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Serial position effects in the identification of letters, digits, symbols, and shapes in peripheral vision

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ABSTRACT

Three experiments measured serial position functions for character-in-string identification in peripheral vision. In Experiment 1, random strings of five letters (e.g., P F H T M) or five symbols (e.g., λ Б Þ Ψ ¥) were briefly presented to the left or to the right of fixation, and identification accuracy was measured at each position in the string using a post-cued two-alternative forced-choice task (e.g., was there a T or a B at the 4th position). In Experiment 2 the performance to letter stimuli was compared with familiar two-dimensional shapes (e.g., square, triangle, circle), and in Experiment 3 we compared digit strings (e.g., 6 3 7 9 2) with a set of keyboard symbols (e.g., % § @ < ?). Eye-movements were monitored to ensure central fixation. The results revealed a triple interaction between the nature of the stimulus (letters/digits vs. symbols/shapes), eccentricity, and visual field. In all experiments this interaction reflected a selective left visual field advantage for letter or digit stimuli compared with symbol or shape stimuli for targets presented at the greatest eccentricity. The results are in line with the predictions of the modified receptive field hypothesis proposed by Tydgat and Grainger (2009), and the predictions of the SERIOL2 model of letter string encoding.

1. Introduction

Our ability to read is undoubtedly one of the most complex of human skills that is not innate. Understanding this ability first requires an understanding of the basic building block of the reading process, visual word recognition, which in turn requires understanding how we process the component letters of each word (for words in languages like French and English that use an alphabetic script). Today, there is a growing consensus that the very first stage of orthographic processing involves the parallel processing of each letter in the word, leading to the computation of identity and position information for each component letter. The importance of understanding the mechanisms involved has been nicely illustrated by the recent finding that increased letter spacing can facilitate reading in dyslexic children (Perea, Panadero, Moret-Tatay, & Gómez, 2012; Zorzi et al., 2012). This finding can be seen as a logical extension of recent research suggesting that one of the key factors in learning to read concerns the adaptation of basic visual object processing to the specificities of parallel letter identification. Most important is the hypothesis, put forward by Tydgat and Grainger (2009), that these adaptations are aimed at reducing inter-letter interference in the highly crowded conditions imposed by reading. Zorzi et al.'s (2012) letter spacing manipulation was specifically designed to reduce crowding during letter-string processing.

It is generally acknowledged that observed variations in the visibility of letters in strings of letters that are fixated, can be accurately captured by the combined effects of two factors: visual acuity and crowding. Much prior research has investigated the variation of letter visibility as a function of position-in-string in conditions where the letter string is typically fixated near the center of the string. In particular, a number of these studies have compared performance to letter strings with performance to strings of other types of visual stimuli such as digits, symbols, and simple shapes. The standard finding in these studies is that for strings of letters and digits, performance is maximal at the first and last positions and at the fixated position. This gives rise to the classic M-shaped serial position function for response times in a target search paradigm where participants have to respond whether a given target stimulus is present or not in a string of different stimuli (Hammond & Green, 1982; Ktori & Pitchford, 2008; Mason, 1975, 1982; Mason & Katz, 1976; Pitchford, Ledgeway, & Masterson, 2009), and the W-shaped function for identification accuracy in a post-cued character-in-string identification paradigm (Tydgat & Grainger, 2009; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010).[1] In these same studies, the performance to strings of symbol stimuli or

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[1] It should be noted that although there is systematically an advantage for the initial position in strings for letter and digit stimuli, a final position advantage is not systematically observed (e.g., Tydgat & Grainger, 2009).

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simple geometric shapes was found to be maximal for targets on fixation, and with performance decreasing outward from fixation as a function of eccentricity. Contrary to letter and digit stimuli, there was little or no recovery in performance for the outer positions in the string.

