Journal of Experimental Psychology:
Human Perception and Performance
2010, Vol. 36, No. 3, 673–688

0096-1523/10/$12.00 DOI: 10.1037/a0016888

Crowding Affects Letters and Symbols Differently

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Five experiments examined crowding effects with letter and symbol stimuli. Experiments 1 through 3 compared 2-alternative forced-choice (2AFC) identification accuracy for isolated targets presented left and right of fixation with targets flanked either by 2 other items of the same category or a single item situated to the right or left of targets. Interference from flankers (crowding) was significantly stronger for symbols than letters. Single flankers generated performance similar to the isolated targets when the stimuli were letters but closer to the 2-flanker condition when the stimuli were symbols. Experiment 4 confirmed this pattern using a partial-report bar probe procedure. Experiment 5 showed that another measure of crowding, critical spacing, was greater for symbols than for letters. The results support the hypothesis that letter-string processing involves a specialized system developed to limit the spatial extent of crowding for letters in words.

Keywords: crowding, letter perception, orthographic processing

In languages that use alphabetical orthographies, the very first stage of the reading process involves mapping visual features onto representations of the component letters of the currently fixated word (see Grainger, 2008, for a recent review). This rapid computation of a set of letter identities, likely performed in parallel, is already a major challenge for the literate brain, given the limits in visibility imposed by visual acuity and lateral interference (crowding) across neighboring letters. The challenge is all the greater for the beginning reader, who must rapidly master the new art of processing visual objects in close spatial proximity.

Strings of letters, even when they are meaningless and unpronounceable (e.g., HFKMT), are not processed in the same way as strings of stimuli of similar visual complexity but that typically do not occur in strings. This fact was first demonstrated using the target search task, comparing serial position functions (search time as a function of position in string) for letter stimuli versus symbol stimuli or simple shapes. Search times for a target letter in a string of letters show an approximate M-shaped serial position function (i.e., shortest reaction times [RTs] for the first, third, and fifth positions of a five-letter string). Symbol (e.g., Σ, ψ) and shape stimuli, on the other hand, show a U-shaped function with shortest RTs for targets at the central position (on fixation) that increase as a function of eccentricity (Hammond & Green, 1982; Mason, 1982; Mason & Katz, 1978). Recent research has shown that this phenomenon also holds for data-limited identification paradigms (Tydgat & Grainger, 2009), suggesting that it is related to fundamental differences in the way strings of letters and symbols are processed. The present study is a further attempt at understanding the mechanisms that underlie such differences.

The standard serial position function for letter stimuli (typically obtained by using random strings of consonants) is M-shaped for response times in the letter search task (Hammond & Green, 1982; Ktori & Pitchford, 2008, 2009; Mason, 1975, 1982; Mason & Katz, 1976; Pitchford, Ledgeway, & Masterson, 2008) and W-shaped for studies using data-limited identification procedures (Averbach & Coriell, 1961; Butler, 1975; Butler & Merikle, 1973; Haber & Standing, 1969; Merikle, Coltheart, & Lowe, 1971; Merikle, Lowe, & Coltheart, 1971; Mewhort & Campbell, 1978; Schwantes, 1978; Stevens & Grainger, 2003; Wolford & Hollingsworth, 1974). One classic interpretation of this serial position function is that it reflects the combination of two factors: the drop of acuity from fixation to the periphery, and less crowding on the first and last letter of the string because these are flanked by only one other letter (Bouma, 1970, 1973; Estes, 1972; Estes, Allmeyer, & Reder, 1976; Haber & Standing, 1969; Van der Heijden, 1992). However, this explanation of the serial position function for letters does not account for why the function changes for symbols and non-letter shapes.

One possible account of the different serial position functions found for letters and symbols is that reading-specific attentional factors are at play with alphabetic stimuli. There is a long tradition of research demonstrating attentional influences on the perception of letters and words (e.g., Ducrot & Grainger, 2007; Heron, 1957). On presentation of a centrally fixated string of letters attention could be automatically drawn to the beginning of the stimulus, hence facilitating processing of the first letter. Tydgat and Grainger (2009) tested for the possible role of such attentional biases in generating stimulus-specific serial position functions, by testing letter targets embedded in strings of symbols and symbol

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Part of the research reported in this article was performed while Ilse Tydgat and Joanna Isselé were on an Erasmus exchange between Ghent University and the University of Provence. We thank Marine Salery for running Experiment 4.

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targets embedded in strings of letters. They found that it was the nature of the target, not the surrounding context, which determined the form of the serial position function. This result also allowed Tydgat and Grainger to reject a role for higher-order units (i.e., letter clusters or supra-letter features) as the basis of the different serial position functions for letters and symbols. Finally, randomly intermixing letter and symbol trials in an experiment had no effect on the serial position function compared with blocked lists of letters and symbols.

On the basis of their results, Tydgat and Grainger (2009) tentatively concluded that the different serial position functions found for strings of letters and symbols might be related to differences in the way crowding affects these two types of stimuli. More specifically, Tydgat and Grainger proposed that crowding effects might be more limited in spatial extent for letter stimuli compared with symbol stimuli, such that a single flanking stimulus would suffice to generate close to maximum interference for symbols, but not for letters. This would account for the superior performance at the first and last positions for letter stimuli, but not for symbol stimuli. According to Tydgat and Grainger, during reading acquisition, a specialized system develops in order to optimize processing of strings of letters. One key aspect of this optimization is a reduction in the size of integration fields associated with location-specific letter detectors that perform parallel letter identification (Grainger & van Heuven, 2003).[1] It is this reduction in the size of integration fields, specific to stimuli that typically appear in strings (letters and digits), that results in less crowding for such stimuli compared with other types of visual stimuli such as symbols and geometric shapes (see Figure 1).

According to Tydgat and Grainger's (2009) account of the different serial position functions for letters and symbols, one should be able to observe differential crowding effects for letters and symbols using a standard crowding manipulation. This prediction is illustrated in Figure 1. The hypothesized larger integration fields of symbol detectors (right panel of Figure 1) compared with letter detectors (left panel of Figure 1) would result in greater interference from flanking stimuli. Here we adopt an account of crowding as integration of inappropriate feature information from neighboring stimuli during target identification (Levi, 2008; Pelli et al., 2007). The larger the integration field involved in identifying a given target at a given location, the greater the number of features from neighboring stimuli that can interfere in target identification.

Does crowding vary as a function of type of stimulus? Prior research has demonstrated crowding effects for letter stimuli and nonletter stimuli such as simple shapes using the standard crowding manipulation where accuracy to identify isolated stimuli presented left or right of fixation is compared with identification of the same stimuli at the same location but flanked by two other stimuli (see Levi, 2008, for review). However, to our knowledge, no prior study has directly compared effects of crowding on letters and symbols. Huckauf and Nazir (2007) examined the effects of training on performance to letter and symbol stimuli flanked by two characters, but did not test for differences across these two types of stimuli, and did not include an isolated target condition. Therefore, the first aim of the present study is simply to provide a comparison of standard crowding effects in letters and symbols. Experiment 1 tests letters and symbols with the classic dual flanker paradigm and eccentric stimulus presentation. The exact same stimuli as tested in our prior work on serial position functions were used here for comparability, and the eccentricity of targets corresponds to the eccentricity of the first and last positions of the centrally located five-character strings tested by Tydgat and Grainger (2009). We also chose to use the two-alternative forced-choice (2AFC) procedure used by Tydgat and Grainger, in an attempt to equate overall performance level to letters and symbols by removing possible influences of category size.

Summing up, the present experiments were designed as a test of the crowding explanation of differences in serial position functions found for letter and symbol stimuli put forward by Tydgat and Grainger (2009). To do so, in Experiments 1 through 4 we tested exactly the same letter and symbol targets at the same eccentricity as the first and last positions of the five-letter strings used by Tydgat and Grainger, using the same response procedure (2AFC in Experiments 1–3, bar-probe partial report in Experiment 4), but with a standard crowding manipulation (eccentric targets flanked by other characters). To respect the conditions typically used to investigate serial positions functions, letter targets were always flanked by letters, and symbol targets always flanked by symbols. Finally, Experiment 5 tested a new set of letter and symbol stimuli, that were more closely matched in terms of visual complexity, and applied a critical spacing manipulation that provides a more fine-grained measure of the spatial extent of crowding (e.g., Chung, 2007; Pelli et al., 2007).

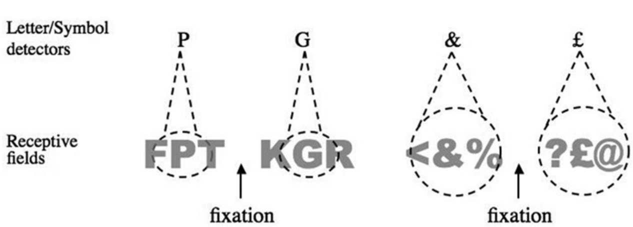

Figure 1. Illustration of the different size of integration fields used to identify letters and symbols at a given retinal location, hypothesized by Tydgat and Grainger (2009). The larger size of integration fields for symbol detectors predicts greater crowding effects for symbols than for letters in a standard flanking experiment with eccentrically located targets. This arises because more information from flanking stimuli falls in the target's integration field. Targets are the central character of three characters presented either left or right of fixation.

Experiment 1

Method

Participants. Twenty-four students of the University of Provence, Marseille, volunteered to participate in the experiment. Their mean age was 20 years. Two were male, and all were native speakers and readers of French and reported having normal or corrected-to-normal vision.

