeared to the right or left of a fixation cross, at an eccentricity of 9°. The displays were separated by a varying interstimulus interval (ISI) ranging from 100 to 400 ms. The target was the letter T, and it could appear in the first or second display of the sequence. The target could have one of four possible orientations, and the task was to identify the target's orientation. In one of the experiments, the duration of the letter displays was 30 ms for all participants (i.e., the ISIs corresponded to SOAs ranging from 130 to 430 ms). This experiment included a baseline condition with uncrowded trials in which only the target appeared, without preceding or succeeding letters. In the other two experiments, the duration of the letter displays was adjusted individually for each participant to avoid ceiling or floor effects (duration range: 10–80 ms). We found a significant effect of ISI in all the experiments of that study, and this effect persisted up to about 300 ms. Importantly, the ISI effect was significant even when we included in the analysis only trials in which the SOA was larger than 150 ms for all observers (i.e., trials with SOA beyond the classical limits of masking). Moreover, a comparison between the baseline condition (i.e., uncrowded trails) and the condition in which a sequence of three letters was presented (i.e., crowded trails) revealed considerably worse performance in the crowded than uncrowded trails, for all SOAs shorter than 330 ms. Hence, we demonstrated temporal crowding for observers with normal vision with peripheral presentation.

The inclusion of the uncrowded trials helped us to rule out two sources of uncertainty as possible explanations of these long-lasting effects of temporal crowding. First, the fact that the target could appear either in the first or second display generated temporal uncertainty—uncertainty regarding the point in time at which the target will appear. Second, the fact that the letters could appear either to the left or to the right of fixation generated spatial uncertainty—uncertainty regarding the location of the letters sequence. However, in the experiment that included a baseline condition, these uncertainties were present in both crowded and uncrowded trials. The fact that performance was significantly worse in the crowded than uncrowded trials suggests that the long-lasting effects of ISIs found in that study are not merely due to these two types of uncertainty, because these uncertainties were also present in the uncrowded trials.

The goal of the current study was to further investigate the role of these uncertainties in the emergence of temporal crowding. Particularly, we examined whether the elimination of either temporal or spatial uncertainty will alleviate temporal crowding. Experiment 1 tested whether "relative" temporal uncertainty (i.e., uncertainty regarding the position of the target within the three letters sequence) plays a critical role in the emergence of temporal crowding. Experiments 2 and 3 tested whether the elimination of spatial uncertainty via the employment of spatial attentional cues can alleviate temporal crowding.

Experiment 1

In Experiment 1, we investigated whether temporal crowding will emerge when there is no temporal uncertainty regarding the position of the target within the sequence of letters. To that end, we conducted a similar experiment to the one detailed above (Yeshurun et al., 2015): A sequence of three rotated letters separated by a varying ISI (106–400 ms) was presented to the right or left of fixation at an eccentricity of 9°. One of the letters was a T, and the task was to indicate its orientation. The duration of the letters display was adjusted individually to avoid ceiling or floor effects (durations range = 24–71 ms, mode = 35 ms). For 11% of the trials (baseline trials), only the target was presented. Critically, unlike our previous study, the temporal position of the target within the sequence (termed *temporal order*) was fixed for an entire block. Thus, in this experiment, there was no temporal uncertainty. If temporal uncertainty does not play a critical role in the emergence of temporal crowding, it should be found here too. Specifically, performance should be worse when there are three consecutive letters than when there is only a single letter, and performance should deteriorate as the ISI between the letters decreases.

Methods

Observers

Twenty-three observers participated in Experiment 1. Observers were students from the University of Haifa, with normal or corrected-to-normal vision, and all were naive to the purpose of the study. This study adhered to the Declaration of Helsinki.

Stimuli and apparatus

Stimuli were presented on a 19-in. monitor of an IBM-compatible PC (1,024 × 768 resolution at refresh

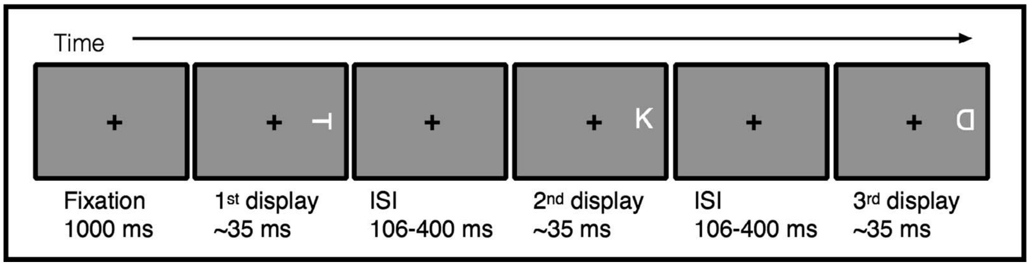

Figure 1. A schematic example of the sequence of events in a single trial of Experiment 1. In the baseline trials, only the target was presented. Note that the duration of the letter displays was adjusted individually for each participant. In the example depicted here, the target appears in the first display and the sequence of letters appears to the right of fixation.

rate of 85 Hz) using MATLAB and the Psychophysics Toolbox extensions (Brainard, 1997). Eye movements were monitored with an EyeLink 1000 eye tracker (temporal resolution of 1000 Hz; SR Research, Ottawa, ON, Canada). The stimuli were three light gray (20.5 cd/m^2) capital letters ($1° \times 1°$, Arial font), and the background was a uniform darker gray (18 cd/m^2). The letters appeared to the right or left of a black fixation cross ($0.3° \times 0.3°$) at an eccentricity of 9°. The target was the letter T, and the other two letters were chosen randomly from all the capital letters in the English language, except for I, J, L, Q, O, X, and W. Each letter could be oriented upright, inverted, 90° to the left, or 90° to the right (Figure 1).

