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Experience-dependent changes in the topography of visual crowding

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Abstract

The present work examined discrimination accuracy for targets that were presented either alone in the visual field (clean displays) or embedded within a dense array of letter distractors (crowded displays). The strength of visual crowding varied strongly across the four quadrants of the visual field. Furthermore, this spatial bias in crowding was strongly influenced by the observers' prior experience with specific distractor stimuli. Observers who were monolingual readers of English experienced amplified crowding in the upper-left quadrant, while subjects with primary reading skills in Korean, Chinese, or Japanese tended towards worse target discrimination in the lower visual field. This interaction with language experience was eliminated when non-alphanumeric stimuli were employed as distractors, suggesting that prior reading experience induced a stimulus-specific change in the topography of visual crowding from English letters.

Keywords

crowding; experience dependent; letters

Introduction

The visual discrimination of targets in the periphery is strongly impaired by the presence of nearby distractors, a phenomenon that is called crowding (Bouma, 1970; Huckauf & Heller, 2004; Pelli, Palomares, & Majaj, 2004). Various studies have suggested that crowding

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impairs target discrimination because of excessive integration of target and distractor features (for a review, see Pelli et al., 2004); this effect can be detected within an “integration zone” that extends outward from the target with a radius of about 0.5 of target eccentricity. Crowding remains strong even with highly over-learned visual discriminations. For example, reading rate is directly proportional to the strength of crowding (Pelli et al., 2007). The robust nature of crowding, however, does not preclude experience-dependent changes in this form of visual interference.

When written text is presented in experimental reading tasks, multiple researchers have found differences in perceptual span (i.e., the window of attention surrounding a central fixation point, in which visual information is likely to be encoded) and in oculomotor activity (i.e., saccadic movement) between people with different linguistic backgrounds, including readers of Arabic, Chinese, Japanese, Hebrew, or English languages (Adamson, 2004; Inhoff & Liu, 1998; McConkie & Rayner, 1975; Osaka, 1992; Pollatsek, Bolozky, Well, & Rayner, 1981; Rayner, 1998). For example, studies that measure oculomotor behavior found that when English and other similarly oriented alphabetic text (such as French or Dutch) is read, the range of characters that influences eye movements extends from the beginning of the fixated word to about 14–15 character spaces to the right and only 3–4 characters to the left. Thus, English readers exhibit a perceptual asymmetry that is biased towards the right visual field (Rayner, 1998). By contrast, when Israelis read right-to-left oriented Hebrew text, the perceptual asymmetry that emerges is to the left of fixation, indicating that written language orientation and reading direction influence the effective range of visual attention around fixation (Pollatsek et al., 1981). Interestingly, the inherent features of different linguistic scripts also appear to influence the size of the perceptual span and the degree of asymmetry: Inhoff and Liu (1998) found that when horizontal Chinese text is read, the effective range of vision was only slightly asymmetric, extending 3 characters to the right of fixation and only 1 character to the left. The researchers hypothesized that this smaller and less asymmetric perceptual span occurs because Chinese uses a morphographic script with linguistic symbols that are often of greater density and complexity than the characters used in alphabetic languages such as English; further, the majority of Chinese words only use two characters, while English words are often longer, necessitating a wider perceptual span. It seems clear, in any case, that prolonged reading experience can have spatially specific effects on how text is processed.

The present studies examine whether reading experience can also have spatially specific effects on the strength of visual crowding. Specifically, we measured the accuracy with which digits could be discriminated either in the presence or absence of strong crowding from English letters. With these stimuli, we found pronounced effects of the observer’s experience with these stimuli. For observers who were monolingual English readers (with negligible experience reading other character sets), crowding effects were markedly stronger in the upper-left quadrant. However, for observers whose first language did not employ the characters of the English alphabet, crowding was strongest in the lower visual field (Experiments 1a and 1b). Our hypothesis that reading experience is the primary factor contributing to these two distinct patterns of visual crowding with alphanumeric stimuli is supported by the fact that in later studies, when unfamiliar non-linguistic stimuli were presented, these differences between language groups were no longer evident (Experiments

2a and 2b). Thus, these studies suggest that the topography of visual crowding from letters is strongly influenced by prior experience with those stimuli.

Experiments 1a and 1b

Method

Subjects—Three separate groups of subjects participated in Experiments 1a and 1b. Experiment 1a included 23 subjects from the University of Oregon community who received either course credit or payment for their participation in a 1.5-hour experimental session. Fourteen of these subjects were native speakers of English (hereafter referred to as the *English 1a* group), while nine subjects were international students who spoke Asian languages natively (the *Asian 1a* group). Specifically, four subjects spoke Chinese natively, four spoke Indonesian natively, and one spoke Nepalese, English, and Hindi natively. In the Asian 1a group, all had studied Chinese and all but one spoke Chinese fluently as either a first or second language. Subjects in the English 1a group either had very limited experience or no experience with any other languages, while all of the other subjects were bilingual, trilingual, and in the case of one subject, quintilingual, with varying levels of English experience and ability. Finally, another group of 10 subjects from Yonsei University in Korea were also recruited to participate in Experiment 1a (*Korean 1a* group).