[1] Tydgat and Grainger (2009) used the term *receptive field* to describe the spatial extent of integration of visual information for letter and symbol detectors. Here we adopt the more theoretically neutral terminology of Pelli and colleagues (e.g., Pelli, Palomares, & Majaj, 2004), using the term *integration field* to underline the scale-invariant property of these location-specific receptive fields.

Stimuli and design. Stimuli were identical to the letter and symbol stimuli tested by Tydgat and Grainger (2009). These were nine uppercase consonants (B, D, F, G, K, N, L, S, or T) and nine keyboard symbols (%, /, ?, @, }, <, £, §, or µ). The target was presented either in isolation, or as the middle character in an array of three characters. In the latter case, the target was flanked by two different characters from the same category. Targets could appear at two possible locations, left or right of fixation at an eccentricity of 1.2° of visual angle. This gave a 2 (Target Type: letter or symbol) × 2 (Crowding: isolated or flanked) × 2 (Visual Field: left or right) factorial design. For the purposes of the forced-choice task, each target character was pseudo-randomly paired with an alternative character and this combination was maintained in the different crowding and visual field conditions. The incorrect alternative presented for forced-choice was never a flanking character of the target. Each letter or symbol stimulus was presented eight times as a target (four times in isolation and four times between two flankers, equally divided between the two visual fields), giving a total of 144 trials. Each target stimulus also appeared eight times as a flanker, and eight times as an incorrect alternative in the forced-choice task. All factors were manipulated as within-participants factors, and all conditions were randomly mixed within the experiment.

Procedure. The experiment was run inside a dimly lit room and was controlled using E-Prime software (Psychology Software Tools, Inc., www.pstnet.com/eprime). Participants were seated in front of a computer screen at a viewing distance of approximately 60 cm. Stimuli were displayed in white on a black background, and were presented in 18-point Courier New font. Each character subtended 0.44° of visual angle, and the center-to-center spacing was 0.6°. Stimuli were exposed at 92 cd/m^2 luminance on a background luminance of 4 cd/m^2.

Participants first saw instructions and practiced the task during 20 trials, randomly chosen out of the stimulus list, to become familiarized with the stimuli and the procedure. Each trial began with two vertical fixation bars above and below the center of the screen. After 1,012 ms, the fixation bars disappeared and the stimulus (that consisted of either one or three characters) immediately appeared for a duration of 100 ms. This was followed by a backward mask in which the stimulus characters were replaced by hash marks (single hash mark for isolated targets, three hash marks for flanked targets). The mask was accompanied by two characters, presented above and below the position of the target. Participants had to decide which of these two characters had been present in the corresponding position of the preceding array (two-alternative forced-choice, 2AFC). They were asked to respond as accurately as possible by pressing one of two keys on the keyboard. They had to choose either the upward arrow key (for the alternative above), or the downward arrow key (for the alternative below). After the response, the screen was cleared, and the two fixation bars appeared again on the screen, introducing the next trial. The participants could take a short break after half of the trials. The experiment lasted approximately 15 min.

Results

Mean accuracies are presented in Table 1. A 2 (Target Type) × 2 (Crowding) × 2 (Visual Field) analysis of variance (ANOVA) was performed on the accuracy data. Performance to letter stimuli was slightly higher than performance to symbol stimuli, and this main effect of Target Type was significant in the participant analysis, $F_1(1, 23) = 21.25$, $p < .001$. There was a main effect of Crowding, $F_1(1, 23) = 159.84$, $p < .001$, $F_2(1, 16) = 81.60$, $p < .001$, with mean performance for targets in isolation at 90.1% compared with 71.8% for flanked targets. Most important, there was an interaction between Target Type and Crowding which was clearly significant in the analysis by participants, $F_1(1, 23) = 11.83$, $p < .01$, and approached significance in the analysis by items $F_2(1, 16) = 2.99$, $p = .103$. A significant crowding effect was found separately for symbols, $F_1(1, 23) = 156.44$, $p < .0001$, $F_2(1, 16) = 57.92$, $p < .001$ and for letters, $F_1(1, 23) = 67.82$, $p < .001$, $F_2(1, 16) = 26.67$, $p < .001$, but the size of this effect was greater for symbols than for letters, with respectively 22.7% and 15.4% decrease in performance in the presence of flankers. There was no effect of Visual Field, and no interactions with this factor.

Table 1
Percentage Correct in the Two-Alternative Forced-Choice Procedure of Experiment 1 for Letters and Symbols in the Left and Right Visual Field, and Either in Isolation or Flanked by Two Other Characters

	Accuracy (%)			
	Letters		Symbols	
Visual field	Isolated	Two flankers	Isolated	Two flankers
Left	91.4 (1.9)	74.1 (2.4)	89.4 (2.0)	67.8 (1.9)
Right	92.1 (2.1)	78.7 (2.2)	90.5 (1.7)	66.7 (2.6)

Note. *SE*s in parentheses.

Discussion

The results of Experiment 1 suggest that symbol targets are more affected by the presence of flanking stimuli than are letter targets. This result is all the more important given the fact that performance to isolated symbols and letters was very similar. Performance to both types of stimuli dropped in the presence of two flankers, independently of visual field, but this drop in performance was greater for symbol stimuli. This result is in line with Tydgat and Grainger's (2009) prediction that crowding effects should be greater for symbols than for letters.

However, Tydgat and Grainger's account of the differences in the serial position functions for letters and symbols, leads to one more precise prediction concerning crowding effects in letters and symbols. That is that letter stimuli should show greater release from crowding in the presence of a single flanking stimulus compared with the standard dual flanker situation. This was proposed in order to account for the greater outer position advantage (better identification of targets in the first and last positions in strings) found for letters than for symbols. Due to the relatively small integration fields of letter detectors, the presence of a single flanking character would generate little interference (see Figure 1). On the other hand, given their relatively large integration fields, symbol stimuli would suffer extensive interference from a single flanker. Experiment 2 tests this prediction by examining effects of a single flanker on performance to letters and symbols. We expect to exaggerate the difference in crowding effects for letters and symbols compared with Experiment 1.

Experiment 2

Method

Participants. Twenty-four students of the University of Provence, Marseille, volunteered to participate in the experiment. Their mean age was 21 years. Six were male, and all were native speakers and readers of French and reported having normal or corrected-to-normal vision. None had participated in the previous experiment.

Stimuli, design, and procedure. The stimuli and procedure were the same as in Experiment 1. The design was also similar, except that the isolated and double flanker conditions were replaced by two single flanker conditions. The target was either accompanied by a single character on the left side, or by a single character on the right side.

Results

A 2 (Target Type) × 2 (Flanker Position) × 2 (Visual Field) ANOVA was performed on the accuracy data. Percentage correct for each condition is shown in Table 2. The main effect of Target Type was significant, $F_1(1, 23) = 66.62$, $p < .001$, $F_2(1, 16) = 14.90$, $p < .01$. Performance was lower for symbol targets than for letter targets, with respectively 76.0% and 90.2% accuracy. There were no significant main effects of Flanker Position (left vs. right) or Visual Field, and there were no significant interactions.

Discussion

The results of Experiment 2 show that symbol stimuli are more subject to interference from a single flanking stimulus than letter stimuli, thus providing a further confirmation of the predictions of Tydgat and Grainger (2009). According to Tydgat and Grainger, letter stimuli would be less prone to interference from a single flanking stimulus than would be symbol stimuli, and this would be the cause of the greater release from crowding at the outer positions in strings for letter stimuli. On the basis of this account, we expect symbol stimuli to show crowding effects from a single flanker that are closer to the effects of double flankers than to the isolated flanker condition, whereas we expect letter targets to show crowding effects from a single flanker that are closer to the isolated target condition than the double flanker condition. A combined analysis of these conditions in Experiments 1 and 2 provides an initial investigation of this prediction.

Table 2
Percentage Correct in the Two-Alternative Forced-Choice Procedure of Experiment 2 for Letters and Symbols in the Left and Right Visual Field, and Either With a Flanker on the Left or on the Right of the Target Character

	Accuracy (%)			
	Letters		Symbols	
Visual field	Left flanker	Right flanker	Left flanker	Right flanker
Left	89.6 (1.8)	91.2 (2.7)	78.0 (2.6)	78.0 (2.8)
Right	89.6 (1.8)	90.5 (1.6)	75.0 (2.2)	72.9 (3.0)

Note. *SE*s in parentheses.

Combined Analysis of Experiments 1 and 2

Results

The results of Experiments 1 and 2 are plotted together in Figure 2. Two analyses were performed using a 2 (Target Type) × 2 (Crowding) × 2 (Visual Field) design. In the first analysis, the Crowding factor contrasted the isolated target condition of Experiment 1 and single flanker condition of Experiment 2. There were significant main effects of Target Type, $F_1(1, 46) = 52.76$, $p < .001$, $F_2(1, 16) = 6.05$, $p < .05$ and Crowding, $F_1(1, 46) = 14.40$, $p < .001$, $F_2(2, 32) = 42.26$, $p < .01$, and a significant Target Type × Crowding interaction, $F_1(1, 46) = 31.26$, $p < .001$, $F_2(2, 32) = 4.47$, $p < .05$. In the second analysis, the Crowding factor contrasted the single flanker condition of Experiment 2 and the double flanker condition of Experiment 1. Again, this analysis showed significant main effects of Target Type, $F_1(1, 46) = 87.17$, $p < .001$, $F_2(1, 16) = 6.05$, $p < .05$, and Crowding, $F_1(1, 46) = 31.09$, $p < .001$, $F_2(2, 32) = 42.26$, $p < .01$, and a significant interaction, $F_1(1, 46) = 4.14$, $p < .05$, $F_2(2, 32) = 4.47$, $p < .05$.