Procedure

Each trial started with a fixation cross positioned at the center of the screen. The fixation cross was present throughout the trial. After 1000 ms, the sequence of letters appeared to the right or left of the fixation cross, with equal probability. All the letters were presented for the same duration, and this duration was adjusted individually for each observer to avoid ceiling or floor effects (durations range from 24 to 71 ms; the most frequent duration was 35 ms). The ISI between the letters was randomly chosen in each trial from the following possible values: 106, 129, 153, 177, 200, 235, 259, 306, 353, and 400 ms. The temporal order of the target was constant within each block. In one block, the target always appeared in the first display of the sequence, and in another block, the target always appeared in the second display. In addition, there was a baseline block (11% of total trials) in which only the target was presented at what would have been the first display in the sequence (i.e., 1000 ms after fixation onset). The order of blocks was counterbalanced between observers. The task was to indicate the orientation of the target, and after the response, an auditory feedback was given. Each observer participated in 80 practice trials and 720 experimental trials.

Results and discussion

One observer was omitted from the analysis because of excessive eye movements (i.e., fixation was broken on more than 20% of the trials). Hence, 22 observers were included in the analysis. The analysis was conducted only on trials in which fixation was not broken (average percentage of trials excluded was 3.97%).

A repeated-measures two-way analysis of variance (ANOVA; ISI[1] × target temporal order) was conducted on the accuracy data. This analysis did not include the baseline trials. A significant main effect was found for the ISI factor, $F(9, 189) = 9.26$, $p < 0.0001$, $\eta_p^2 = 0.31$; accuracy increased as the ISI increased. Importantly, the effect of ISI was still significant, $F(8, 168) = 6.01$, $p < 0.0001$, $\eta_p^2 = 0.22$, even when we removed from the analysis the shortest ISI (106 ms), whose corresponding SOA could have been shorter than 150 ms (depending on the specific stimulus duration) and therefore may still reflect classical masking. Thus, as in our previous study (Yeshurun et al., 2015), a long-lasting effect of ISI was found.

The main effect of target temporal order was not significant. However, the interaction between ISI and target temporal order was significant, $F(9, 189) = 2.21$, $p < 0.03$, $\eta_p^2 = 0.1$. As can be seen in Figure 2, with short ISIs, performance was better when the target appeared in the second display, whereas with long ISIs, performance was better when the target appeared in the first display. This pattern of results was also found in three experiments of our previous study (Yeshurun et al., 2015). As we suggested previously, this interaction implies that different processes mediate the effect of ISI with short and long ISIs, but a more direct test of this hypothesis is required.

To compare performance in the crowded trials, in which a sequence of three letters appeared, with that in the uncrowded trials in which only the target appeared (i.e., baseline trials), we conducted a repeated-measures one-way ANOVA (ISI) on the accuracy data. The baseline trials were included as one of the ISI values (i.e., the variable ISI included 11

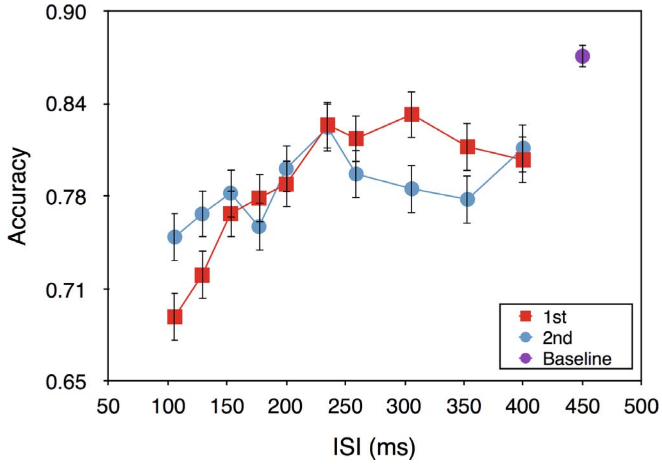

Figure 2. Accuracy as a function of ISI, and target temporal order (first display vs. second display). Error bars correspond to one standard error. For comparison, baseline trials (BL), which included only a single letter, are also presented.

values: 10 ISIs + baseline). The ISI effect was significant, $F(10, 210) = 17.44$, $p < 0.0001$, $\eta_p^2 = 0.45$ (Figure 2). Strikingly, post hoc analysis with Bonferroni correction showed that with all ISIs, the accuracy was significantly worse in the three letters condition than in the baseline condition ($p < 0.03$, for all comparisons). These findings show that temporal crowding emerges even when there is no temporal uncertainty. Note that in our previous study, we also found a significant difference between the crowded and baseline condition; however, in that study, this difference was significant only for ISIs that were shorter than 300 ms (Yeshurun et al., 2015).

To sum up, in our previous study (Yeshurun et al., 2015), we found consistent evidence for temporal crowding with observers with normal vision at the periphery of the visual field. However, in that study, the temporal order of the target within the sequence of letters (i.e., first or second display) varied randomly between trials, introducing temporal uncertainty. In this experiment, the temporal order of the target was fixed for an entire block, ensuring that there was no temporal uncertainty. Nevertheless, observers with normal vision exhibited temporal crowding at the periphery of the visual field. Hence, temporal uncertainty is not critical for the emergence of temporal crowding.

Experiment 2

In this experiment, we tested the role of spatial uncertainty in the emergence of temporal crowding. Here, we were motivated by the finding that spatial attention relieves spatial crowding (Yeshurun & Rashal, 2010). Spatial attention improves overall performance with spatially crowded displays and reduces the critical distance (i.e., the minimal distance between target and flankers that eliminates spatial crowding). To test whether we can find similar attentional effects with temporal crowding, we performed two experiments in which we used different types of attentional cues. In this experiment, we employed an auditory spatial cue. We have chosen an auditory cue because we were worried that a visual cue that precedes the onset of the sequence of letters may cause additional temporal crowding, and it was already shown that attracting attention to the location of a visual target by an auditory precue could result in the typical costs and benefits of cueing effects (e.g., Koelewijn, Brinkhorst, & Theeuwes, 2009).

The basic design of Experiment 2 was similar to Experiment 1 but with the addition of a cueing manipulation. The cue was a brief auditory white noise that was presented prior to the onset of the first letter display, and it could be valid or neutral. In the valid condition, the cue indicated the side on which the sequence of letters will appear. In the neutral condition, the cue did not indicate a side. Unlike Experiment 1, in this experiment, the temporal order of the target varied between trials, and the target could also appear in the third display of the letters' sequence. The range of ISIs was 129 to 459 ms, and the letter displays' duration was adjusted individually to avoid ceiling or floor effects (durations range = 35–71 ms, mode = 35 ms). Observers were asked to identify the orientation of the target.