The now standard account of the observed serial position functions for letter stimuli (W-shaped for accuracy, M-shaped for RTs) is that they reflect the combined operation of two factors: visual acuity and crowding. Visual acuity accounts for the drop in performance from fixation outwards to more peripheral locations, while reduced crowding for outer letters is one prominent account for why letters in the outer positions are processed so efficiently (see Tydgat & Grainger, 2009, for more detailed discussion). The proposed reason for why symbol strings do not show the same release from interference at the outer positions as compared with letters and digits, is that symbol stimuli are subject to almost maximal interference from a single flanking stimulus, whereas letters and digits show significantly greater interference from double flankers compared with single flankers (Tydgat & Grainger, 2009). This hypothesis was confirmed by Grainger, Tydgat, and Isselé (2010) in experiments testing identification of letters and symbols presented to the left and to the right of fixation, and either accompanied by a single flanker or two flankers (one on each side of the target), or presented in isolation. Letter targets were indeed less sensitive to crowding than symbol targets, and this was particularly pronounced when there was a single flanking stimulus. We now examine possible mechanisms that could account for why letters are less sensitive to crowding than symbols.

1.1. The modified receptive field (MRF) hypothesis

Tydgat and Grainger (2009) proposed what we will refer to here as the “modified receptive field (MRF) hypothesis” in order to account for the observed differences in serial position functions for letters, digits, and symbols. They first proposed that, in order to optimize the parallel independent processing of letter stimuli (as an initial phase of visual word recognition; Grainger & Van Heuven, 2003), the receptive field size of retinotopic letter detectors is reduced in spatial extent compared with other kinds of visual object.[2] Tydgat and Grainger (2009) argued that when receptive fields have a large spatial extent, such that they completely encompass immediately adjacent stimuli, then it suffices to have one flanker in order to induce close to maximal interference. Letter stimuli, on the other hand, having smaller receptive fields, will be sensitive to the number of flanking elements, with a significant reduction in crowding when there is only one flanker compared with two flanking stimuli.

Most important for the present study, is that Tydgat and Grainger further proposed that in order to optimize processing of initial letters in words, receptive fields are elongated to the left in the left visual field (for languages read from left-to-right). Maintaining a constant surface for receptive fields for a given type of stimulus at a given eccentricity implies that an elongation to the left is accompanied by a reduction in the rightward extent of the receptive field. Hence, flankers on the left generate more interference than flankers on the right. This provides a simple mechanism for giving priority to the processing of the first letter of fixated words during reading in languages that are read from left-to-right. There are at least two reasons to give priority to the first letter of words. The first is that this is often the most informative letter with respect to word identity (e.g., Dandurand, Grainger, Duñabeitia, & Granier, 2011). The second is that accurate generation of a phonological code depends critically on getting the first letter correct, and the masked onset priming effect attests to this importance (e.g., Grainger & Ferrand, 1996; Schiller, 2004).

Initial evidence in favor of this hypothesis was found in the Grainger et al. (2010) study. In an analysis of the effects of single flankers on letter identification, it was found that crowding was greater for flankers to left of the target than to the right of the target when target and flankers appeared in the Left Visual Field (LVF). No such asymmetry was found for letter stimuli when targets and flankers were presented in the Right Visual Field (RVF), and symbol stimuli did not show an asymmetry in either the LVF or the RVF (Grainger et al., 2010, p. 678, Fig. 4). In the present study we sought further evidence for a selective first position advantage in the LVF when processing longer strings, and when testing visibility at all positions in the string. We first describe prior work examining letter-in-string visibility for peripherally located stimuli.

1.2. Serial position effects for letters in peripheral vision

A number of studies have examined variations in letter visibility as a function of position-in-string under peripheral viewing conditions (i.e., with the entire string to the right or to the left of a central fixation point). Although there are major procedural differences across the different studies, a certain number of consistent patterns in the results have emerged from this research. First and foremost, there is always an outer letter advantage (i.e., the first and last positions in the string) compared with letters that occupy inner positions in the string (Butler & Currie, 1986; Estes, Allmeyer, & Reder, 1976; Jordan, Patching, et al., 2003; Lefton, Fisher, & Kuhn, 1978; Legge et al., 2001; Townsend, Taylor, & Brown, 1971), although the benefit for the final letter compared with the penultimate letter position was found to be greatly reduced with the use of a left-to-right full report procedure and longer strings (9-letters) in Wolford and Hollingsworth's (1974) study.[3]

Several studies have also reported an advantage for the most eccentric positions (i.e., those furthest from fixation) compared with letters appearing the closest to fixation (Bouma, 1973; Estes et al., 1976; Legge et al., 2001). This pattern led Bouma (1973) to propose an inward–outward asymmetry in the effects of lateral interference, with stronger interference arising from flankers that are further from fixation than the target. On the basis of this finding, Bouma proposed a more general version of the modified receptive field hypothesis under test in the present study: that receptive fields are elongated toward the periphery, and therefore to the left in the LVF and to the right in the RVF (Bouma, 1978). Given that the inward–outward asymmetry has also been found with other kinds of stimuli (e.g., Petrov & Popple, 2007) this is thought to be a general property of crowding (see Levi, 2008; Whitney & Levi, 2011, for reviews of the evidence, and Nandy & Tjan, 2012, for a recent model).