Discussion

The combined analysis of Experiments 1 and 2 suggests that letter stimuli indeed show the greatest release from crowding in the presence of a single flanking stimulus compared with the standard dual flanker situation. The difference between letter and symbol targets is exaggerated in the single flanker condition of Experiment 2 (14%) compared with the double flanker condition of Experiment 1 (9%). This result is in line with the predictions derived from Tydgat and Grainger's (2008) account of different serial position functions for letters and symbols. Identification of symbol targets is greatly affected by the presence of a single flanking stimulus, whereas letter identification is hardly affected at all. This therefore explains why outer letters (first and last position in strings) are identified better than interior letters, whereas symbols at the outer positions in strings are not identified better than at interior positions. Experiment 3 provides a further test of the predicted differential effects of single flankers on letter and symbol identification, while reducing stimulus exposure duration in order to remove any possible ceiling effects that might have occurred in Experiments 1 and 2.

Experiment 3

Method

Participants. Twenty students of the University of Provence, Marseille, volunteered to participate in the experiment. None had participated in Experiments 1 or 2. Their mean age was 22 years. Five were male, and all were native speakers and readers of French and reported having normal or corrected-to-normal vision.

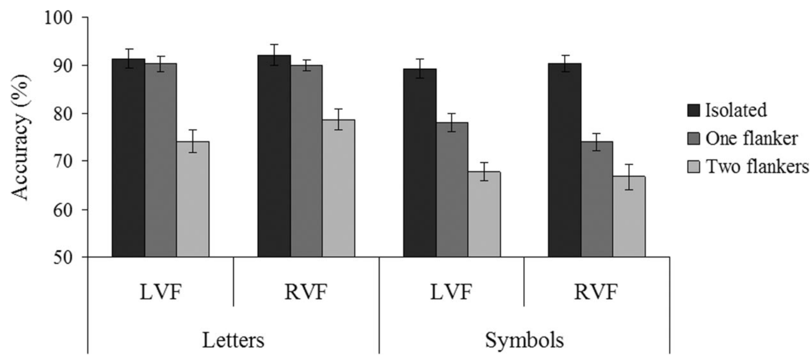

Figure 2. Percent correct in the two-alternative forced-choice procedure of Experiments 1 and 2 for letters and symbols in isolation, flanked by one character (averaged across left and right flankers) or flanked by two characters, in the left visual field (LVF) and right visual field (RVF). Stimulus duration was 100 ms, and vertical bars represent *SE*s.

Stimuli, design, and procedure. The design was a combination of Experiments 1 and 2, such that the Crowding manipulation now involved four levels. Targets were presented in isolation, with a single flanker to the left, a single flanker to the right, or with two flankers (one flanker on each side of the target). Stimuli were presented for 66 ms. Participants received 288 experimental trials. Otherwise the procedure was identical to the previous experiments.

Results

The results of Experiment 3 are shown in Figure 3. A 2 (Target Type) × 4 (Crowding) × 2 (Visual Field) ANOVA was performed on 2AFC accuracy in each condition. There was a main effect of Target Type in the participant analysis, $F_1(1, 19) = 51.47$, $p < .001$, but not in the item analysis. There was also a main effect of Crowding, $F_1(3, 57) = 29.84$, $p < .001$, $F_2(3, 48) = 24.88$, $p < .001$, and of Visual Field, $F_1(1, 19) = 6.11$, $p < .05$, $F_2(1, 16) = 9.22$, $p < .01$. The interaction between Target Type and Crowding was significant, $F_1(3, 57) = 6.31$, $p < .01$, $F_2(3, 48) = 3.60$, $p < .05$.

Follow-up analyses were performed separately for letters and symbols. A 4 (Crowding) × 2 (Visual Field) ANOVA for letters revealed a significant main effect of Crowding, $F_1(3, 57) = 20.08$, $p < .001$, $F_2(3, 24) = 19.09$, $p < .001$. Contrast analyses (collapsing data across the two single flanker conditions) further showed that performance to isolated letters was significantly higher than performance to single flanked letters, $F_1(1, 19) = 9.94$, $p < .01$, $F_2(1, 16) = 5.97$, $p < .05$, and performance to single flanked letters was significantly higher than to double flanked letters, $F_1(1, 19) = 25.03$, $p < .001$, $F_2(1, 16) = 13.71$, $p < .01$. There was also a main effect of Visual Field, $F_1(1, 19) = 5.26$, $p < .05$, $F_2(1, 8) = 5.29$, $p < .05$, and a significant Crowding x Visual Field interaction in the participant analysis, $F_1(3, 57) = 4.28$, $p < .01$. As can be seen in Figure 3, this interaction is driven by the different effects of the single flanker condition as a function of visual field. Indeed, when the analysis was restricted to these two crowding conditions (a 2 × 2 ANOVA), the Crowding × Visual Field interaction was still significant in the participant analysis, $F_1(1, 19) = 12.35$, $p < .01$, and now approached significance in the item analysis, $F_2(1, 8) = 4.23$, $p = .07$. Identification of target letters in the left visual field (LVF) was affected by flanker position (left vs. right), but not in the right visual field (RVF; see Figure 4).

The separate analysis (4 × 2 ANOVA) for symbols only revealed a significant main effect of Crowding, $F_1(3, 27) = 10.78$, $p < .001$, $F_2(3, 24) = 11.95$, $p < .001$. Performance to single

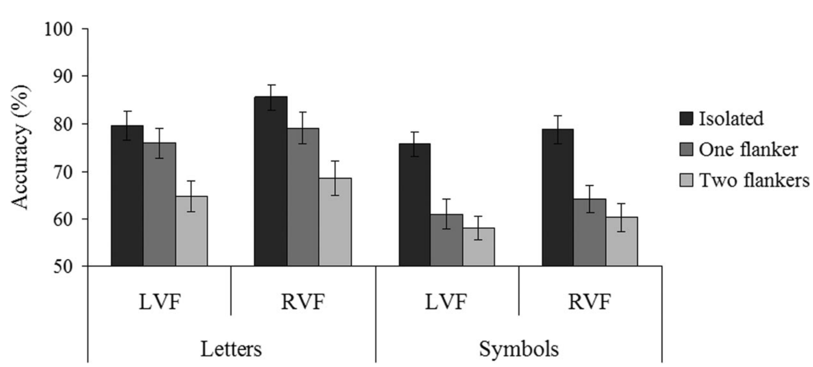

Figure 3. Percent correct in the two-alternative forced-choice procedure of Experiment 3 for letters and symbols in isolation, flanked by one character (averaged across left and right flankers), or two characters with one character at each side, in the left visual field (LVF) and right visual field (RVF). Stimulus duration was 66 ms, and vertical bars represent *SE*s.

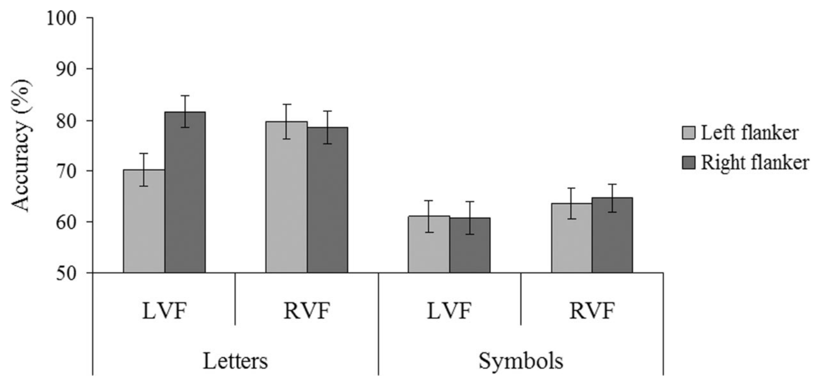

Figure 4. Percent correct in the two-alternative forced-choice procedure of Experiment 3 for letters and symbols flanked by one character on the left side, or flanked by one character on the right side, in the left visual field (LVF) and right visual field (RVF). Stimulus duration was 66 ms, and vertical bars represent *SE*s.

flanked symbols (collapsing across flanker position) did not differ significantly from performance to double flanked symbols, but was significantly lower than performance to isolated symbols, $F_1(1, 19) = 24.58$, $p < .001$, $F_2(1, 16) = 20.75$, $p < .001$.

Discussion

The results of Experiment 3 provide a direct replication of the combined results of Experiments 1 and 2. Symbol targets were more affected by crowding than were letter stimuli, and this was particularly evident in the single flanker condition. For symbol targets, performance with a single flanker did not differ significantly from the double flanker condition, while for letter targets performance in the single flanker condition was closer to the isolated target condition. This result is in line with Tydgat and Grainger's (2009) prediction that symbol targets presented in strings suffer practically maximum interference from a single flanking stimulus. Letters, on the other hand, show about half as much interference from a single flanker compared with double flankers.