If the cue was successful in attracting attention, overall performance should be better in the valid than neutral condition, especially when the target appeared in the first display. This is because there was uncertainty regarding the letters' location only with the first letter in the sequence. With the other two letters, there was no spatial uncertainty because they always appeared at the same location as the first letter. In addition, if attention reduces temporal crowding, a significant interaction between the factors of ISI and cue condition should emerge: The ISI effect should be smaller in the valid than neutral condition. More specifically, because the attentional cue is helpful only with the first letter display, if attention can affect temporal crowding, there should be an interaction between ISI, cue condition, and target temporal order, with which the valid cue should reduce the ISI effect when the target appears in the first display.

Methods

Observers

Twenty-eight observers participated in this experiment, 11 of whom also participated in Experiment 1.

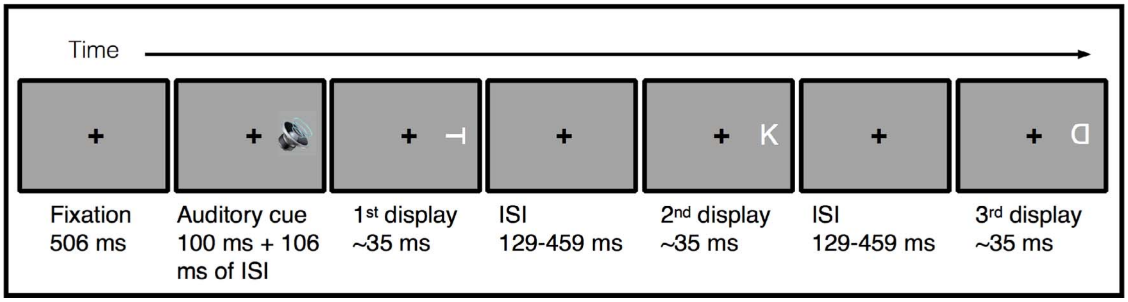

Figure 3. A schematic example of the sequence of events in a single trial of Experiment 2. Note that the duration of the letter displays was adjusted individually for each participant. In the example depicted here, the cue is valid, the target appears in the first display, and the sequence of letters appears to the right of fixation.

All observers were students from the University of Haifa, with normal or corrected-to-normal vision and normal hearing. All were naive to the purpose of the study.

Stimuli, apparatus, and procedure

The stimuli, apparatus, and procedure were identical to Experiment 1, except for the following: In this experiment, the presentation of the sequence of letters was preceded by an auditory cue, a brief (100 ms) white noise presented via headphones (Figure 3). In the valid condition, the cue was presented to the left or right ear, and it was always valid with respect to the side on which the letters were about to appear. That is, if the sequence of letters was about to appear on the right side, the cue was presented to the right ear and vice versa. In the neutral condition, the cue was presented to both ears simultaneously, and therefore, it did not indicate a side. The auditory cue was presented 506 ms after fixation onset, and following additional 106 ms of the fixation display, the sequence of letters appeared. The target could appear in one of the three letter displays, and the ISI between the displays was randomly chosen on each trial from the following possible ISIs: 129, 153, 200, 259, 306, and 459 ms. As in Experiment 1, the letter displays' duration was adjusted individually for each observer (durations range = 35–71 ms, mode = 35 ms). The values of the various variables—target temporal order within the sequence (first display, second display, or third display), target orientation (0°, 90°, 180°, or 270°), letters' location relative to fixation (right or left), ISI, and cue condition (valid or neutral)—were chosen randomly but occurred equally often throughout the experimental session. Each observer participated in 48 practice trials, in which she confirmed that she could hear the sound and could discriminate correctly whether the sound was presented to the right, left, or both ears. The practice trials were followed by 864 experimental trials.

Results and discussion

Two observers were excluded from the analysis because of excessive eye movements (i.e., they broke fixation on more than 20% of the trials). Hence, the analysis was conducted on 26 observers. Only trials in which fixation was not broken were included in the analyses (average percentage of trials excluded = 5.27%).

A repeated-measures three-way ANOVA (ISI × cue condition × target temporal order) was conducted on the accuracy data. As in Experiment 1, there was a significant main effect of ISI, $F(5, 125) = 3.7$, $p < 0.004$, $\eta_p^2 = 0.13$; accuracy increased as the ISI increased. Note that because in this experiment the shortest stimulus duration was 35 ms, all the ISIs employed here result in SOAs that are larger than 150 ms, that is, larger than the established limit of classical masking.

The main effect of target temporal order was also significant, $F(2,50) = 16.65$, $p < 0.0001$, $\eta_p^2 = 0.4$, showing decreased accuracy as the target temporal order increased. Bonferroni post-hoc analysis indicated that accuracy was significantly lower ($p < 0.03$) when the target appeared in the third display than in either of the other two displays (first 0.82, $SD = 0.38$; second 0.79, $SD = 0.41$; third 0.74, $SD = 0.44$). Additionally, accuracy was significantly higher ($p < 0.02$) when the target appeared in the first than second display. The interaction between target temporal order and ISI was significant, $F(10,250) = 5.52$, $p < 0.0001$, $\eta_p^2 = 0.18$. The increased accuracy with increasing ISI was found only when the target appeared in the first or second display (Figure 4). When the target appeared in the third display, accuracy decreased with increasing ISI. This reduction in accuracy does not seem to be a robust finding. Such a decrease in performance with ISI was not found in our previous study of temporal crowding (Yeshurun et al., 2015), nor was it found in Experiment 3 of this study.