Experiment 1b included a new group of 29 students from the University of Oregon community. Thirteen of these subjects (the *English 1b* group) were monolingual American English readers, and sixteen subjects (the *Asian 1b* group) were international students learning English as a second language. In the Asian 1b group, five subjects were Korean, three were Chinese, and eight were Japanese. All subjects had normal or corrected-to-normal vision. Before beginning the experiment, each subject received both verbal and written instructions, the latter of which were presented in his/her native language. At the end of the experiment, all subjects completed a self-report language questionnaire in their respective native language that allowed us to record the subjects' reading experience and abilities in both their native language(s) and in English. Demographics information was also collected at this time.

Stimuli—Figure 1 illustrates the sequence of events in clean and crowded trials of both Experiments 1a and 1b. The target was a number between 1 and 9 (randomly selected on each trial) and was presented in one of the four quadrants on the screen (also randomly selected on each trial). During crowded trials, the distractor letters were centered over a 6 × 6 grid of positions. The distractors were all uppercase and were randomly selected from the English alphabet (excluding *I* because of its similarity to the number 1). The alphabetic letters were positioned randomly within the grid on each trial and no letter appeared more than twice in the same grid. Target characters and distractors were presented in Arial font. The 6 × 6 grid of distractors subtended 5.1° in both height and width. The spacing between characters had a visual angle of 0.45° and the height and width of both distractor and target stimuli were 0.65° and 0.5°, respectively. The target and distractors were white and presented on a black background.

Design and procedure—Experiments 1a and 1b employed the same design and procedure with the following exceptions. The presence of distractors was blocked in Experiment 1a and varied randomly within block in Experiment 1b. In addition, to ensure an adequate level of difficulty in the clean condition of Experiment 1b, the luminance of all stimuli (including targets, distractors, masks, fixation, and cue) was decreased from an RGB value of 255 (white) to 75 (gray).

Each trial involved the following sequence of events. First, sitting approximately 18 inches away from the computer screen, subjects directed their gaze towards a central fixation dot, which subtended 0.4° in diameter and appeared for 1.6 s. Next, a cue dot subtending 0.1° in diameter was presented for 59 ms at one of four locations peripheral to the central fixation area. This cue indicated the target location with 100% validity. Immediately following cue-offset, the target array was presented. The target digit was centered over the position of the dot cue (eccentricity 2.5°). Immediately after the offset of the target, masking symbols (#) were presented for 401 ms over all stimulus positions. We note here that the brief duration of the precue and target display (less than 200 ms on average for the crowded displays) precluded eye movements before the onset of the masking stimuli. Finally, a question mark located in the target location prompted participants to type in the number that they had seen, with all priority given to accuracy. Subjects were allowed to view and change their typed responses before finally submitting them. Visual feedback was presented at the end of each trial with the words “correct” or “incorrect.”

Experiment 1a began with four blocks of staircasing (see Timing procedure) for each display type (clean and crowded) which determined the exposure duration used during the subsequent experimental blocks. The order of these conditions was counterbalanced across subjects. These experimental sections were composed of 5 blocks of 40 trials each. Targets were equally likely to appear in each of the four quadrants. Target discrimination accuracy was measured for each quadrant and each type of display. For Experiment 1b, the crowded and clean trials were randomly intermixed in both the timing and experimental procedures. Because trial types were intermixed in Experiment 1b, observers completed 8 blocks of the timing procedure (three more than in Experiment 1a) so that there was enough time to reach asymptote followed by 10 blocks of the experimental procedure (40 trials per block).

Timing procedure—We used a staircase timing procedure to set exposure duration on a within-subject basis. By adjusting exposure durations separately for each display type, discrimination difficulty was equated across the clean and crowded conditions. The timing procedures both comprised 4 blocks of 40 trials for each display type in Experiment 1a, or 8 blocks of 40 trials (including both display types randomly intermixed) in Experiment 1b. The sequence of events in each staircasing trial was the same as in the experimental trials. Following each correct response, the exposure duration decreased by 11.8 ms or one 85 Hz monitor refresh cycle. Following an incorrect response, exposure duration increased by 23.5 ms or two monitor refresh cycles. The average exposure duration over the last two blocks was calculated and used to determine the constant exposure duration value for the experimental sections. A minority of subjects were given an extra block or two of the timing procedure if at the end of the procedure the exposure duration had not yet reached a stable asymptote.