Finally, although the effects of visual field on letter-in-string identification tend to be quite small when letter strings are nonwords compared with word stimuli (e.g., Chanceaux & Grainger, submitted for publication; Jordan, Patching, et al., 2003; Jordan, Thomas, et al., 2003), there is some evidence for differences in serial position effects as a function of visual field. In a study by Hellige, Cowin, and Eng (1995) participants had to report the identity of the three letters that formed a CVC syllable that was briefly presented to the right or to the left of the fixation, or centered on fixation. Hellige et al. (1995) found an overall superiority in accuracy of report for the first letters of target strings, and this initial letter advantage was found to be greatly exaggerated with target presentation in the LVF or with fixation on the center of the string. A similar pattern was reported by Wolford and Hollingsworth (1974) in a study where 9-letter consonant strings were presented centered on fixation or in the LVF or RVF, and in certain conditions the two letters to the left

[2] Empirical research on crowding measures the minimal inter-object spacing necessary for accurate object identification at a given eccentricity (e.g., Pelli, Palomares, & Majaj, 2004; see Levi, 2008, and Whitney & Levi, 2011, for reviews). These measures define the crowding zone of a given object at a given eccentricity, which can be compared with theoretically defined receptive fields such as in the MRF hypothesis.

[3] Estes et al. (1976) and Jordan, Patching, and Thomas (2003), Jordan, Thomas, Patching, and Scott-Brown (2003) tested 4-letter strings, and Legge, Mansfield, and Chung (2001) tested trigrams.

or the two letters to the right of the central letter were replaced by spaces. Identification of the central letter was improved when there were two spaces to the left compared with two spaces to the right, but only for LVF presentation. Such asymmetries are perfectly in line with the asymmetric version of the modified receptive field hypothesis proposed by Tydgat and Grainger (2009).

1.3. The present study

The present study is a straightforward combination of the prior work of Tydgat and Grainger (2009) on the one hand, and Grainger et al. (2010), on the other. That is, here we measure identification accuracy for all positions in a string of five characters (as in the Tydgat & Grainger study) for strings presented in peripheral vision in the LVF or RVF (as in the Grainger et al. study). More precisely, we measured identification accuracy at each position[4] in strings of 5 letters and strings of 5 symbols (Experiment 1), 5 letters or 5 shapes (Experiment 2), and 5 digits or 5 symbols (Experiment 3), with strings presented to the left or to the right of fixation, at an eccentricity of 1.2° for the closest character. It is important to note that to our knowledge no prior research has compared serial position functions obtained for strings of letters with other types of stimuli under peripheral presentation, yet this comparison has been instrumental in discovering the mechanisms that underlie the serial position functions found for centrally fixated strings of letters. This comparison allows one to pinpoint processes that are specific to strings of letters compared with strings of other kinds of visual object.

According to the MRF hypothesis described above, there should be one condition where performance to letters and to symbols maximally diverges — that is at the first position of strings presented in the LVF. Another way to look at the predictions of the MRF hypothesis is in terms of visual field differences for equivalent eccentricity. The MRF hypothesis predicts that letters should show a large LVF advantage for the most eccentric position (initial position in the LVF, final position in the RVF), whereas the more typical RVF advantage or no visual field differences should be seen in the other conditions. In both cases, the MRF hypothesis predicts a triple interaction between Eccentricity, Visual Field, and Stimulus Type. On the other hand, a model with generic edge effects predicts an advantage for the first and last positions independent of stimulus type and visual field (main effect of Eccentricity and no interactions). The same holds for a model with a generic first position advantage except that now the serial position functions should show a selective advantage for the first position independently of Stimulus Type and Visual Field. A model with letter-specific edge effects predicts a selective advantage for the first and last positions for letter stimuli only, that would be revealed by an Eccentricity × Stimulus Type interaction independently of Visual Field. Similarly, a model with a letter-specific first position advantage (e.g., Pitchford et al., 2009) predicts a selective advantage for letters over symbols at the first position only, and independently of Visual Field. Again, there should only be a two-way Eccentricity × Stimulus Type interaction in this case.