Finally, none of the effects regarding the attentional cue reached significance (Figure 5). Such a lack of cueing effects could indicate that spatial attention may

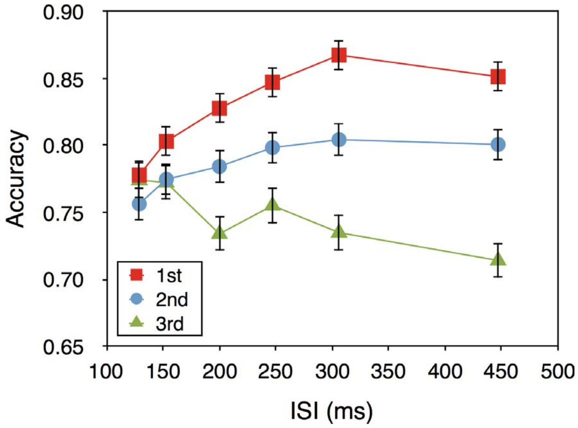

Figure 4. Accuracy as a function of ISI and target temporal order (first display, second display, or third display) in Experiment 2. Error bars correspond to one standard error.

not be able to alleviate temporal crowding, as it does with spatial crowding. However, this lack of effect might also be due to the fact that the auditory cue indicated only the side on which the letters will appear but not their specific location. This possibility is examined in Experiment 3.

Experiment 3

In this experiment, we examined whether an effect of spatial attention will emerge when the attentional cue will indicate a specific location rather than just a side. To that end, we used here a visual cue—a green dot—presented prior to the onset of the first letter display. This cue was the same as in the study of Yeshurun and Rashal (2010), in which the effect of spatial attention on spatial crowding was demonstrated. In the valid condition, the dot was presented next to the location of the upcoming letters, indicating the exact location in which the letters will appear. In the neutral condition, the dot did not indicate a location as it was presented at the center of the screen. If the lack of attentional effect in Experiment 2 reflected an inability of spatial attention to affect temporal crowding, there should also be no effect of attention in this experiment. In contrast, if the lack of effect was due to the specific attentional cue employed there, then an attentional effect should emerge here. Specifically, overall performance should be better in the valid than neutral condition, especially when the target appears in the first display. Furthermore, if attention reduces temporal crowding, a significant interaction between ISI, cue condition, and target temporal order should emerge, such that the ISI effect should be smaller in the valid than neutral condition, especially when the target appears in the first display.

Methods

Observers

Twenty-six observers participated in Experiment 3, nine of whom also participated in one or more of the other experiments (one in Experiment 1, two in Experiment 2, and six in Experiments 1 and 2). All observers were students from the University of Haifa, with normal or corrected-to-normal vision, and all were naive to the purpose of the study.

Stimuli, apparatus, and procedure

The stimuli, apparatus, and procedure were identical to Experiment 2, except for the following: In the valid condition, a green dot with a diameter of 0.35° was presented next to the location of the upcoming letters, at 8° of eccentricity (Figure 6). In the neutral condition, a green dot with a diameter of 0.55° was presented at the center of the screen. The ISI between the letter

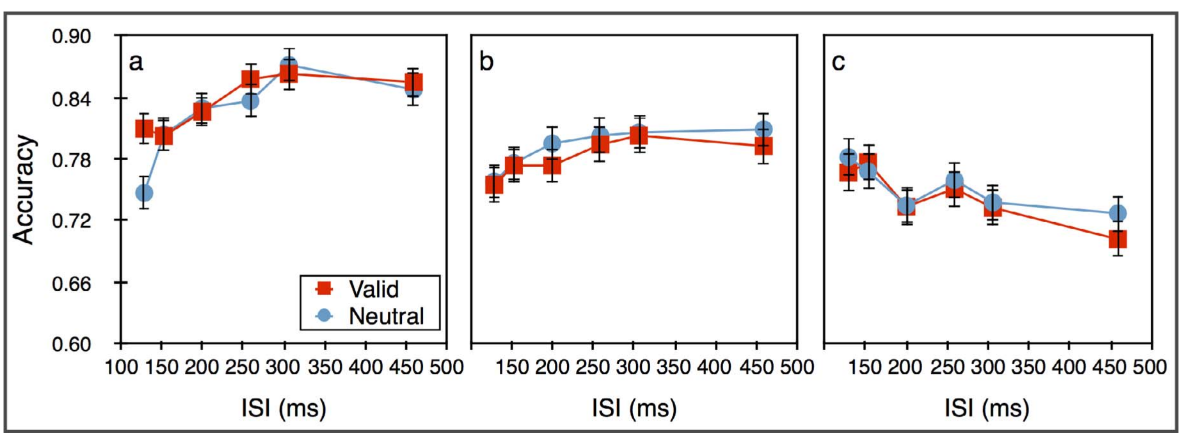

Figure 5. Accuracy in Experiment 2 as a function of ISI, cue condition, and target temporal order: (a) first display, (b) second display, (c) third display. Error bars correspond to one standard error.

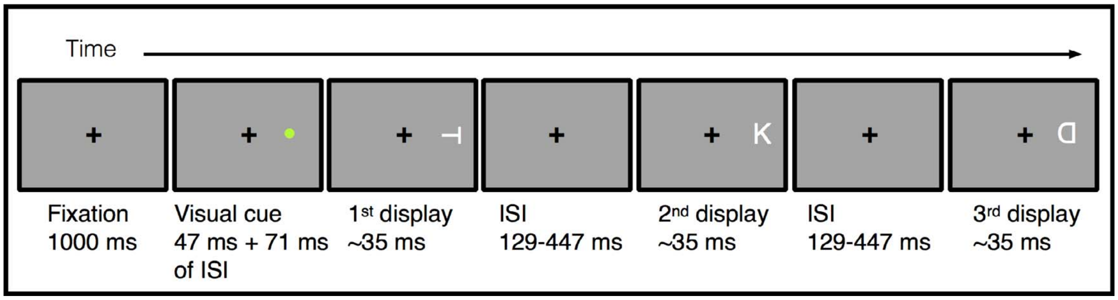

Figure 6. A schematic example of the sequence of events in a single trial of Experiment 3. Note that the duration of the letter displays was adjusted individually for each participant. In the example depicted here, the cue is valid, the target appears in the first display, and the sequence of letters appears to the right of fixation.

displays was randomly chosen in each trial from the following possible values: 129, 153, 200, 247, 306, and 447 ms. The visual cue appeared 1000 ms after fixation onset and was presented for 47 ms. Following an additional 71 ms of the fixation display, the sequence of letters was presented. The duration of the letter displays was adjusted individually for each observer (durations range = 35–71 ms, mode = 35 ms).