One particularity of the results with letter targets is that there is a distinct asymmetry in the effects of flanker position (left vs. right) in the single flanker condition, and this asymmetry only appeared for letter targets presented in the LVF. No such asymmetry was apparent in Experiment 2, but this might be due to the overall higher level of performance to letter stimuli in that experiment (a ceiling effect). Indeed, prior research examining effects of single flanker stimuli with letter targets has shown such an asymmetrical effect, with stronger interference arising when the flanker appears in the peripheral position (to the left for stimuli presented to the left, and to the right for stimuli presented to the right), compared to flankers positioned on the foveal side of targets (Banks, Bachrach, & Larson, 1977; Banks, Larson, & Prinzmetal, 1979; Bouma, 1970; Chastain, 1982; Krumhansl & Thomas, 1976, 1977; White, 1981). There is also evidence from prior research that such asymmetrical crowding effects are stronger in the LVF than the RVF, at least in studies using letter stimuli (Krumhansl & Thomas, 1977; White, 1976). This was clearly the case in Experiment 3, where flanker position only affected performance to letter targets in the LVF. We return to discuss the relevance of this particular finding with respect to serial position functions for letters and symbols in the General Discussion.

Experiment 4

One possible limitation of the 2AFC task used in Experiments 1–3 is that it does not allow for location errors when a participant has identified the target but incorrectly reports the identity of a flanking stimulus (the flanking stimuli were never presented as a possible response). It is therefore possible that a partial report procedure, including such location errors, might produce a different pattern of results. Experiment 4 therefore tests the generality of the findings of Experiment 3 using a partial report procedure. The same stimulus exposure as Experiment 3 is used, plus a shorter duration, given that Tydgat and Grainger (2009) found that the partial report procedure generated a higher level of performance than 2AFC.

Method

Participants. Forty-one students of the University of Provence, Marseille, volunteered to participate in the experiment. None had participated in the previous experiments. Their mean age was 23 years. Seven were male, and all were native speakers and readers of French and reported having normal or corrected-to-normal vision.

Stimuli, design, and procedure. The procedure was identical to Experiment 3 except that the 2AFC task was replaced by a partial report bar-probe task, and presentation duration of the stimulus was either 50 ms or 66 ms (manipulated between-participants). The backward mask was accompanied by two hyphen marks positioned above and below one of the positions in the string (hence mimicking the position of the two alternative letters in the 2AFC procedure). Participants were asked to identify the character they had seen at this position by pressing one of 18 marked response keys (9 letters and 9 symbols) on the keyboard placed in front of them.

Results

The results of Experiment 4 are shown in Figures 5 and 6. A 2 (Stimulus Duration) × 2 (Target Type) × 2 (Visual Field) × 4

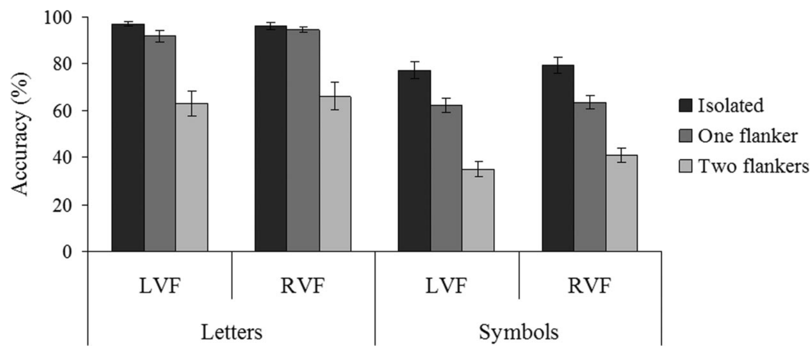

Figure 5. Percent correct in Experiment 4 (partial report bar-probe task) for letters and symbols in isolation, flanked by one character (averaged across left and right flankers), or double flanked with one character at each side, in either the left visual field (LVF) or right visual field (RVF). Vertical bars represent *SE*s.

(Crowding) ANOVA was performed on identification accuracy in each condition. There were main effects of Stimulus Duration, $F_1(1, 39) = 5.23$, $p < .05$, $F_2(1, 16) = 97.92$, $p < .001$, Target Type, $F_1(1, 39) = 203.72$, $p < .001$, $F_2(1, 16) = 22.71$, $p < .001$, Visual Field, $F_1(1, 39) = 8.67$, $p < .01$, $F_2(1, 16) = 2.04$, $p < .1$, and Crowding, $F_1(3, 117) = 195.11$, $p < .001$, $F_2(3, 48) = 98.80$, $p < .001$. Except for Stimulus Duration × Target Type, $F_1(1, 39) = 1.66$, $p = .21$, $F_2(1, 16) = 8.24$, $p < .05$, none of the interactions with Stimulus Duration approached significance.[2] The critical interaction between Target Type and Crowding was significant in the participants analysis, $F_1(3, 117) = 6.20$, $p < .001$, and approached significance in the item analysis, $F_2(3, 48) = 2.30$, $p < .1$, and Crowding significantly interacted with Visual Field, $F_1(3, 117) = 43.86$, $p < .001$, $F_2(3, 48) = 12.58$, $p < .001$. As can be seen in Figures 5 and 6, the pattern of crowding effects was different for letters and symbols, and effects of single flankers were different in the LVF and RVF. As in the previous experiments, separate analyses were performed for letter and symbol targets to investigate these interactions.

A 4 (Crowding) × 2 (Visual Field) ANOVA for letters revealed a significant main effect of Crowding, $F_1(3, 120) = 91.99$, $p < .001$, $F_2(3, 24) = 45.13$, $p < .001$. Contrast analyses (collapsing data across the two single flanker conditions) further showed that performance for isolated letters was significantly higher than for single flanked letters, $F_1(1, 40) = 20.61$, $p < .001$, $F_2(1, 8) = 8.03$, $p < .05$, and performance for single flanked letters was significantly higher than for double flanked letters, $F_1(1, 40) = 121.62$, $p < .001$, $F_2(1, 8) = 51.05$, $p < .001$. There was a significant interaction between Crowding and Visual Field, $F_1(3, 120) = 17.72$, $p < .001$, $F_2(3, 24) = 6.39$, $p < .01$. Figure 6 reveals that this interaction was driven by differences in the single flanker condition as a function of visual field. Contrast analyses revealed an asymmetrical effect of flanker position in the LVF, with greater interference from a left flanker (peripheral) compared with a right flanker (foveal), $F_1(1, 40) = 32.15$, $p < .001$, $F_2(1, 8) = 58.88$, $p < .001$. In the RVF, there was a trend toward greater interference from a right flanker (peripheral) compared with a left flanker (foveal), $F_1(1, 40) = 3.10$, $p < .1$, $F_2(1, 8) = 7.17$, $p < .05$.

The separate analysis (4 × 2 ANOVA) for symbols also revealed a significant main effect of Crowding, $F_1(3, 120) = 157.32$, $p < .001$, $F_2(3, 24) = 57.25$, $p < .001$. Performance for isolated symbols was significantly higher than for single flanked symbols, $F_1(1, 40) = 86.33$, $p < .001$, $F_2(1, 8) = 27.59$, $p < .001$, and performance for single flanked symbols was significantly higher than for double flanked symbols, $F_1(1, 40) = 203.75$, $p < .001$, $F_2(1, 8) = 116.58$, $p < .001$. There was a significant interaction between Crowding × Visual Field, $F_1(3, 120) = 27.19$, $p < .001$, $F_2(3, 24) = 6.77$, $p < .01$. Figure 6 reveals that this interaction reflects an asymmetrical effect of flanker position in both the left and right visual fields. Flankers in the outer (peripheral) position generated more interference than flankers in the inner (foveal) position for symbol targets in the left and right visual field, $F_1(1, 40) = 45.56$, $p < .001$, $F_2(1, 8) = 34.20$, $p < .001$, and $F_1(1, 40) = 13.29$, $p < .001$, $F_2(1, 8) = 4.99$, $p < .1$, respectively.

Error analyses. In the partial report task used in Experiment 4, errors can be classified as item errors—when the erroneous response is not one of the flanking characters, or location errors—when one of the flanking characters is reported instead of the target. A 2 (Error Type) × 2 (Target Type) × 2 (Visual Field) × 3 (Crowding) was performed. The isolated crowding condition was excluded from this analysis since errors in this condition were always item errors. The results broken down by Error Type are reported in Table 3. Of most relevance here is the significant

[2] To verify that the different pattern of crowding effects for letters and symbols was not being driven by a ceiling effect for letter targets, we performed an ANOVA introducing the performance level of our participants as a between participants variable. Participants were divided into two equal groups according to their average performance in the experiment (20 participants with the lowest performance in one group, and 20 participants with the highest performance in the other group, with 1 participant removed). Performance Level interacted with Crowding, $F_1(3, 114) = 5.06$, $p < .01$, $F_2(3, 48) = 6.91$, $p < .001$, and there was a significant Performance Level × Target Type × Crowding interaction, $F_1(3, 114) = 16.56$, $p < .001$, $F_2(3, 48) = 12.92$, $p < .001$. A separate ANOVA for the low-performance group was performed in order to remove the ceiling effect for letter targets that was driving these interactions. The results of the low-performance group largely mimicked the pattern of the whole group, with main effects of Target Type, $F_1(1, 19) = 107.42$, $p < .001$, $F_2(1, 16) = 25.86$, $p < .001$, and Crowding, $F_1(3, 57) = 101.22$, $p < .001$, $F_2(3, 48) = 71.44$, $p < .001$, and the critical Target Type × Crowding interaction was significant, $F_1(3, 57) = 10.62$, $p < .001$, $F_2(3, 48) = 4.38$, $p < .001$.