Results and discussion

Experiment 1a—As expected, the distractor letters elicited a reliable crowding effect, as evidenced by longer exposure durations for the crowded displays (145 ms) than for the clean displays (35 ms) ($t(61) = 8.4$, $p < .001$) in the staircase timing procedures. These durations did not differ between language groups ($p = .82$ and .28 for the clean and crowded displays, respectively). In addition, note that the exposure duration for the crowded displays (145 ms) was not long enough to allow eye movements to the target position. Thus, the interaction of display type and quadrant described below cannot be explained by differential eye movements for the clean and crowded displays. Target discrimination accuracy from Experiments 1a and 1b is illustrated in Figure 2. Panels a and b show target discrimination accuracy for Experiment 1a; here, it is apparent that accuracy depended strongly on which quadrant held the target for the crowded trials, but quadrant had little or no effect on performance with clean displays. Moreover, this interaction between display type and quadrant interacted strongly with language group. For the English 1a group, target discrimination in the crowded displays was much less accurate in the upper left quadrant than in the other three quadrants. By contrast, both the Asian 1a and Korean 1a groups showed no evidence of deficits in the upper left quadrant; instead these groups had somewhat lower accuracy for target discrimination in the lower visual field.

To confirm the apparent differences between the English 1a and Asian 1a groups, a repeated measures ANOVA with display type, language group, and quadrant as factors was carried out on target discrimination accuracy. This analysis revealed a significant three-way interaction between display type, language group, and quadrant, $F(3,63) = 16.12$, $p < 0.001$, partial $\eta^2 = 0.434$, in line with the observation that target discrimination accuracy with crowded displays was markedly lower in the upper left quadrant for the English 1a group but not for the Asian 1a group. Accordingly, post hoc *t*-tests showed that English 1a accuracy was lower in the upper left quadrant than in all other quadrants for the crowded displays (all p values $< .001$), but not for the clean displays (all p values $> .4$). By contrast, post hoc *t*-tests of Asian 1a crowded trials revealed a trend towards *higher* accuracy in both the upper left quadrant relative to the lower right quadrant ($p = .07$) and in the upper right quadrant relative to the lower right quadrant ($p = .08$); no other paired comparison between quadrants reached significance.

A similar analysis revealed the same pattern of differences between the English 1a and Korean 1a groups. A repeated measures ANOVA revealed a significant three-way interaction between display type, language group, and quadrant, $F(3,66) = 17.6$, $p < .001$, partial $\eta^2 = .561$, in line with the observation that target discrimination in crowded displays was lowest in the upper right quadrant for the English 1a group but not for the Korean 1a group. Post hoc *t*-tests of Korean 1a data revealed significantly higher accuracy with crowded displays in both upper field quadrants relative to both lower field quadrants (upper right quadrant vs. lower left quadrant: $p = .02$; upper right quadrant vs. lower right quadrant: $p = .02$; upper right vs. lower left quadrants: $p = .01$; upper right vs. lower right quadrants: $p = .01$).

Experiment 1b—The results of Experiment 1b are illustrated in panels c and d of Figure 2. Recall that the key difference between Experiments 1a and 1b was that display type was blocked in Experiment 1a but varied randomly in Experiment 1b. Thus, Experiment 1b tested whether or not the differential effect of quadrant on performance with the crowded and clean displays was contingent on subjects' ability to predict the type of display on each trial. Contrary to this hypothesis, the same qualitative pattern of results was found in Experiment 1b when display type varied unpredictably. Once again, accuracy with crowded displays was lowest in quadrant 1 for the English 1b group but not for the Asian 1b group. This replication of the results seen in Experiment 1a argues against the hypothesis that the differential target position effects with crowded and clean displays resulted from differences in the top–down attentional state of the observers when display type was predictable (for demonstrations of such contextual effects see Awh, Matsukura, & Serences, 2003; Awh, Sgarlata, & Kliestik, 2005).

A repeated measures ANOVA confirmed the apparent differences in performance between the English 1b and Asian 1b groups. This analysis revealed a significant three-way interaction between display type, language group, and quadrant, $F(2.6, 70.2) = 6.01$, $p = .002$ partial $\eta^2 = 0.182$. (We used the conservative Greenhouse–Geisser correction here because sphericity could not be assumed for quadrant, $\chi^2(5) = 13.15$, $p = .02$.) Here again, the triple interaction confirms the observation that target discrimination with crowded displays was lowest in the upper left quadrant for the English 1b group, but not for the Asian 1b group. Post hoc tests confirmed this explanation of the triple interaction. For the English 1a group, discrimination accuracy with crowded displays was significantly lower in the upper left quadrant than in all the other quadrants (all p values < .05). For the Asian 1b group, however, discrimination accuracy with crowded displays did not vary across quadrants; all paired comparisons were nonsignificant.

To summarize the results of Experiments 1a and 1b, two independent groups of monolingual English readers (English 1a and 1b) showed much lower target discrimination accuracy in the upper left quadrant with crowded displays, but no differences across quadrants with clean displays. This restriction of quadrant effects to the crowded displays suggests a specific increase in the strength of visual crowding in the UL quadrant rather than location-specific differences in visual acuity or digit discrimination. In addition, the increased strength of crowding in the upper left quadrant appears to depend in part on the prior reading experience of the observers; three separate samples of bilingual native readers of Asian languages (Asian 1a, Asian 1b, and Korean 1a) showed no trace of a similar increase in crowding in the UL quadrant. Instead, these groups showed a consistent trend towards *higher* accuracy in the upper visual field with the crowded displays. Thus, these data suggest that prior reading experience led to marked changes in the topography of visual crowding between digits and letters.