Results and discussion

One observer was excluded from the analysis because of excessive eye movements (i.e., the fixation was broken on more than 20% of the trials). Hence, the analysis was conducted on 25 observers. Only trials in which fixation was not broken were included in the analyses (average percentage of trials excluded = 5.44%).

A repeated-measures three-way ANOVA (ISI × cue condition × target temporal order) was conducted on the accuracy data. Like before, a significant main effect of ISI was found, $F(5, 120) = 9.42$, $p < 0.0001$, $\eta_p^2 = 0.28$, reflecting the same pattern of results: increased accuracy with increasing ISI. As in Experiment 2, in this experiment, the shortest stimulus duration was 35 ms, and therefore, all of the ISIs employed here result in SOAs that are larger than the established limit of classical masking (i.e., larger than 150 ms). Thus, like before, we found evidence of temporal crowding.

The main effect of target temporal order was also significant, $F(2, 48) = 5.15$, $p < 0.01$, $\eta_p^2 = 0.18$. Similar to Experiment 2, accuracy was lower when the target appeared in the third display than in either of the other two displays (first = 0.78, $SD = 0.41$; second = 0.78, $SD = 0.41$; third = 0.74, $SD = 0.44$). Bonferroni post hoc analysis indicated that this accuracy decrement was significant in comparison to the first display ($p < 0.02$) and marginally significant ($p = 0.052$) in comparison with the second display. Also similar to Experiment 2, the interaction between target temporal order and ISI was significant, $F(10, 240) = 6.72$, $p < 0.0001$, $\eta_p^2 = 0.22$, showing increased accuracy with increasing ISI only when the target appeared in the first or second display (Figure 7).

Most important for the goal of this experiment were the effects of the cueing manipulation. Unlike Experiment 2, the employment of a visual cue led to the emergence of a significant cue condition × target temporal order interaction, $F(2, 48) = 5.34$, $p < 0.009$, $\eta_p^2 = 0.18$. As expected, the valid cue improved overall accuracy in comparison to the neutral cue, but only when the target appeared in the first display. Critically, the three-way interaction of ISI × cue condition × target temporal order was also significant, $F(10, 240) = 3.66$, $p < 0.0002$, $\eta_p^2 = 0.13$ (Figure 8). To further explore this interaction, we performed an additional repeated-measures two-way ANOVA (cue condition × ISI) on each of the three possible target temporal orders. The analysis of the trials in which the target appeared in the first display (Figure 8a) revealed significant main effects of cue condition and ISI, both in the expected direction: Accuracy was higher in the valid than in the neutral condition, and it increased as the ISI increased: cue condition, $F(1, 24) = 6.71$, $p < 0.02$, $\eta_p^2 = 0.22$; ISI, $F(5, 120) = 21.51$, $p < 0.0001$, $\eta_p^2 =$

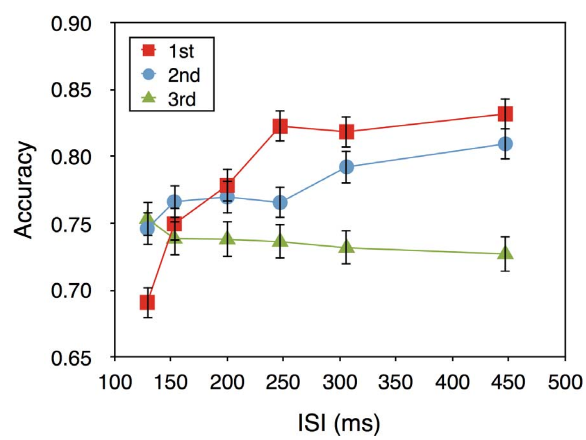

Figure 7. Accuracy as a function of ISI and target temporal order (first display, second display, or third display) in Experiment 3. Error bars correspond to one standard error.

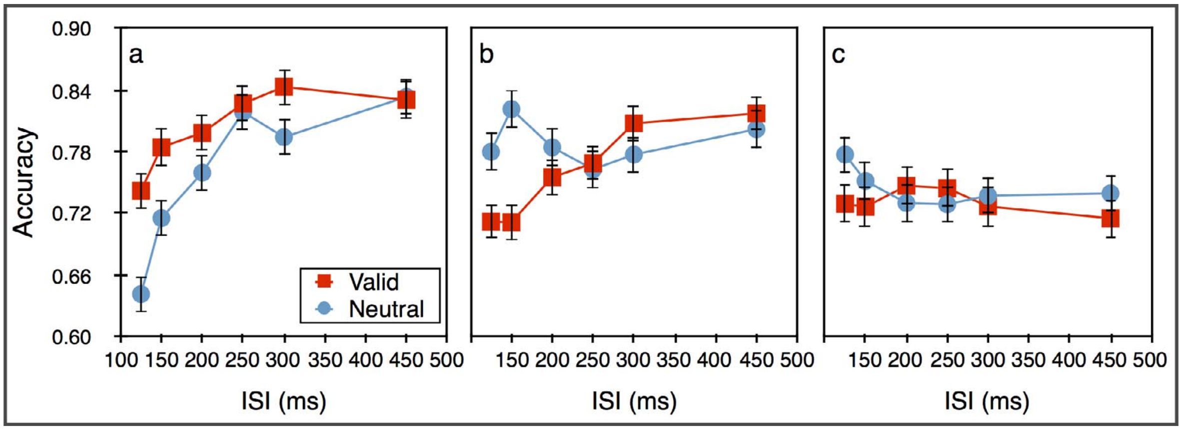

Figure 8. Accuracy in Experiment 3 as a function of ISI, cue condition, and target temporal order: (a) first display, (b) second display, (c) third display. Error bars correspond to one standard error.