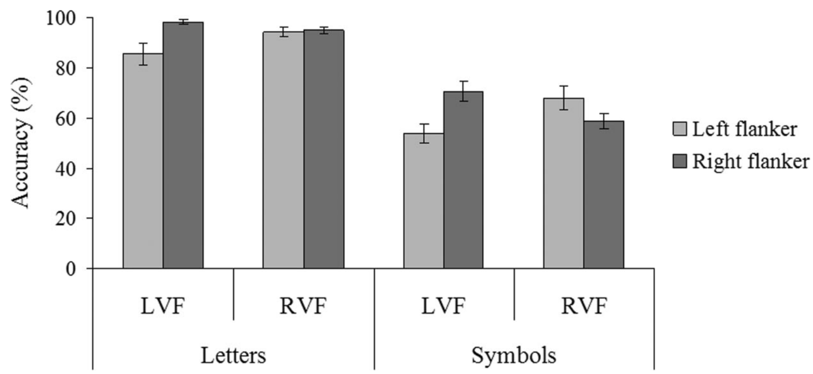

Figure 6. Percent correct in Experiment 4 (partial report bar-probe task), for letters and symbols flanked by one character on the left side, or flanked by one character on the right side, in either the left visual field (LVF) or right visual field (RVF). Vertical bars represent *SE*s.

interaction in the by participants analysis between Error Type, Target Type, Visual Field, and Crowding, $F_1(2, 76) = 3.80$, $p < .05$, $F_2(2, 32) < 1$. Follow-up analyses examined the results separately for each type of error.

A 2 (Target Type) × 2 (Visual Field) × 3 (Crowding) ANOVA on *location errors* revealed significant main effects of Target Type, $F_1(1, 40) = 53.16$, $p < .001$, $F_2(1, 16) = 10.42$, $p < .01$, and Crowding, $F_1(2, 80) = 153.72$, $p < .001$, $F_2(2, 32) = 124.49$, $p < .001$. The pattern of Crowding effects was quite similar for letter and symbol targets, with significant main effects of Crowding for both letters, $F_1(2, 80) = 78.95$, $p < .001$, $F_2(2, 16) = 58.78$, $p < .001$, and symbols, $F_1(2, 80) = 99.32$, $p < .001$, $F_2(2, 16) = 66.74$, $p < .001$, and a significant Visual Field × Crowding interaction for both types of target, $F_1(2, 80) = 10.37$, $p < .001$, $F_2(2, 16) = 1.15$, $p = .34$, and $F_1(2, 80) = 11.23$, $p < .001$, $F_2(2, 16) = 4.27$, $p < .05$, respectively. For letters, this interaction reflected an asymmetrical effect of flanker position in the LVF—with greater interference from a left flanker (peripheral) compared with a right (foveal) flanker, $F_1(1, 40) = 15.80$, $p < .001$, $F_2(1, 8) = 39.76$, $p < .001$—and no asymmetrical effect in the RVF. For symbol targets, flankers in the outer (peripheral) position generated more interference than flankers in the inner (foveal) position in both the left and right visual field, $F_1(1,40)=5.01$, $p < .05$, $F_2(1, 8) = 16.29$, $p < .01$, and $F_1(1, 40) = 17.04$, $p < .001$, $F_2(1, 8) = 9.78$, $p < .05$, respectively.

A 2 (Target Type) × 2 (Visual Field) × 3 (Crowding) ANOVA on *item errors* revealed significant main effects of Target Type, $F_1(1, 40) = 120.26$, $p < .001$, $F_2(1, 16) = 25.83$, $p < .001$, Visual Field, $F_1(1, 40) = 14.91$, $p < .001$, $F_2(1, 16) = 4.98$, $p < .05$, and Crowding, $F_1(2, 80) = 31.13$, $p < .001$, $F_2(2, 32) = 9.37$, $p < .001$. The significant two-way interaction between Target Type and Crowding, $F_1(2, 80) = 8.70$, $p < .001$, $F_2(2, 32) = 3.01$, $p < .1$, reflects the fact that letter targets showed a large difference between the single and double flanker conditions, $F_1(1, 40) = 47.62$, $p < .001$, $F_2(1, 8) = 15.69$, $p < .01$, whereas this difference was not significant for symbols. There was a significant interaction between Visual Field and Crowding, $F_1(2, 80) = 23.02$, $p < .001$, $F_2(2, 32) = 8.65$, $p < .001$, which did not interact with Target Type. For both letters and symbols this interaction reflects an asymmetrical effect of flanker position in the LVF—with greater interference from a left (peripheral) flanker compared with a right (foveal) flanker, $F_1(1, 40) = 19.82$, $p < .001$, $F_2(1, 8) = 22.15$, $p < .01$ for letters, and $F_1(1, 40) = 29.66$, $p < .001$, $F_2(1, 8) = 16.61$, $p < .01$ for symbols, while there was no effect of flanker position in the RVF for either letters or symbols.

Discussion

The results of Experiment 4 provide a straightforward replication of the results of Experiment 3 with a partial report bar-probe procedure replacing 2AFC. Crowding was once again found to

Table 3
Results Broken Down by Type of Error in Experiment 4

	Letters			Symbols		
Visual field	Left flanker	Right flanker	Two flankers	Left flanker	Right flanker	Two flankers
			Location errors			
Left	93.5 (1.6)	98.8 (0.5)	79.9 (2.5)	89.7 (1.4)	93.2 (1.2)	67.2 (2.1)
Right	97.8 (0.6)	96.9 (0.9)	76.6 (2.7)	93.0 (1.6)	85.5 (1.3)	70.1 (2.1)
			Item errors			
Left	88.5 (2.2)	97.3 (0.8)	78.6 (2.4)	58.1 (3.2)	71.3 (3.2)	61.0 (2.7)
Right	95.3 (1.2)	92.3 (2.1)	84.3 (1.8)	69.2 (3.1)	68.3 (2.9)	66.8 (2.8)

Note. Data are percentage correct target identification when counting only location errors (upper panel) or only item errors (lower panel), with *SE*s in parentheses.

have a different effect on the identification of letters compared with symbol stimuli. However, in Experiment 4 the critical Crowding × Target Type interaction was mostly driven by the differential effects of single flankers compared with the isolated target condition. In line with the results obtained with 2AFC, symbol targets were more affected by the presence of a single flanker than were letter targets. This result was particularly marked in the item errors, when a character other than the target or the flankers was reported. When counting only such item errors, there was no difference in performance to symbol targets with single or double flankers, while letter targets showed significantly more item errors with double flankers than single flankers. These results provide further support for Tydgat and Grainger's (2009) hypothesis that the outer position advantage found for letters compared with symbols in target-in-string identification is because of differential crowding effects from single flankers.

There were some other notable differences in the pattern of results obtained in the bar-probe partial report procedure of Experiment 4 compared with 2AFC in Experiment 3 (remember that the experiments were otherwise identical except for the use of an additional shorter stimulus duration). First, performance to isolated symbol stimuli was significantly lower than to isolated letters in Experiment 4. As noted in our presentation of the 2AFC procedure, this might be because the 2AFC procedure reduces possible differences due to category set size, which would endow an advantage for the closed-set category of letter stimuli relative to the open-set category of symbols. Second, Experiment 4 showed a significant decrement in performance in the double flanker condition compared with the single flanker condition for both letters and symbols, whereas in Experiment 3 this was not the case for symbol stimuli. This pattern actually fits very well with the variation in serial position functions found by Tydgat and Grainger (2009) as a function of type of report (2AFC vs. partial report). The serial position function for symbol stimuli became slightly W-shaped (with a significant quadratic component) in the partial report procedure, whereas a systematic inverted U-shaped function (with no quadratic component) was always found with the 2AFC procedure. The results of Experiment 4 of the present study suggest that this could be because of the increased effect of number of flankers (single vs. double) for symbol stimuli in the partial report procedure compared with 2AFC. The 2AFC task removes location errors (since the two alternatives were never a flanking character), and it was such location errors that were found to be driving the difference between the single and double flanker conditions for symbol targets. Finally, the effects of flanker position in the single flanker condition with symbol targets showed a different pattern in Experiment 4. While letter targets continued to show stronger interference from peripheral flankers in the LVF, symbol targets now showed this asymmetric effect in both visual fields (where there was no effect of flanker position in Experiment 3).

Experiment 5

The differential effects of crowding for letters and symbols found in Experiments 1 through 4 could be driven by differences in visual complexity across these two types of stimuli. Although Pelli et al. (2007) have argued that crowding should not depend on anything else but stimulus eccentricity, there is some evidence for an influence of stimulus complexity on crowding (e.g., Põder, 2008). Therefore, to test for a possible role of stimulus complexity in Experiments 1 through 4, we first calculated the complexity of all individual letters and symbols used in these experiments. To this end, we computed the perimetric complexity and the stroke frequency of each of our letter and symbol stimuli (Pelli, Burns, Farell, & Moore-Page, 2006). Because we are comparing small subsets of stimuli in our experiments, instead of whole alphabets as in Pelli et al. (2006), we adopted the stroke frequency calculation proposed by Zhang, Zhang, Xue, Liu, and Yu (2007) for Chinese characters. This involves drawing multiple horizontal, vertical and oblique slices through each stimulus and counting the number of the times these strokes cross a line in the stimulus, giving a mean stroke frequency per stimulus. We adapted their method for our letters and symbols using 3 horizontal and 3 vertical slices. These three slices were drawn at respectively 25%, 50%, and 75% of the total width and height. T-tests revealed that the letters and symbols used in Experiments 1 through 4 did not differ significantly with respect to either stroke frequency ($p = .48$) or perimetric complexity ($p = .28$).[3]

As a further test of any possible role for stimulus complexity, Experiment 5 uses a new set of letter and symbol stimuli selected to be more closely matched on these measures of visual complexity. Furthermore, Experiment 5 applies a target-flanker spacing manipulation in order to measure critical spacing values for letter and symbol stimuli.