Nevertheless, although reading experience provides an attractive explanation of the marked differences between language groups, other alternative explanations need to be considered. For example, it is possible that the differences which we observed between language groups arose because of some unforeseen difference between these populations rather than the groups' differential experiences with the digit and letter stimuli. There are countless potential cultural differences that may have contributed to the modification of target discrimination ability across quadrants, such as differences in education, differences in the presentation of information in the media, and divergent cultural perspectives about what aspects of an environment are most relevant. The latter possibility has been suggested by Nisbett and colleagues as an explanation for certain differences observed between East Asians and Americans in perception and attention (Masuda & Nisbett, 2001; Nisbett & Miyamoto, 2005; Nisbett, Peng, Choi, & Norenzayan, 2001).

Given these alternative possibilities, Experiments 2a and 2b tested whether the differences in the topography of crowding across language groups were specific to the alphanumeric stimuli used in Experiments 1a and 1b. If the differences were caused by differential reading experience with English letters and digits, then these differences should be eliminated for non-alphanumeric stimuli (i.e., stimuli that were equally familiar across language groups). By contrast, if the differences between language groups reflect broader changes in visual perception crowding, possibly linked to cultural differences beyond reading experience per se, then the interaction between language group and crowding may generalize to non-alphanumeric stimuli.

Experiments 2a and 2b

In Experiments 2a and 2b, two different stimulus sets (illustrated in Figure 3) were used to evaluate whether the differences in the topography of crowding across language groups were specific to the letter distractors used in Experiments 1a and 1b. In Experiment 2a, observers once again discriminated digit targets, but the 25 possible letter distractors were replaced by 20 false font characters. In Experiment 2b, geometric shapes were used for both targets and distractors. Thus, these studies tested whether the previously observed differences between language groups would extend to these non-alphanumeric stimuli.

Method

Subjects—For Experiment 2a, twenty-two students from the University of Oregon community were tested in a 1.5-hour experimental session. Thirteen of these subjects were monolingual American English readers (the English 2a group), and nine were Chinese (n = 4) or Japanese (n = 5) international students learning English as a second language (Asian 2a). These individuals were recruited from the American English Institute at the University of Oregon. For Experiment 2b, 16 monolingual American students from the University of Oregon (English 2b) and 16 Korean students from Yonsei University (Asian 2b) participated in a 1. 5-hour experiment.

All subjects had normal or corrected-to-normal vision and received either course credit or pay for their participation. The same language questionnaires from Experiment 1b were administered at the end of the experiment.

Stimuli, design, and procedure—The possible target and distractor stimuli were different from the previous studies, but all other methodological details were identical to those of Experiment 1a.

Results and discussion

For both sets of stimuli, a significant crowding effect was indicated by a longer exposure duration needed to perform the task with distractors (for false fonts: *M* = 130 ms, *SD* = 44 ms; for shapes: M = 236 ms, *SD* = 128 ms) than without distractors (false fonts: *M* = 36 ms, *SD* = 19 ms; shapes: M = 60 ms, *SD* = 128 ms) (paired *t*-tests of crowded vs. clean displays, $p < .001$ in both cases). A two-way ANOVA with display type and language group as factors revealed no difference in exposure duration between language groups ($p = .35$) and no interaction between display type and language group ($p = .27$); thus, exposure durations for both display types were equivalent between groups.

Experiment 2a—Recall that the primary purpose of Experiments 2a and 2b was to determine whether or not the strong differences between language groups would be observed with non-alphanumeric stimuli. Thus, a key aspect of the Experiment 2a results was that there was no longer a reliable interaction between language group, display, and quadrant as in Experiments 1a and 1b, $F(3,60) = 2.18$, *NS*, nor was there a significant interaction between the variables of quadrant and language group, $F(3,60) = 1.51$, *NS*, even when only the data from the crowded displays were considered, $F(3,60) = 1.82$, *NS*. Instead, as the result illustrated in Figure 4 shows, the pattern of accuracy across quadrants was qualitatively similar across language groups, with a bias towards higher accuracy in the right visual field with crowded displays. Similar to Experiments 1a and 1b, quadrant did not have a reliable effect on performance with clean displays. The right visual field bias in crowded trials was confirmed by post hoc *t*-tests on right vs. left visual field performance. The Asian 2a group showed significantly higher target discrimination performance in the right visual field ($M = 0.80$, $SD = 0.03$) than in the left visual field ($M = 0.73$, $SD = 0.04$), $t(8) = 2.96$, $p = .02$, as did the English 2a group (right: $M = .80$, $SD = .02$; left: $M = .61$, $SD = .03$), $t(12) = 5.34$, $p < .01$.