Finally, the original SERIOL model (Whitney, 2001, 2008) predicts a generic (i.e., stimulus-independent) first position advantage in the LVF, since the mechanisms driving such an advantage are hypothesized to operate at the level of visual features. The mechanism in question is hemisphere-specific directed inhibition operating at the level of visual features. This mechanism is used to generate a monotonically decreasing activation gradient from the first letter to the last letter in the string, by counteracting the effects of increased eccentricity in the left visual field. However, Whitney (2011) has recently described a new version of the SERIOL model (SERIOL2) that introduces retinotopic letter detectors, as in the Grainger and Van Heuven (2003) model. Most important, however, is that just like our MRF hypothesis, SERIOL2 proposes mechanisms specific to letter and digit string processing that are adaptations of basic visual object processing mechanisms. The key difference between our approach and SERIOL2 is that the latter appeals to abstract, location-invariant letter detectors that are activated sequentially, from left-to-right in languages that are read from left-to-right, and that send activation onto higher-level open-bigram detectors. Introducing abstract letters in between retinotopic letters and bigrams is one way to solve the difficult problem of how readers learn to map retinotopic information onto location-invariant orthographic representations. Without going into the details here, for the present purposes it suffices to note that SERIOL2 generates predictions that are identical to those of our MRF hypothesis. We return to discuss the differences between these two approaches in the General discussion section.

2. Experiment 1

2.1. Method

2.1.1. Participants

Twenty students from Aix-Marseille University participated in the experiment and received 10 €. All of them reported normal or corrected-to-normal vision and were native speakers of French.

2.1.2. Stimuli and design

Fifteen consonant letters (B, C, D, F, G, H, J, K, L, M, N, P, R, S, T) were used to construct random combinations of 5 different consonants, and fifteen symbols, the majority of which were Greek letters (Δ, Θ, £, Π, Σ, Φ, δ, λ, Þ, Б, ¥, Γ, Ω, Ψ, Λ), were used to construct random combinations of 5 different symbols. The stimuli were presented in uppercase Courier New font. For each string of 5 characters, one character served as the target on a given trial. Each letter and symbol character served as the target on 20 trials, half in the Right Visual Field (RVF) and half in the Left Visual Field (LVF), and for each position of the 5 positions in the string. Thus, Stimulus Type (letters vs. symbols) was crossed with Visual Field (LVF vs. RVF) and Eccentricity (corresponding to the 5 possible positions of the target within the string) in a 2 × 2 × 5 factorial design.

2.1.3. Apparatus and procedure

An EyeLink 1000 eyetracker (SR Research) was used to control for eye movements. Participants rested their head on a chin rest, at 80 cm from the monitor. The eye tracker recorded right eye movements (sampling frequency of 1000 Hz), in the cognitive configuration (saccadic detection based on a velocity threshold of 30°/s and an acceleration threshold of 8000°/s^2). Stimuli were presented on a ViewSonic P227 monitor (refresh rate 100 Hz, screen size 1024∗768 px) using Experiment Builder software (SR Research). Stimuli were presented in white 21-point Courier New font on a black background. A character subtended about 0.6° horizontally and the center of the string was at an eccentricity of 2.4°. Targets could appear at one of the 5 positions in the string, corresponding to the 5 levels of Eccentricity (1.2°, 1.8°, 2.4°, 3.0°, 3.6°). Note that letter size is greater than in normal reading conditions (typically 0.25–0.5° of visual angle). Note also that although our stimuli extended further towards the periphery than words in normal reading, their initial letters were presented no further from fixation than in normal reading (1.2° compared to 1.5–3° in normal reading), and all the items, even those at the most eccentric locations, were above the critical print size (CPS) — that is the smallest print size that yields maximum reading speed (see Chung, Mansfield, & Legge, 1998).