0.47. Importantly, the cue condition × ISI interaction was also significant, revealing a smaller ISI effect in the valid than in neutral condition, $F(15, 120) = 2.54$, $p < 0.04$, $\eta_p^2 = 0.10$. However, although the effect of ISI was smaller when only the valid trials were included in the analysis, it was still significant: valid ISI effect, $F(5, 120) = 6.08$, $p < 0.0001$, $\eta_p^2 = 0.20$; neutral ISI effect, $F(5, 120) = 15.70$, $p < 0.0001$, $\eta_p^2 = 0.40$. Thus, spatial attention can alleviate temporal crowding when it is allocated in advance to the specific location of the upcoming target, but it cannot completely eliminate it.

Interestingly, when the target appeared in the second display, both main effects and the interaction were also significant; however, this time, we actually found a reversed cueing effect: cue condition, $F(1, 24) = 6.13$, $p < 0.03$, $\eta_p^2 = 0.20$; ISI, $F(5, 120) = 3.05$, $p < 0.02$, $\eta_p^2 = 0.11$; cue × ISI interaction, $F(5, 120) = 4.46$, $p < 0.001$, $\eta_p^2 = 0.16$. As can be seen in Figure 8b, with short ISIs, performance was worse in the valid than in the neutral condition. This reversed effect might be due to the fact that the cue attracted attention to the first letter in the sequence, and because with this temporal order the first letter was not the target, performance was impaired. Finally, when the target appeared in the third display, none of the effects were significant (Figure 8c).

General discussion

In this study, we examined how eliminating temporal and spatial uncertainty will affect temporal crowding. In Experiment 1, we tested whether temporal crowding can occur even when there is no uncertainty regarding the point of time at which the target appears. In Experiments 2 and 3, we investigated whether the elimination of spatial uncertainty via the employment of spatial attentional cues will affect temporal crowding. In all three experiments, we found significant long-lasting effects of ISI that we term *temporal crowding*. Considering that such ISI effects were also found in the five experiments of the study by Yeshurun et al. (2015), it seems that temporal crowding is a robust phenomenon. Moreover, Experiment 1 of the current study demonstrated temporal crowding, even when there was no temporal uncertainty, suggesting that temporal uncertainty is not vital for the emergence of temporal crowding. This finding, however, does not mean that temporal uncertainty plays no role in temporal crowding, as in this experiment we did not compare directly the magnitude of temporal crowding with and without temporal uncertainty. A more comprehensive understanding of the role of temporal uncertainty awaits future research.

As mentioned above, previous studies suggest that both forward and backward masking are over by an SOA of 100–150 ms (e.g., Breitmeyer, 1984; Breitmeyer & Ogmen, 2000, 2006; Enns & Di Lollo, 2000; Gorea, 1987; Michaels & Turvey, 1979; Scheerer, 1973). Unlike these classical types of masking, *temporal crowding* refers to performance impairment with longer SOAs that go beyond this limit of classical masking. For instance, in Experiment 1, target identification was considerably worse when it was preceded or succeeded by nontarget stimuli than when it appeared alone, even with the longest ISI of 400 ms. Still, we cannot tell whether or not the same processes that mediated classical masking also operate with temporal crowding. That is, the experiments of the current study and those of Yeshurun et al. (2015) demonstrated that the detrimental effect of preceding and succeeding stimuli last for a considerably longer duration than what was thought before, but they do not provide unequivocal evidence that temporal crowding and classical masking are different phenomena. However, we do have some initial evidence to support the latter. In Experiment 1, as well as in Yeshurun et al. (2015), qualitative differences were found between short ISIs that fall within the traditionally defined limits of backward and forward masking and longer ISIs. Specifically, we found that with short ISIs, performance was better when the target appeared in the second than the first display, but this was reversed with long ISIs. This pattern of results suggests that different processes may underlie performance decrement with short and long ISIs, but more direct testing is required before we can establish with confidence that classical masking and temporal crowding are different phenomena.

To examine the effects of spatial attention on temporal crowding, we added a cueing manipulation to the basic experimental design of Experiment 1. In Experiment 2, we used an auditory cue, and in Experiment 3, we used a visual cue. Both attentional cues reduced spatial uncertainty as they indicated with 100% validity either the side or the exact location at which the letters are about to appear. Although with both experiments there was a significant effect of ISI, providing once more evidence of temporal crowding, only with the visual cue did we find significant effects of cueing condition. In line with our predictions, when the target appeared in the first display, overall performance was significantly higher in the valid than in the neutral cueing condition. As detailed above, because the three letters in the sequence were presented to the same location, there was uncertainty about the sequence location only with regard to the first letter; hence, we expected to find cueing effects only with respect to the first letter. Most important, when the target appeared in the first display, temporal crowding was significantly smaller with the valid cue. Hence, directing spatial attention via a visual cue can reduce temporal crowding, although it does not completely eliminate it. The fact that temporal crowding remains even when attention is focused on the target suggests that temporal crowding cannot be entirely explained by spatial attention. That is, temporal crowding does not seem to be caused by lack of attention. This attentional alleviation of temporal crowding is similar to the attentional alleviation of spatial crowding that was previously found in our lab (Rashal & Yeshurun, 2014; Yeshurun & Rashal, 2010). In these studies, we have used very similar visual attentional cues and found attentional improvement of overall accuracy as well as attentional decrement of the flanker-target distance at which the flankers no longer affect performance (i.e., reduction of the size of the critical distance). As with temporal crowding, spatial crowding was not completely eliminated by the allocation of attention to the target. It was suggested in these studies that attention alleviates spatial crowding by reducing the region over which information is integrated. This hypothesis is supported by the finding that the attentional decrement of the critical distance does not interact with the decrement in critical distance brought about by increasing the target contrast, because this finding rules out an alternative account suggesting that the attentional effect on spatial crowding reflects contrast enhancement (Rashal & Yeshurun, 2014). Currently, we cannot determine whether the similar pattern of attentional effects found with spatial and temporal crowding reflects similar attentional processes in time and space. In other words, it seems premature to conclude that similar to its effect in space, attention alleviates temporal crowding by narrowing the temporal window over which information is integrated.