Method

Participants. Twenty-nine students of the University of Provence, Marseille, volunteered to participate in the experiment. None participated in any of the prior experiments. Their mean age was 22 years. Fourteen were female, and all were native speakers and readers of French and reported having normal or corrected-to-normal vision.

Stimuli and design. The experiment consisted of 2 (Target Type) × 2 (Visual Field) × 5 (Spacing) conditions. All variables were manipulated within-subjects. Ten letter and ten symbol targets were selected on the basis of their scores on two measures of visual complexity. The letter stimuli were lowercase consonants (c, f, g, h, m, s, p, v, w, z) and the symbol set contained both keyboard symbols and non-keyboard symbols (Σ, <, Ψ, &, @, £,

[3] To provide a further test of the role of visual similarity in driving the different effects of crowding for letters and symbols we selected a subset of 7 letters (D, F, G, L, N, S, T) and 7 symbols (%, ?, @, <, £, §, μ) that were very closely matched on our measures of visual complexity. We chose to re-analyze the results of Experiment 3 with this subset of stimuli, since this Experiment was not subject to possible ceiling effects, and the subset of stimuli for re-analysis produced higher levels of performance than the complete set. A 2 (Target Type) × 4 (Crowding) ANOVA was conducted by participants. Overall accuracy was the same for symbols and letters (74%). There was a main effect of Crowding, $F(3, 57) = 33.49$, $p < .001$, and a significant Target Type × Crowding interaction, $F(3, 57) = 5.50$, $p < .01$. Follow-up analyses revealed a significant difference between the isolated and the single flanker condition only for symbols, $F(1, 19) = 15.66$, $p < .001$, and a significant difference between the single flanker and two flankers conditions only for letters, $F(1, 19) = 7.84$, $p < .05$. This analysis establishes different effects of crowding for letters and symbols in conditions where overall performance is matched, and both ceiling and floor effects are avoided.

∞, λ, Π, ♂). We computed perimetric complexity and mean stroke frequency for both sets of stimuli (see description of these measures in the preceding section). The two types of stimuli did not differ significantly on either of these measures ($p > .75$). Target-to-flanker separation (Spacing) was measured as the center-to-center distance in visual angle. Each target appeared in the five spacing conditions and in both visual fields. Target stimuli were always the central character of the trigram. Two characters from the same stimulus category as the target were randomly assigned to each target and functioned as flankers. Trials were divided into two experimental blocks such that each target appeared at all five spacing conditions in each block and either in the right or left visual field (half of the targets in the RVF and half in the LVF). Visual field location of each target was therefore counterbalanced across blocks, and presentation of the trials was randomized within each block, with a total of 100 trials per block.

Procedure. Viewing distance, font, luminance, stimulus size and fixation duration were identical to the previous experiments. After receiving the instructions, participants completed a practice block of 20 trials. Subsequently, the experimental phase started. Stimuli were presented in the right or left visual field at an eccentricity of 3°. On the basis of a pilot study conducted with 20 participants, stimulus duration was set at 80 ms (well below durations that would allow eye movements to the target), and the target-flanker separations were chosen to be 0.5°, 0.9°, 1.3°, 1.7° and 2.1°. Stimuli were presented in black on a white background at the same luminance values as the previous experiments, and were followed immediately by a blank screen, which lasted until a response was triggered. Participants responded to the target by choosing the corresponding key on the keyboard among the 20 alternatives (10 letters and 10 symbols). They were instructed to respond on every trial, and the next trial began after participants' response. The participants could take a short break at the end of the first block. The experiment lasted approximately 15 min.

Results

Two participants were excluded from the analysis because of failure to follow the instructions. A 2 (Target Type) × 2 (Visual Field) × 5 (Spacing) ANOVA was performed on the data for identification accuracy in each condition. The main effect of Target Type was significant in the participant analysis, $F_1(1, 26) = 17.32$, $p < .001$, $F_2(1, 18) = 0.73$, $p = .40$, reflecting a higher overall accuracy for letters (82.6%) than for symbols (76.7%). There was a main effect of Spacing, $F_1(4, 104) = 172.33$, $p < .001$, $F_2(4, 74) = 34.59$, $p < .001$. Mean accuracies ranged from 58.9% in the smallest spacing condition to 91.3% in the largest spacing condition. There was a main effect of Visual Field, $F_1(1, 26) = 30.10$, $p < .001$, $F_2(1, 18) = 7.36$, $p < .05$, with higher levels of performance for targets presented in the RVF. Most important is that the Target Type × Spacing interaction was clearly significant in the participant analysis, $F_1(4, 104) = 10.70$, $p < .001$ and marginally significant in the item analysis, $F_2(4, 72) = 2.06$, $p < .10$. As can be seen in Figure 7, the interaction reflects the decreasing difference in identification scores for letters and symbols as spacing increases. None of the other interactions were significant (Table 4).

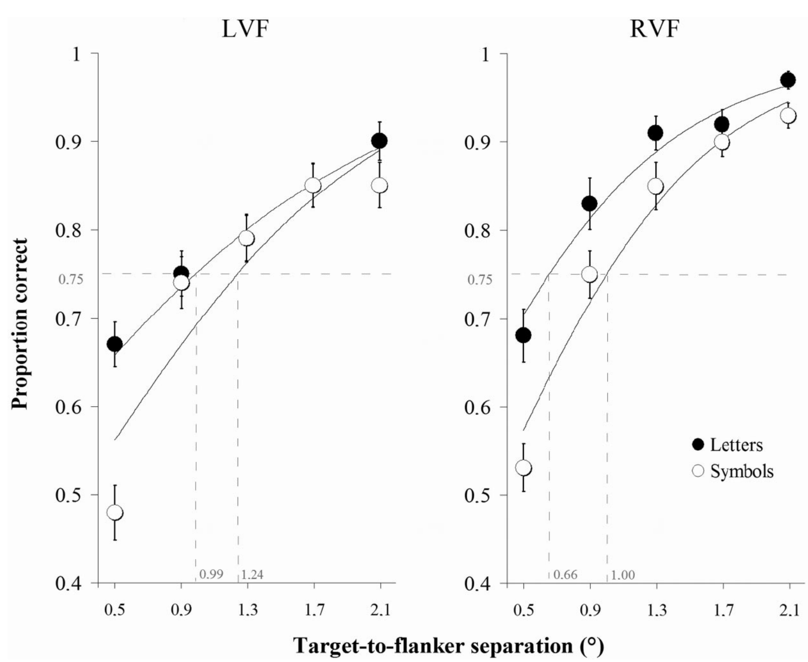

Figure 7. Proportion correct target identification plotted as a function of target-to-flanker spacing (visual angle in degrees), in both the left visual field (LVF, left panel) and the right visual field (RVF, right panel) in Experiment 5. Fitted curves are cumulative-Gaussian functions. Critical spacing is defined as the target-to-flanker spacing at which the proportion correct is equal to 0.75 (indicated with dotted lines and values shown above the *x*-axis). Vertical bars represent *SE*s.

Table 4
Percentage Correct Identification of Letter and Symbol Targets in Experiment 5 for the Different Target-to-Flanker Spacing Conditions and for Both Visual Fields

	Accuracy (%)			
	LVF		RVF	
Spacing (°)	Letters	Symbols	Letters	Symbols
0.5	66.8 (2.5)	47.8 (3.1)	68.3 (3.0)	52.6 (2.7)
0.9	74.7 (2.5)	73.8 (2.9)	83.3 (2.9)	74.7 (2.7)
1.3	78.9 (2.6)	79.4 (2.7)	90.5 (1.9)	85.2 (2.7)
1.7	84.5 (2.5)	84.9 (2.4)	92.5 (1.7)	89.9 (1.7)
2.1	90.1 (2.2)	85.2 (2.6)	96.6 (1.0)	93.2 (1.4)

Note. LVF = left visual field; RVF = right visual field. *SE*s in parentheses.

Critical spacing values for letters and symbols were calculated by fitting a cumulative Gaussian function to the proportion correct scores as a function of target-flanker distance for each participant and each condition of the Target Type and Visual Field factors. We then calculated the value for target-to-flanker spacing that corresponded to a pre-defined criterion level of 75% accuracy. These scores per Target Type and Visual Field were entered in a by-participant ANOVA. The critical spacing was significantly smaller for letters (0.82°) than for symbols (1.12°), $F(1, 26) = 5.93$, $p < .05$. Furthermore, there was a significant main effect of Visual Field, $F(1, 26) = 6.65$, $p < .05$, reflecting a larger critical spacing in the LVF (1.12°), compared with the RVF (0.83°). Although Figure 7 reveals that the difference between letters and symbols is numerically greater in the RVF, the interaction between Target Type and Visual Field was not significant.