To calibrate the eye tracker, a nine-point calibration routine was performed at the beginning of the session and then every 50 trials, with a second 9-point calibration grid used to calculate the accuracy of the calibration. On each trial, participants had first to gaze at the fixation cross at the center of the screen. This fixation cross

[4] Note that position is defined in terms of eccentricity in the present study rather than left-to-right serial position as in the Tydgat and Grainger (2009) study, since the same serial position has a different eccentricity in the LVF and RVF.

disappeared after a period of 200 ms during which there were no eye movements outside an area of 50∗120 px around the cross (0.7° left or right). Then the stimulus appeared either on the left or on the right of the fixation cross for 300 ms (Fig. 1). Participants had to maintain central fixation during stimulus presentation, otherwise the trial was canceled. After stimulus presentation, a mask was presented, and a post-cue showed the position of the target character that had to be identified. Two characters were also displayed above and below the fixation cross, one of them was the target and the other was another character that was not present in the stimulus. This final display remained until participants responded by choosing one of the alternatives. Participants were instructed to respond as accurately as possible by pressing either the upward arrow key (for the alternative above) or the downward key (for the alternative below), following the standard 2-alternative forced choice (2AFC) procedure. An audio tone signaled a correct response. After participants' response a blank screen was displayed and the next trial began.

The experiment was divided in two sessions corresponding to the two types of stimuli. Half of the participants started with the letter stimuli (300 trials) followed by the symbol stimuli (300 trials), and the remaining participants received stimuli in the opposite order. Visual Field and Eccentricity varied randomly across all trials within each session. The experiment lasted about 1 h.

2.2. Results

Five participants were removed from further analyses because they failed to reach above chance-level accuracy in the experiment (Chi-squared test, $p>.01$, circles in Fig. 2).

A repeated measures ANOVA was performed on the data for identification accuracy per condition and participant. The within-participant variables were Stimulus Type (letters or symbols), Visual Field (LVF or RVF) and Eccentricity (1.2°, 1.8°, 2.4°, 3.0°, 3.6°). The main effect of Stimulus Type was significant, $F(1,14)=73.05$, $p<.001$, with letter stimuli being more accurately identified than the symbol stimuli (67.82% vs. 59.53%). There was also a main effect of Eccentricity, $F(4,56)=20.57$, $p<.001$, with variation in performance with eccentricity following a U-shaped function (see Fig. 3). The main effect of Visual Field was only marginally significant ($p=.08$). Most critical with respect to the hypotheses under test in the present study is that there was a significant three-way interaction between Stimulus Type × Visual Field × Eccentricity, $F(4,56)=6.33$, $p<.001$. As can be seen in Fig. 3, the three-way interaction is driven by the fact that the Stimulus Type × Eccentricity interaction is significant in the LVF, $F(4,56)=5.52$, $p<.001$, but is not significant in the RVF, $p=.52$.

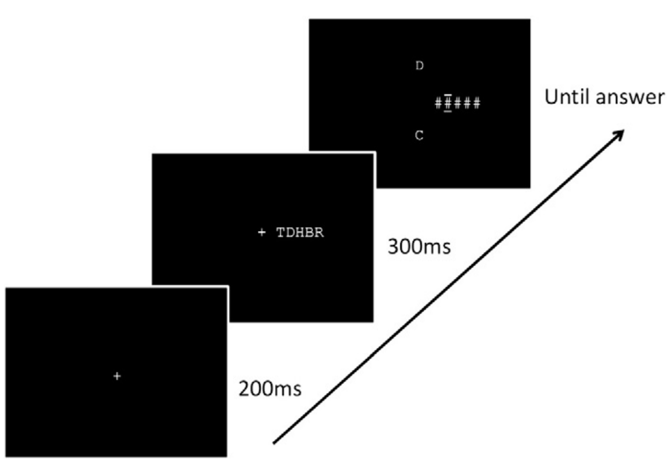

Fig. 1. A typical trial. Fixation cross for 200 ms, followed by a 5-character string presented to the left or right of the fixation for 300 ms, and finally a backward mask occupying the same location as the character string and accompanied by a post-cue and two alternatives for the 2AFC procedure.