Experiment 2b—The pattern of results in Experiment 2b closely mirrored the findings in Experiment 2a. Here again, the triple interaction between language group, display type, and quadrant (that was observed in Experiments 1a and 1b) was no longer statistically significant when geometric shapes were used as targets and distractors in Experiment 2b, $F(3,90) = 2.02$, *NS*, nor was there an interaction between language group and quadrant, $F(3,90) = 3.03$, *NS* (Figure 5). Instead, performance across groups was much more similar across language groups. Specifically, Experiment 2b revealed the same right visual field bias that was apparent with the crowded displays in Experiment 2a. The Asian 2b group had significantly reduced accuracy in the left visual field ($M = 0.73$, $SD = 0.13$) compared to accuracy in the right visual field ($M = 0.80$, $SD = 0.11$): $t(15) = 3.16$, $p < 0.001$. Likewise, the English 2b group had significantly lower accuracy in the left visual field ($M = 0.69$, $SD = 0.13$) than in the right visual field ($M = 0.79$, $SD = 0.08$), $t(15) = 3.32$, $p < 0.01$. However, one unexpected finding was that the English 2b group also exhibited a significant difference in accuracy between visual fields (left VF: $M = 0.69$, $SD = 0.08$, right VF: $M = 0.75$, $SD = 0.07$) in the clean condition: $t(15) = 3.72$, $p < .01$. The Asian 2b group showed no effect of quadrant in the clean condition, and this was the only time that we saw such quadrant effects with clean displays in monolingual English group. We have no clear explanation of this finding. Nevertheless, the results of Experiments 2a and 2b taken together make a clear point; the strong differences in crowding effects across language groups were eliminated by the use of false font distractors (Experiment 2a) or shape targets and distractors (Experiment 2b). This result suggests that the strong differences in the topography of visual crowding observed in Experiments 1a and 1b were a direct result of prolonged differences in reading experience with English letters *per se* rather than broader, stimulus-general differences in visual crowding.

Conclusions

Admittedly, our first observations of the strong interaction between visual crowding, spatial position, and reading experience were unexpected. Nevertheless, this striking empirical pattern was documented in two independent samples of monolingual English readers and three separate samples of bilingual Asian readers. These data suggest that prolonged reading experience with English letters leads to a stable increase in the relative strength of crowding from those stimuli in the upper left quadrant of the visual field. Moreover, these strong effects of prior reading experience were eliminated when the distractor stimuli were replaced by either false font characters or geometric shapes. The stimulus-specific effect of prior reading experience suggests that the strong differences we observed between language groups were caused by reading experience *per se* rather than more general cultural differences that should have influenced visual processing across a wider range of stimuli. These data dovetail with past observations that crowding effects were reduced for familiar stimuli (i.e., standard letters) compared to unfamiliar stimuli (rotated or pseudoletters) (Huckauf & Heller, 2004; Huckauf, Heller, & Nazir, 1999) by showing that experience influences the spatial distribution of crowding as well as the average strength of this form of visual interference.

These experience-dependent effects on the topography of crowding dovetail with previous studies that have shown strong effects of prior experience on the efficacy of processing within specific sensory modalities. For example, Röder and colleagues (1999) found that auditory attention was more sharply tuned in congenitally blind subjects, suggesting that visual deprivation can enhance the efficacy of auditory selection. These authors suggested that the regions of the brain typically devoted to visual attention may have been co-opted for the benefit of auditory selection. In line with this possibility, Neville and colleagues have also documented experience-based changes in attentional processing in observers with different auditory and linguistic experience, such as congenitally deaf individuals who communicate with sign language (e.g., Neville, 2004; Neville, Mills, & Lawson, 1992; Proksch & Bavelier, 2002). Therefore, a complete understanding of attention requires consideration of how experience modifies function. Likewise, our results suggest that visual crowding is modifiable by large differences in perceptual experience.

Can the present findings be explained by differences in how the language groups allocated spatial attention when English letters were expected in the distractor positions? This explanation is challenged by previous observations that that visual crowding is not ameliorated by spatial attention (e.g., Nazir, 1992; Scolari, Kohnen, Barton, & Awh, 2007; Strasberger, 2005; Wilkinson, Wilson, & Ellemberg, 1997). For example, Scolari et al. (2007) measured critical spacing or the closest distance that distractors could appear to a target before interference from visual crowding could be detected. Across four separate experiments, all of which demonstrated better visual discrimination at attended than at unattended locations, there was no change in critical spacing when spatial attention was directed at the target position. By contrast, when bottom–up factors enabled a clearer segregation of the target from nearby distractors based on color popout or temporal asynchrony, clear reductions in critical spacing were observed. Scolari et al. suggested that popout and temporal asynchrony of targets and crowding elements might facilitate the perceptual segregation of targets and distractors, thereby preventing the harmful pooling of features that is thought to underlie visual crowding. One possibility is that extended experience reading English characters also facilitates the segregation of these characters from digit stimuli, but in a way that is biased away from the upper left quadrant. From this perspective, experience-dependent changes in the perceptual segregation of digits and letters may be driven more by low-level changes in the degree to which such stimuli are integrated during crowding rather than by changes in the distribution or efficacy of attention selection. That is, experience may have influenced the degree to which harmful pooling of target and distractors occurred across the visual field rather than the degree to which attention is able to ameliorate this pooling in different locations.