Discussion

Experiment 5 applied a critical spacing manipulation whereby character triples were presented with varying levels of intercharacter spacing in order to establish the spacing required to attain a criterion level of correct identification of the central target. Stimuli were presented at a fixed eccentricity (3°) along the horizontal meridian in either the LVF or RVF. The results are clear-cut. Critical spacing values were found to be significantly greater for symbols than for letters. Criterion levels of letter identification were reached with a smaller inter-character spacing compared with the spacing required to attain the same level of performance with symbol stimuli. These results suggest once again that crowding affects letters and symbols differently, at least for the eccentricities and locations tested in the present study.

General Discussion

The results of the present study can be summarized as follows.

(1) Flanking stimuli interfere more strongly in the identification of symbol targets than letter targets in a standard crowding manipulation with eccentrically located targets (left and right of a central fixation point).

(2) This differential crowding effect was found with a 2AFC procedure in Experiments 1 through 3, a partial-report bar-probe procedure in Experiment 4, and using a critical spacing manipulation in Experiment 5.

(3) In Experiments 1 through 4, letter stimuli showed very little interference from single flankers compared with the isolated condition, while symbol targets always showed sizeable interference from single flankers.

(4) Visual field influences on crowding effects were seen with letter targets and single flankers in Experiments 2 through 4, where identification of targets in the left visual field was hurt more by a leftward flanker than a rightward flanker.

(5) Post-hoc analyses allowed us to exclude a possible role for stimulus complexity in driving the observed differences in crowding effects for letters and symbols, and this factor was explicitly controlled for in Experiment 5.

The experiments of the present study were designed to test the predictions derived from a recent account of serial position functions found for letter and symbol stimuli (Tydgat & Grainger, 2009). In certain conditions, letter stimuli showed a clear advantage for the first and last positions of the string that was not found with symbol stimuli. Because one classic interpretation of the shape of the serial position function found for letters is in terms of reduced crowding at these external positions (e.g., Bouma, 1970; Estes, 1972), Tydgat and Grainger suggested that symbol stimuli might be affected differently by crowding. More precisely, a single flanking stimulus might be sufficient to generate almost maximal crowding effects with such stimuli, hence the lack of reduction in crowding effects at the outer positions. In other words, letter stimuli benefit from a greater release from crowding at the outer positions than do symbol stimuli.

The results of the present study confirm the predictions derived from this "crowding" interpretation of the different serial position functions found for letter and symbol stimuli. In all experiments, target letters were found be more prone to crowding than were symbol targets. This was found to be the case in Experiments 1 through 4 using the classic flanker paradigm and the same letter and symbol stimuli as Tydgat and Grainger placed at the same location as the first and last positions of the five-character strings tested in their experiments. Post-hoc analyses strongly suggested that the different effects of crowding for letters and symbols could not be attributed to differences in stimulus complexity across these two types of stimuli. Experiment 5 provided a further confirmation of greater crowding with symbols than letters using a new set of stimuli matched for visual complexity, and applying a critical spacing manipulation with targets located at greater eccentricities than in Experiments 1 through 4. Critical spacing was found to be smaller for letters than for symbols, with letter targets being identified more accurately than symbol targets at the lowest levels of intercharacter spacing.

Relative to the predictions of Tydgat and Grainger (2009), it is important to note that in Experiments 1 through 4, target letters were found to be practically immune to the present of a single flanker compared with the isolated target condition. Symbol targets, on the other hand, were systematically affected by the presence of a single flanker, with significantly lower levels of identification compared with the isolated target condition. The outer-position advantage found for letter stimuli but not for symbol stimuli in the target-in-string identification paradigm would therefore be due to the reduction in crowding from single flankers at the outer positions in strings that occurs more for letters than for symbols.

Mechanisms of Crowding

The fact that crowding was found to be affected by stimulus type in the present study would appear to contradict purely bottom-up accounts of this phenomenon (e.g., Pelli & Tillman, 2008; Pelli et al., 2004, 2007), and be more in line with accounts that appeal to top-down mechanisms such as spatial attention (e.g., He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001). However, our preferred interpretation of the present results appeals uniquely to bottom-up mechanisms, whose operation can vary as a function of stimulus type via off-line as opposed to on-line influences. These off-line influences of stimulus type involve differences in perceptual learning driven by differential exposure to the different types of stimuli.

We follow other authors in proposing excessive feature integration as one key mechanism in crowding (Huckauf & Heller, 2002; Pelli et al., 2004, 2007). In doing so, we follow Pelli and colleagues (Pelli et al., 2004, 2007) and Levi (2008) as describing crowding as a bottleneck for object recognition that occurs during the mapping of visual features onto object representations. In this account, it is the large overlapping structure of integration fields that causes crowding (see Figure 1). When a flanking stimulus falls within the integration field of the target, features from that stimulus are incorrectly integrated with the features of the target, hence interfering with target identification. Here we briefly present an extension of this general account of crowding that postulates some specific mechanisms that might be driving the interference. Our model of crowding is shown in Figure 8. This model combines knowledge from research on crowding, as reviewed by Levi (2008), and our own research on character string processing and letter perception that was the motivation behind the present study. It can be thought of as a specific implementation of the general two-stage model of crowding described by Levi (2008).

Overlapping integration fields are implemented within a generic interactive-activation framework for object identification (McClelland & Rumelhart, 1981), illustrated here for the specific case of letter stimuli. There are two ways that flankers can inhibit target identification in this model: (1) between-level feature-object inhibition, and (2) within-level object-object inhibition. Any inappropriate feature that falls in the integration field of a given letter detector will inhibit the activity of that letter detector via bottom-up feature-object inhibition. This same feature can also contribute to activation in a different letter detector, and thereby further inhibit activity in the correct letter detector via within-level object-object inhibition. Figure 8 shows two versions of our interactive-activation model of crowding, one that includes bottom-up feature-object inhibition (left panel), and one without (right panel). The version without bottom-up inhibition is proposed in the light of recent evidence suggesting the absence of such a mechanism in foveal letter perception (Rey, Dufau, Massol, & Grainger, 2009). However, it is not clear how a model without such bottom-up inhibition could account for the stronger interference generated by pseudo-letter flankers compared with letter flankers on target letter identification, a finding reported by Huckauf, Heller, and Nazir (1999).

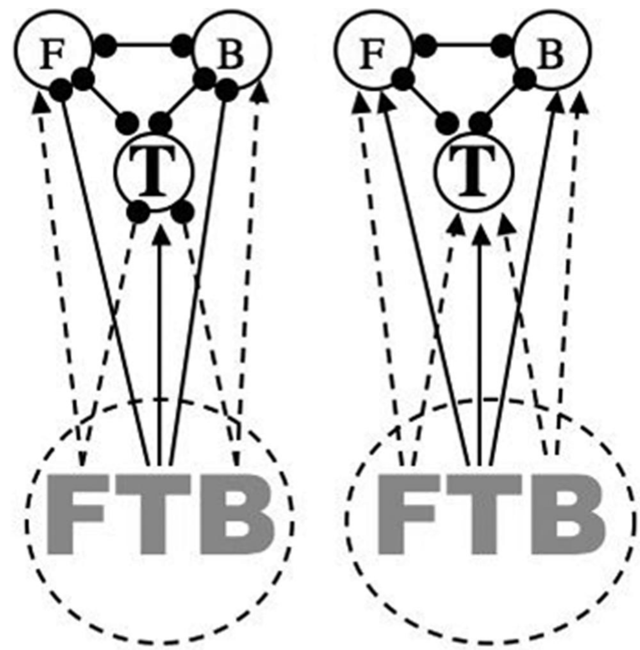

Figure 8. An interactive-activation model of crowding. A target (T) and two flanking stimuli (F, B) fall within a large peripheral integration field. Features extracted at the first layer (large grey letters) send activation to letter detectors that compete for identification of a single letter at that location (small black letters with lateral inhibitory connections indicated by small filled circles). Strength of feature-letter excitation and inhibition is depicted by full (stronger) versus dashed (weaker) lines. The left-hand panel shows a version of the model that incorporates bottom-up feature-object inhibition, and the right-hand panel a version with no bottom-up inhibition. The model on the right further illustrates the possibility that features of the target can also be compatible with the flanker stimuli, and vice versa.

The effect of flanker similarity can be explained in this framework as increased within-level (object-object) inhibition caused by the target stimulus providing bottom-up support for the similar flanker. This is illustrated in the right panel of Figure 8, where connections from the target letter feed activation into the letter detectors corresponding to the flanker stimuli. Furthermore, given the evidence that more similar flankers generate stronger crowding, it is clear that the differential effects of crowding on letters and symbols found in the present study cannot be interpreted in terms of different levels of visual similarity between targets and flankers. Our letters are arguably visually more similar to each other than our symbol stimuli, so any effects of target-flanker similarity would be acting against our hypothesis that symbols are subject to greater levels of crowding than letters.

Why did the number of flankers (one or two) not have additive effects with symbol targets in our study? This result fits our model of crowding according to which part (if not all) of the interference from flanker stimuli is generated by competing object representations (see Kalarickal & Marshall, 1999, for such a model of receptive-field dynamics). The dynamics of lateral inhibition in an interactive-activation model, in which all activated object representations are in competition, are such that a single strong competitor can be just as effective (in terms of target-directed inhibition) as several weaker competitors (see Grainger & Jacobs, 1996, for an example of such nonlinearities in lateral inhibition for word stimuli). This can therefore account for why a single flanker can be just as effective as two flankers, when these fall entirely within the integration field of the target.