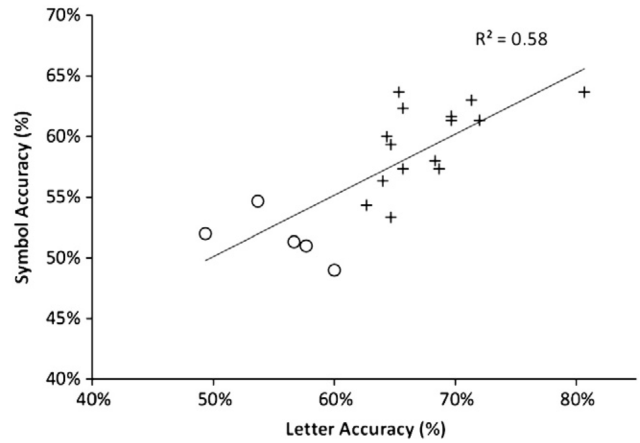

Fig. 2. Average performance on letter stimuli and symbol stimuli for the 20 participants tested in Experiment 1. Crosses represent the 15 participants retained for further analysis.

Although there was only a marginally significant main effect of Visual Field, and the interaction between Visual Field and Stimulus Type was not significant ($F(1,14)=.89$, $p=.36$), the triple interaction between Visual Field, Stimulus Type, and Eccentricity also reflects a qualitatively different influence of Visual Field on the processing of strings of letters and strings of symbols. As shown in Fig. 4, there was a significant Visual Field × Eccentricity interaction for letter stimuli, $F(4,56)=11.71$, $p<.001$, but not for symbol stimuli, $F(4,56)=.30$, $p=.88$. Pairwise comparisons revealed that the only condition to show a significant LVF advantage was the letter targets at the greatest eccentricity, $t(14)=5.23$, $p<.001$. All other conditions either showed a RVF advantage or no visual field differences.

2.3. Discussion

The results of Experiment 1 revealed the triple interaction between Stimulus Type, Eccentricity, and Visual Field that was predicted by Tydgat and Grainger's (2009) modified receptive field (MRF) hypothesis. Moreover, the results of Experiment 1 allow us to reject alternative versions of the MRF hypothesis, discussed in the Introduction section. They also are incompatible with the explanation of serial position effects offered by Whitney (2008) in terms of hemisphere-specific directed inhibition operating at the level of visual features. Any mechanism operating at the level of visual features should have generated a similar pattern of serial position functions for letters and symbols.

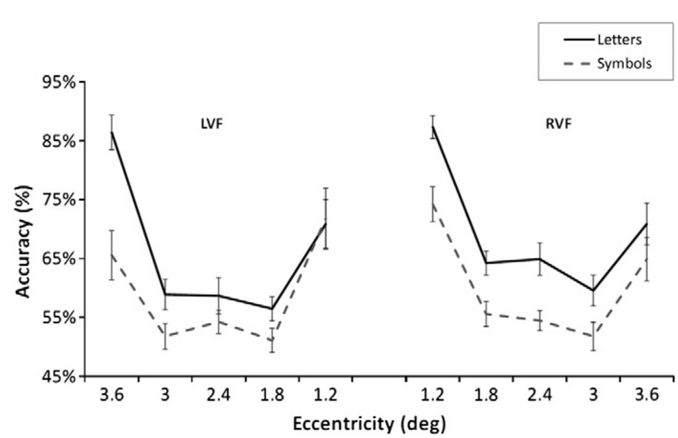

Fig. 3. Mean 2AFC accuracy as a function of Stimulus Type (letters vs. symbols), Visual Field (LVF vs. RVF), and Eccentricity in Experiment 1, showing the significant Stimulus Type X Eccentricity interaction in the LVF but not in the RVF. Error bars are standard errors of the mean. Eccentricity is plotted in reverse order in the LVF so as to maintain left-to-right order in both visual fields.

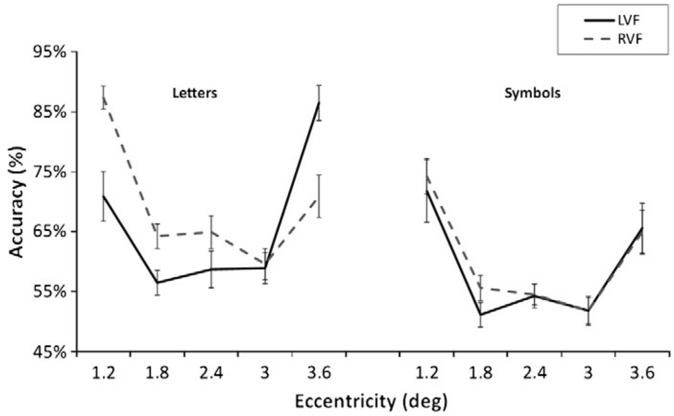

Fig. 4. Interactive effects of Visual Field (LVF vs. RVF) and Eccentricity for letter stimuli but not for symbol stimuli. Error bars are standard errors of the mean.