In fact, unlike spatial crowding, in which excessive spatial integration is often flagged as the process underlying crowding (e.g., Balas, Nakano, & Rosenholtz, 2009; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli et al., 2004; van den Berg, Roerdink, & Cornelissen, 2010), we do not find excessive temporal integration as a likely "candidate" to which temporal crowding could be attributed. This is because, at least in the context of sequential presentation of stimuli to the same location, temporal integration is viewed as merging or combining the signals of two events into a single unit at early levels of visual processing. Accordingly, it was suggested in several studies that such temporal integration occurs mainly with short ISIs—up to an SOA of about 100 ms (e.g., Bachmann & Allik, 1976; Di Lollo, Enns, & Rensink, 2000; Enns & Di Lollo, 2000; Scheerer, 1973). Given that in our current Experiment 1, performance with three consecutive letters was worse than with a single letter, even with the longest ISI of 400 ms (i.e., four times longer than the previously stated limit of integration), it does not seem likely that this performance decrement is mediated by temporal integration. Interruption or substitution (e.g., Bachmann & Allik, 1976; Di Lollo et al., 2000; Enns & Di Lollo, 2000; Scheerer, 1973) seem to be more feasible accounts of temporal crowding. That is, rather than low-level merging of the target and succeeding or preceding stimuli, temporal crowding more likely reflects disruption of the processing of the target, by subsequent stimuli that appear before the target is fully identified or substitution of the target representation/processing by that of the following stimulus. The finding that there is no ISI effect when the target appeared in the last display is consistent with this account of temporal crowding because it suggests that temporal crowding does not occur when nothing can interrupt the processing of the target. However, this implies that the processing of a peripheral letter is not fully completed even when more than 400 ms passed since the onset of the target. This is considerably longer than what one would expect given the limits of classical masking.

If indeed the long-lasting effects of ISI, found here and in Yeshurun et al. (2015), reflect interruption of target processing by succeeding stimuli, a sensible account of the attentional reduction of temporal crowding would be an attentional speeding up of target processing. That is, if the allocation of attention to the target location shortens the time required for completing the target's processing, then with attention, the chances that the appearance of the subsequent letter will interfere with target identification should be smaller, and the ISI effect should be reduced. This account of the effect of attention is similar to the role assigned to attention in the context of object substitution masking (e.g., Enns, 2004; Enns & Di Lollo, 2000). According to the object substitution theory, focusing attention on the target speeds up iterative processes that are required for a stable representation of the target. This ensures that these iterative processes will be completed before new input activity that is generated by the mask could lead to the initiation of mask-related iterative processing. Thus, although object substitution theory refers to considerably shorter ISI effects and predicts no ISI effects when attention is directed in advance to the target location (a prediction that was not confirmed by our findings), the ideas of the theory seem highly relevant to the phenomenon of temporal crowding and corresponding effects of spatial attention.

The hypothesis that the attentional alleviation of temporal crowding is due to facilitation of processing is also consistent with the study by Shore et al. (2001). That study demonstrated, using the temporal order judgement paradigm, that the attended stimulus is perceived earlier than the unattended stimulus. Clearly, attentional facilitation of processing can account for this finding. It is also consistent with Carrasco and McElree's (2001) study that employed the response-signal speed-accuracy tradeoff procedure with a visual search task and a visual attentional cue that is similar to the one we employed here. This procedure allowed these authors to demonstrate that cueing the target location increased asymptotic performance and sped processing dynamics. These findings suggest that spatial attention increased overall discriminability, but more important for our current findings, it also increased processing speed.

Interestingly, the cueing effect that was found when the target appeared in the first display was reversed when the target appeared in the second display. That is, when the target appeared in the second display and ISIs were relatively short (125 or 150 ms), performance was worse in the valid than neutral condition. We think that this is because the cue attracted attention to the first letter in the sequence. It is well established that the allocation of transient attention to the stimulus location, based on peripheral cues like the one employed here, results in signal enhancement (e.g., Carrasco, Penpeci-Talgar, & Eckstein, 2000; Yeshurun & Carrasco, 1999), in addition to attentional effect on processing speed. However, this signal enhancement is restricted to the attended stimulus. Hence, when the target appeared in the second display, attention was attracted to the first letter, which was not the target, thereby enhancing only the processing of this attended letter on the expense of the second letter in the sequence, which was the target. The fact that this reversed attentional effect was found only with short ISIs supports this explanation because the effects of transient attention decay relatively quickly (e.g., Nakayama & Mackeben, 1989; Posner & Cohen, 1984), and so with longer ISIs, the attentional enhancement of the first letter was no longer a relevant factor.

Finally, no cueing effect was found with the auditory cue, not even when the target appeared in the first display of the sequence. This might be because the auditory cue did not indicate the exact location of the upcoming sequence of letters, only the side on which the sequence will appear. In contrast, the visual cue did indicate a specific location, and indeed, with this cue, there was a significant cueing effect. Although attentional effects with similar auditory cues were found in several previous studies (e.g., Buchtel & Butter, 1988; Koelewijn et al., 2009; Spence & Driver, 1997), it is possible that the reduction of temporal crowding is evident only with attentional cues that provide finer spatial information. Another possible explanation for the absence of cueing effect in our auditory cue experiment is provided by the study of Yang and Yeh (2014). Yang and Yeh found facilitatory effects between the auditory and visual systems only when the sound was presented from the same depth plane as the visual target. In our study, the auditory cue was produced through headphones, and so the depth plane of the cue did not match that of the visual stimuli. This might have prevented an integrated percept of the auditory cue and the cued side of the screen. Following Yang and Yeh, the auditory cue had to be produced through loudspeakers positioned next to the screen in order to provide useful information that could attract attention to the relevant side. Although repeating the experiment with loudspeakers was not necessary given the goal of this study, as a cueing effect emerged with the visual cue, future experiments that wish to employ an auditory cue with visual stimuli may wish to take this into account. Be that as it may, a failure to reveal effects of spatial attention due to the employment of cues that are not optimal triggers of spatial attention was also observed with spatial crowding (e.g., Chung & Legge, 2009; Greenwood, Sayim, & Cavanagh, 2014).