Although at first glance it is tempting to conclude that the results from the English reader group are a consequence of the left-to-right organization of typical English text, a straightforward prediction based on typical reading orientation does not explain the results seen with Asian subjects. Although for many of these subjects, primary reading experience was with texts of a different orientation from English, many of these subjects also had primary proficiency in languages that have a left-to-right orientation (e.g., Korean, Indonesian, and often, modern Japanese text). Thus, although the Asian language reader group certainly had more experience with different text orientations, the left-to-right orientation is also a consistent part of this group’s reading history. So, although the results strongly suggest that reading experience led to long term changes in the topography of visual crowding, a strong conclusion regarding the role of typical reading orientation is not warranted.

In conclusion, our results show that strong differences in prior experience with English characters lead to striking changes in the topography of visual crowding from these stimuli. These results provide a clear demonstration of experience-dependent modifications in visual crowding. Because visual crowding is one of the core limiting factors in our ability to encode information from cluttered visual scenes, it will be useful to understand further how experience and training can modify this source of visual interference (e.g., Green & Bavelier, 2007).

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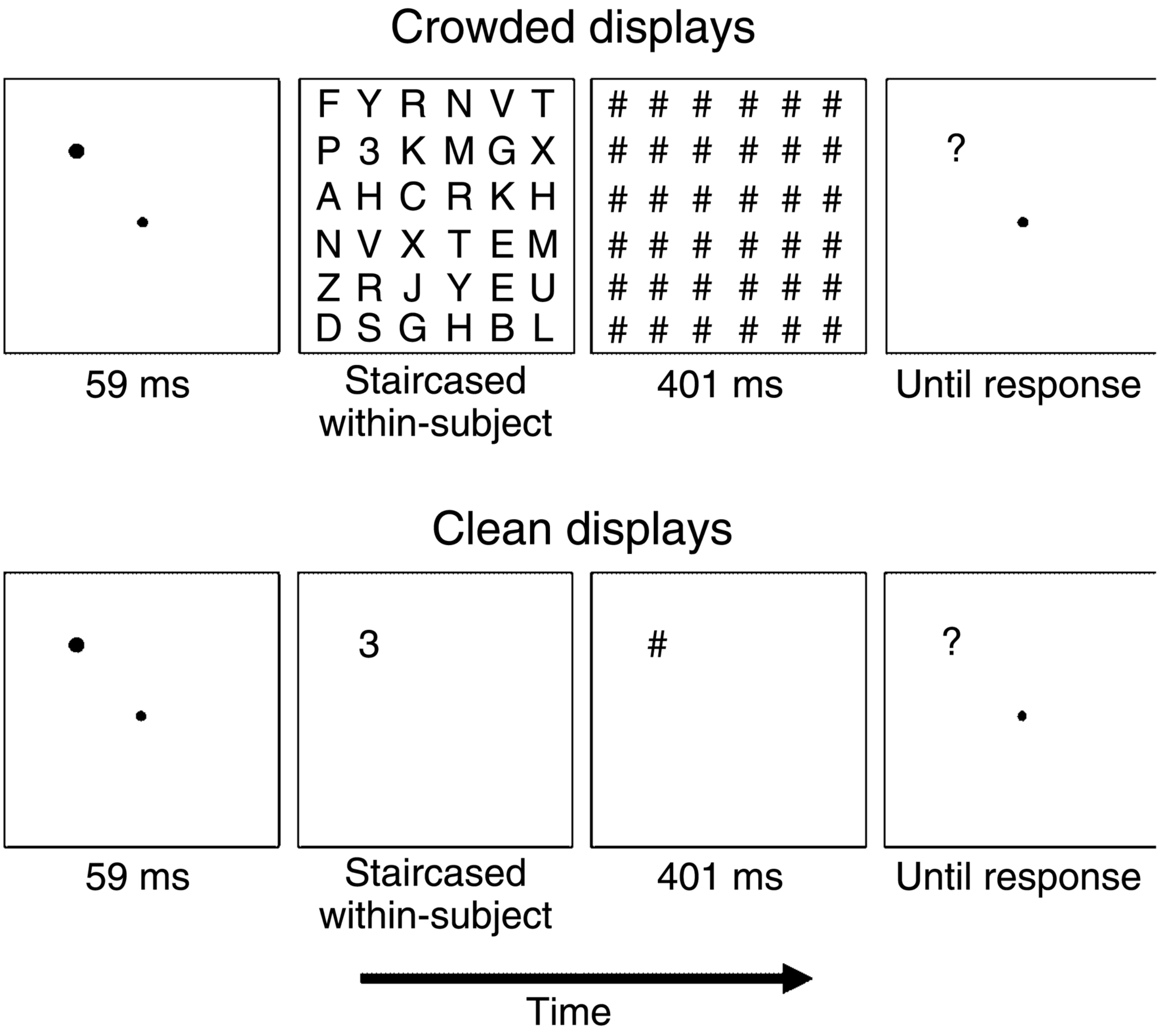

Figure 1.