Crowding and Reading Development

Why are letters less sensitive to crowding than symbols? The answer to this question is very likely related to the extensive experience that we have, as skilled readers, in processing strings of letters compared with strings of symbols. Tydgat and Grainger (2009) hypothesized that when children learn to read they develop a specialized system that is custom built to handle the very specific nature of written words (see McCandliss, Cohen, & Dehaene, 2003, for one version of this hypothesis). Most notably, this system would develop in order to optimize processing in the extremely crowded conditions that arise with printed words, compared with other visual objects that do not typically occur in such a cluttered environment. One way to achieve such optimization is to establish a bank of letter detectors that enable parallel independent identification of letters in a string (Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger et al., 2006; Grainger & van Heuven, 2003). Because these letter detectors are designed to identify a given letter at a relatively precise location in space, they do not require the relatively wide integration fields necessary to achieve location invariance in object recognition. A reduction in the integration field size of these letter detectors could be the mechanism responsible for the reduced effects of crowding found with letter stimuli compared with symbols. This was the central hypothesis tested and supported by the results of the present study, and illustrated in Figure 1 in the introduction.

Some additional support for this hypothesis was provided by Atkinson, Anker, Evans, Hall, and Pimm-Smith (1988), who found greater crowding effects with letter targets and a combination of horizontal and vertical flankers in 3- to 4-year-old children compared with 5- to 7-year-old children. More recent research examining the development of reading fluency provides further support for this hypothesis. Kwon and Legge (2006) found that crowding effects were stronger in children than adults. Furthermore, Kwon, Legge, and Dubbels (2007) found a strong correlation between the development of reading speed and the size of the visual span (number of letters that can be identified without eye movements). Because Pelli et al. (2007) have shown that crowding is the critical factor determining the size of the visual span, one can again conclude that reduced crowding in letter strings is a key factor at play in the development of reading fluency.

Finally, there is research showing that crowding can be modified by training. Huckauf and Nazir (2007) reported that training participants to identity targets surrounded by two flankers reduces the effects of crowding, but mostly for the specific stimuli, eccentricities, and spacing used during training. Their results suggested that more extensive training might be necessary to observe greater levels of transfer to untrained stimuli. This was done by Chung (2007), who trained observers to identify target letters flanked by two other letters with pretest and posttest phases separated by 6,000 training trials. The results of Chung's study showed that training produced a large improvement in letter identification accuracy accompanied by an equally large reduction in critical spacing (the inter-letter spacing allowing 50% correct target identification). However, given the huge exposure to letter strings of the average adult participant in the above-cited studies, it seems unlikely that even extensive training as in Chung's study, is having the same influence as years of exposure to print. What is missing at present is a developmental investigation of crowding effects from pre-readers to skilled readers. We hypothesize that the integration fields of letter detectors decrease in size during the process of learning to read. Therefore, a measure of critical spacing for letter trigrams (e.g., Chung, 2007; Pelli et al., 2007) should reveal a gradual decrease in the size of integration fields as a function of reading age.

A possible neurophysiological correlate of such developmental changes in orthographic processing is the N1 or N170 ERP component. Maurer et al. (2006) measured N1 activity in kindergarten pre-readers and the same children after 2 years of reading instruction (grade 2). The children were presented with words, pseudowords, and strings of symbols. They found a significant increase in N1 amplitude to word stimuli as a function of reading experience, and no such developmental change for symbol strings. Furthermore, the difference in N1 amplitude for words and symbols correlated significantly with a measure of reading fluency in second grade.

Finally, in future research it will be important to investigate differences in crowding effects to letter and digit stimuli, as well as other types of non-alphanumeric stimuli. Tydgat and Grainger (2009) showed identical serial position curves with letter and digit strings, both showing the classic W-shaped curve that was significantly different from the inverted U-shaped curve found for strings of symbols. In the light of the present results, this would suggest that digit stimuli benefit from the same reduction in crowding as letter stimuli due to similar conditions of exposure to these stimuli as strings of elements (i.e., multi-digit numbers). Nevertheless, some developmental differences between letters and digits might be expected given the different amounts of exposure to these two types of stimuli, and differences in the average length of words and numbers.

Asymmetrical Crowding and the Initial Position Advantage

In their analysis of differences in the serial position functions for letters and symbols, Tydgat and Grainger (2009) observed a systematic advantage for the initial position of strings of letters compared with symbols. While the advantage for the final position in letter strings was found to depend on masking conditions, the advantage for the initial position was robust across all conditions for letters, and was never present for symbols. This suggests that the initial position of strings of letters benefits from an additional advantage over and above that of reduced crowding via smaller integration field size. In an attempt to provide an integrated account of the complete pattern of effects found in their study, Tydgat and Grainger proposed that not only does the size of integration fields of location-specific letter detectors change with exposure to printed stimuli, but that there is also a change in the shape of these integration fields.

According to Tydgat and Grainger (2009), the hypothesized change in shape of integration fields would arise in order to optimize processing at the first position in strings of letters and digits. Letters in the first position tend to provide more constraint on lexical identity than any other position in the string (e.g., Clark & O'Regan, 1999; Grainger & Jacobs, 1993). Furthermore, the first position is critical for translating an orthographic code into a phonological code, since the correct graphemes (letters and letter clusters corresponding to a phoneme) can only be computed with precise order information (Perry, Ziegler, & Zorzi, 2007). Such optimization can be achieved by asymmetric integration fields that are elongated in the direction of the initial position (i.e., to the left for languages read from left-to-right). Letter detectors with integration fields of this shape will mostly suffer interference from characters immediately to their left, hence endowing an advantage for the initial position in strings. We further hypothesized that such optimization only operates for stimuli that are fixated, and therefore only for detectors receiving input from the LVF.

This hypothesized visual-field specificity of the shape of integration fields for letter detectors accounts for why in Experiments 3 and 4 letter targets presented to the left of fixation showed asymmetrical crowding effects with single flankers, whereas letter targets presented to the right of fixation did not. Target letters presented in the LVF showed stronger crowding from a single flanker on their left, compared with the right. This is the equivalent of an advantage for letters at the first position of a string of two letters. This is exactly the pattern predicted by an elongation of integration fields to the left for letter detectors in the LVF. Such letter detectors suffer more interference from flankers falling to the left of the target than flankers falling to the right. Furthermore, the results of Experiment 5 showed that critical spacing values were greater in the LVF than the RVF, and although the interaction between visual field and target type was not significant, the difference between letters and symbols was numerically smaller in the LVF. Because targets in Experiment 5 were always accompanied by two flankers (applying the standard critical spacing manipulation), this pattern is again in line with a hypothesized elongation of integration fields in the LVF.

Bouma (1973) was among the first to report visual field differences in letter identification in unpronounceable nonwords (note that only the first and last positions were tested in Bouma's study). For a fixed eccentricity, there was a strong advantage for initial over final position in the LVF which diminished and even reversed (final position superior to initial position) in the RVF. This led Bouma to suggest that ". . . the spatial extent of foveally oriented masking is smaller in the R field than the Left" (p. 775). This is in fact an alternative version of the present hypothesis. Indeed, there is a general consensus in favor of an inward-outward anisotropy in crowding effects for various types of stimuli (see Levi, 2008, for review, and Petrov & Popple, 2007, for an example), and the effects of single flankers with symbol targets in the partial report task of Experiment 4 of the present study fits this general pattern. This would suggest that in general (i.e., for different types of stimuli) integration fields are elongated to the left in the LVF and to the right in the RVF (Bouma, 1978). However, our results suggest that the asymmetric effects found for symbol targets in the RVF are driven primarily by location errors in the partial report task, and this might explain the absence of such effects in the 2AFC task (because the two alternatives were never a flanking character). It might also be possible that stronger asymmetries would arise with greater target eccentricities than tested in the present study. The pattern found for letter targets, on the other hand, did not depend on task, with a systematic effect of flanker position arising in the LVF and not in the RVF. This is in line with prior observations that the asymmetrical effects of single flankers are stronger in the LVF for letter stimuli (Krumhansl & Thomas, 1977; White, 1976). Current research in our laboratory aims to plot the integration fields for letter and symbol stimuli with independent manipulations of left and right flankers. By separately measuring critical spacing left and right of the target, we ought to be able to measure the hypothesized asymmetric form of integration fields hypothesized in our model.

Conclusions

The present study investigated effects of crowding on the identification of letters and symbols using a standard flanker manipulation with eccentrically located targets. In line with the predictions of Tydgat and Grainger (2009), effects of crowding interacted with target type, with stronger effects being found with symbol targets compared with letter targets. When the number of flankers was manipulated, this differential crowding effect was found to be driven mostly by the effects of single flankers, which always interfered with symbol identification but hardly affected letter identification. Single flanker interference was found to be robust for letter targets presented in the LVF when the flanker was located to the left of the target. Finally, a manipulation of target-flanker spacing showed that symbols required a greater degree of separation (larger critical spacing) than letters in order to reach a criterion level of identification. These results are taken as evidence in support of the hypothesis that during reading acquisition, the size and shape of the integration fields of location-specific letter detectors are modified, with an overall reduction in size with increasing exposure to print, and a visual field specific modification of shape.

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Received May 28, 2008
Revision received January 29, 2009
Accepted April 13, 2009 ■