In summary, the current study investigated whether temporal and spatial uncertainties play a vital role in generating temporal crowding. Our results show that normal vision observers exhibit temporal crowding (i.e., long-lasting effects of ISI) even when there is no temporal or spatial uncertainty. However, eliminating

spatial uncertainty via a visual attentional cue did reduce the magnitude of temporal crowding when the target was the first letter in the sequence (i.e., when there was uncertainty regarding the sequence location). This suggests that spatial attention can alleviate both spatial and temporal crowding.

Keywords: temporal crowding, spatial attention, temporal uncertainty, spatial uncertainty, precue

Acknowledgments

This study was supported by the Israel Science Foundation Grant 1081/13 to YY. Part of this research formed the M.A. thesis of ST-D under the supervision of YY.

Commercial relationships: none.
Corresponding author: Shira Tkacz-Domb.
Email: shirtzi@yahoo.com.
Address: Psychology Department and Institute of Information Processing and Decision Making, University of Haifa, Haifa, Israel.

Footnote

[1]We entered into the analysis the variable of ISI rather than SOA, because the SOA was somewhat different for different observers, however, we have already shown in Yeshurun et al., 2015 that similar results are obtained with both ISI and SOA.

References

Bachmann, T., & Allik, J. (1976). Integration and interruption in the masking of form by form. *Perception*, *5*, 79–97.

Balas, B., Nakano, L., & Rosenholtz, R. (2009). A summary-statistic representation in peripheral vision explains visual crowding. *Journal of Vision*, *9*(12):13, 1–18, doi:10.1167/9.12.13. [PubMed] [Article]

Bonneh, Y. S., Sagi, D., & Polat, U. (2007). Spatial and temporal crowding in amblyopia. *Vision Research*, *47*, 1950–1962.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*, 177–178.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436.

Breitmeyer, B. (1984). *Visual masking: An integrative approach*. New York: Oxford University Press.

Breitmeyer, B. G., & Ogmen, H. (2000). Recent models and findings in visual backward masking: A comparison, review, and update. *Perception & Psychophysics*, *62*, 1572–1595.

Breitmeyer, B. G., & Ogmen, H. (2006). *Visual masking: Time slices through conscious and unconscious vision*. New York: Oxford University Press.

Buchtel, H. A., & Butter, C. M. (1988). Spatial attentional shifts: Implications for the role of polysensory mechanisms. *Neuropsychologia*, *26*, 499–509.

Carrasco, M., & McElree, B. (2001). Covert attention accelerates the rate of visual information processing. *Proceedings of the National Academy of Sciences, USA*, *98*, 5363–5367.

Carrasco, M., Penpeci-Talgar, C., & Eckstein, M. (2000). Spatial covert attention increases contrast sensitivity across the CSF: Support for signal enhancement. *Vision Research*, *40*, 1203–1215.

Chung, S. T. L., & Legge, G. E. (2009). Precision of position signals for letters. *Vision Research*, *49*, 1948–1960.

Di Lollo, V., Enns, J. T., & Rensink, R. A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General*, *129*, 481–507.

Enns, J. T. (2004). Object substitution and its relation to other forms of visual masking. *Vision Research*, *44*, 1321–1331.

Enns, J. T., & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences*, *4*, 345–352.

Gorea, A. (1987). Masking efficiency as a function of stimulus onset asynchrony for spatial-frequency detection and identification. *Spatial Vision*, *2*, 51–60.

Greenwood, J. A., Sayim, B., & Cavanagh, P. (2014). Crowding is reduced by onset transients in the target object (but not in the flankers). *Journal of Vision*, *14*(6):2, 1–21, doi:10.1167/14.6.2. [PubMed] [Article]

Koelewijn, T., Brinkhorst, A., & Theeuwes, J. (2009). Auditory and visual capture during focused visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 1303–1315.

Michaels, C. F., & Turvey, M. T. (1979). Central sources of visual masking: Indexing structures supporting seeing at a single, brief glance. *Psychological Research*, *41*, 1–61.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631–1647.

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A., & Morgan, M. (2001). Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience*, *4*, 739–744.

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision*, *4*(12):12, 1136–1169, doi:10.1167/4.12.12. [PubMed] [Article]

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bowhuis (Eds.), *Attention & performance X* (pp. 531–556). Hillsdale, NJ: Lawrence Erlbaum Associates.

Rashal, E., & Yeshurun, Y. (2014). Contrast dissimilarity effects on crowding is not simply another case of target saliency. *Journal of Vision*, *14*(6):9, 1–12, doi:10.1167/14.6.9. [PubMed] [Article]

Scheerer, E. (1973). Integration, interruption and processing rate in visual backward masking. *Psychologische Forschung*, *36*, 71–93.

Shore, D. I., Spence, C., & Klein, R. M. (2001). Visual prior entry. *Psychological Science*, *12*(3), 205–212.

Spence, C., & Driver, J. (1997). Audiovisual links in exogenous covert spatial orienting. *Perception & Psychophysics*, *59*, 1–22.

Toet, A., & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research*, *32*, 1349–1357.

van den Berg, R., Roerdink, J. B. T. M., & Cornelissen, F. W. (2010). A neurophysiologically plausible population code model for feature integration explains visual crowding. *PLoS Computational Biology*, *6*(1), e1000646, doi:10.1371/journal.pcbi.1000646.

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences*, *15*, 160–168.

Yang, Y. H., & Yeh, S. L. (2014). Unmasking the dichoptic mask by sound: Spatial congruency matters. *Experimental Brain Research*, *232*, 1109–1116.

Yeshurun, Y., & Carrasco, M. (1999). Spatial attention improves performance in spatial resolution tasks. *Vision Research*, *39*, 293–305.

Yeshurun, Y., & Rashal, E. (2010). Precueing attention to the target location diminishes crowding and reduces the critical distance. *Journal of Vision*, *10*(10):16, 1–12, doi:10.1167/10.10.16. [PubMed] [Article]

Yeshurun, Y., Rashal, E., & Tkacz-Domb, S. (2015). Temporal crowding and its interplay with spatial crowding. *Journal of Vision*, *15*(3):11, 1–16, doi:10.1167/15.3.11. [PubMed] [Article]