Sequence of events in crowded and clean trials of Experiments 1a and 1b.

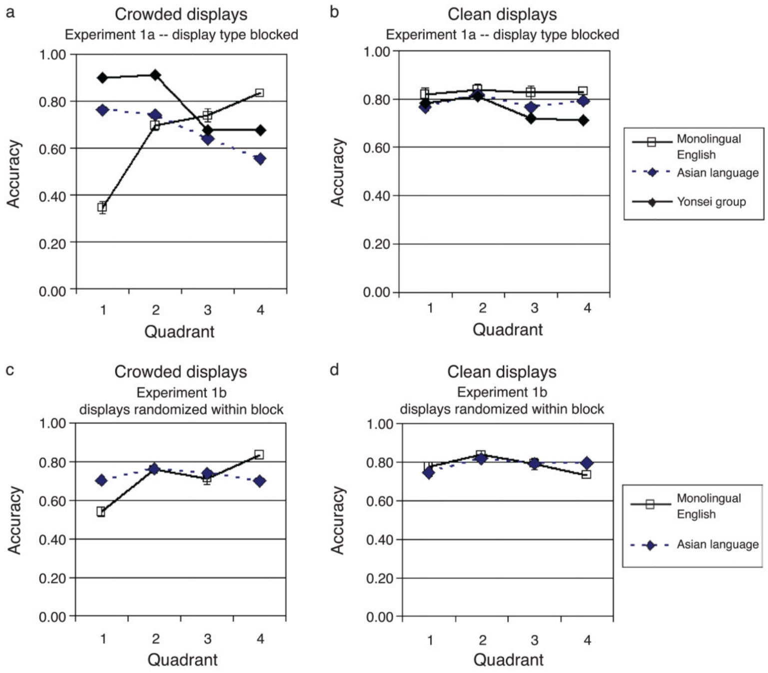

Figure 2.

Target discrimination accuracy from Experiments 1a (panels a and b) and 1b (panels c and d), as a function of display type, language group, and quadrant. Error bars represent standard error across subjects.

Figure 3.
Target discrimination accuracy from Experiment 2a as a function of display type, language group, and quadrant. Error bars represent standard error across subjects.

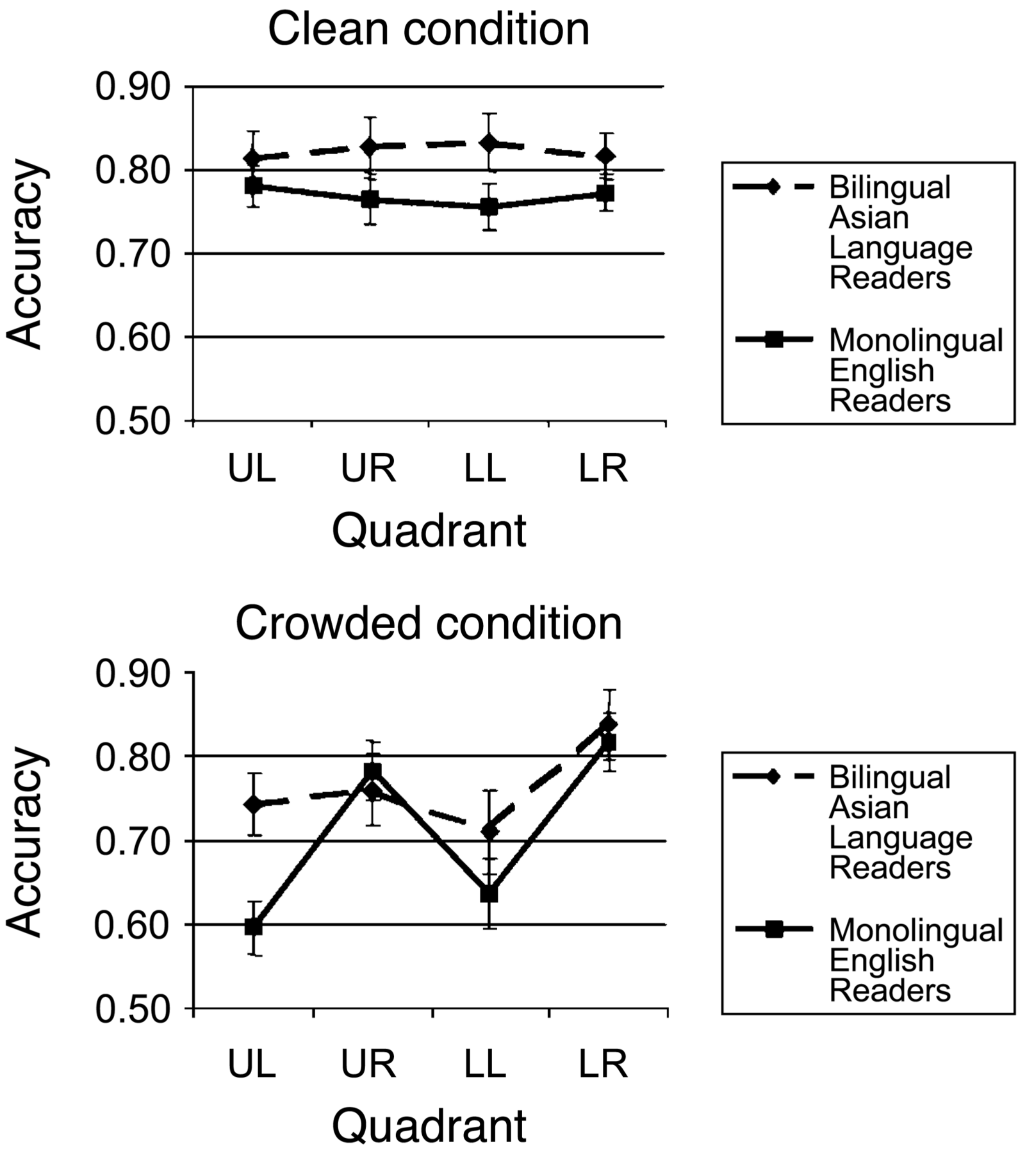

Figure 4.

Target and distractor stimuli from Experiments 2a and 2b.

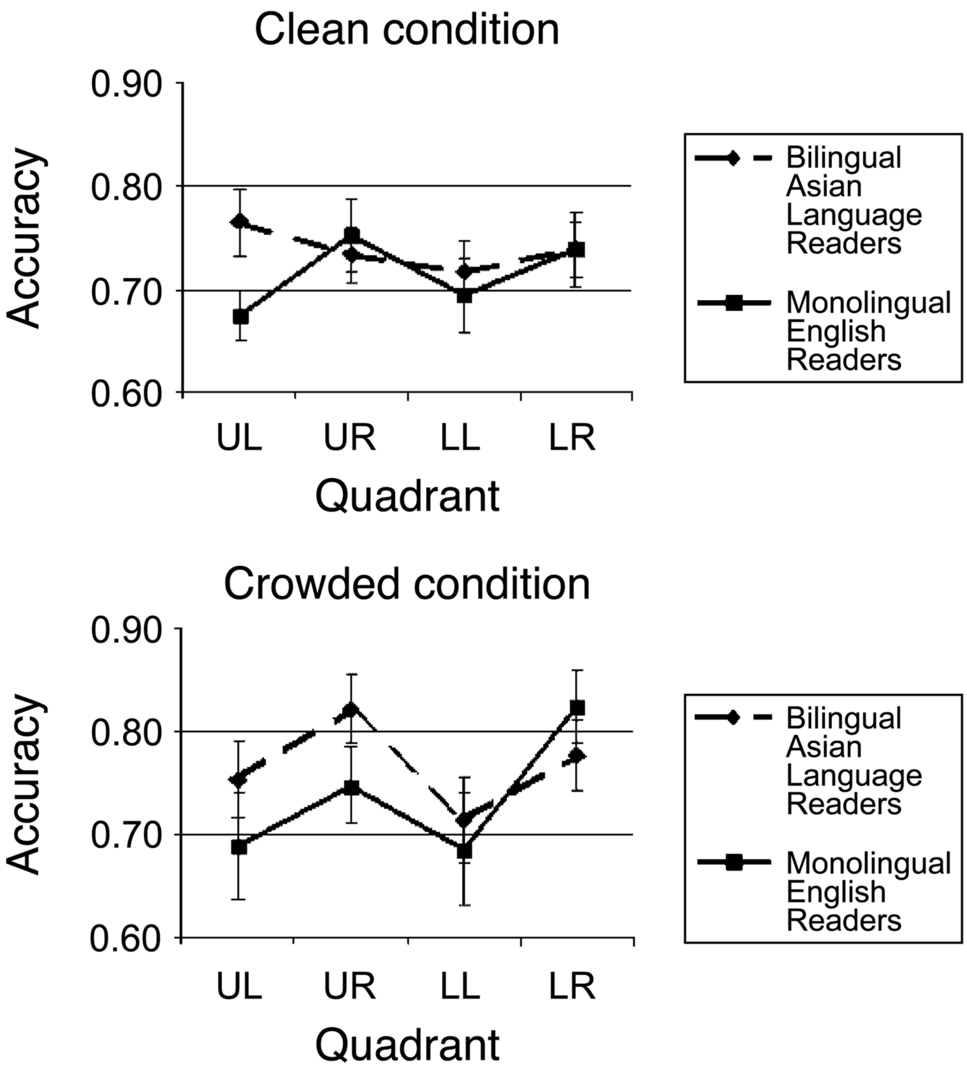

Figure 5.

Target discrimination accuracy from Experiment 2b as a function of display type, language group, and quadrant. Error bars represent standard error across subjects.