The complete pattern of results found in Experiment 1 can be best captured by a combination of Bouma's (1978) proposed elongation of receptive fields plus Tydgat and Grainger's (2009) proposed letter-specific and visual-field-specific asymmetry of this elongation. Generic elongation towards the periphery accounts for edge effects seen for both letters and symbols, while the letter-specific and visual-field-specific components account for the selective advantage for letter stimuli at the initial position of strings presented to the LVF.

The distinct serial position functions found for letters and symbols presented to the LVF in Experiment 1 are all the more striking given that we used relatively "letter-like" symbols in order to match the letters and symbols in terms of visual complexity. However, this implied using symbols that were less familiar than letters, and indeed performance was overall lower to symbol stimuli than to letters. It could therefore be this difference in stimulus familiarity at the individual object level that is driving the different serial position functions (although it is not clear what kind of familiarity driven mechanism could be behind this). Therefore, as a further test of Tydgat and Grainger's MRF hypothesis, Experiment 2 attempts to replicate the pattern observed in Experiment 1, but with the symbol stimuli replaced by highly familiar two-dimensional shapes.

3. Experiment 2

The symbol stimuli tested in Experiment 1 were less familiar than the letter stimuli. In Experiment 2 we examine whether the same pattern of results will be seen with more familiar non-letter stimuli. To this end, we tested a set of simple and highly familiar geometric shapes. Prior research (Hammond & Green, 1982) suggests that performance to these stimuli will be similar to what was seen for the symbol stimuli in Experiment 1. Note that familiarity is defined here at the level of individual objects. It is clear that strings of letters are more familiar than strings of non-letter shapes, and it is precisely familiarity with strings of letters that is the basis of Tydgat and Grainger's (2009) MRF hypothesis.

3.1. Method

3.1.1. Participants

Twenty-five students from Aix-Marseille University participated in the experiment and received 10 €. All of them reported normal or corrected-to-normal vision and were native speakers of French.

3.1.2. Stimuli and design

Nine consonant letters (B, D, G, H, K, M, N, R, S) were used to construct random combinations of 5 different consonants, and 9 familiar geometric shapes (see Fig. 5) were used to construct random combinations of 5 different shapes. The shapes were chosen to be highly familiar and the letters were selected so as to best match the shapes in terms of number of pixels. For each string of 5 characters, one character served as the target on a given trial. Each letter and shape served as the target on 20 trials, half in the Right Visual Field (RVF) and half in the Left Visual Field (LVF), and for each position of the 5 positions in the string. Thus, Stimulus Type (letters vs. shapes) was crossed with Visual Field (LVF vs. RVF) and Eccentricity (1.2°, 1.8°, 2.4°, 3.0°, 3.6°) in a $2\times2\times5$ factorial design.

3.1.3. Apparatus and procedure

These were the same as in Experiment 1 except that a fixation dot was used rather than a cross (because of the use of a cross-shape target), and the number of trials per condition was reduced so that each letter and shape appeared the same number of times as in Experiment 1. The experiment was divided in two sessions corresponding to the two types of stimuli. Half of the participants started with the letter stimuli (180 trials) followed by the shape stimuli (180 trials), and the remaining participants received the stimuli in the opposite order. Visual Field and Eccentricity varied randomly across all trials within each session. The experiment lasted about 45 min.

3.2. Results

Seven participants were removed from further analyses because they failed to reach above chance-level accuracy in the experiment (Chi-squared test, $p>.01$, circles in Fig. 6).

A repeated measures ANOVA was performed on the data for identification accuracy per condition and participant. The within-participant variables were Stimulus Type (letters or shapes), Visual Field (LVF or RVF) and Eccentricity (1.2°, 1.8°, 2.4°, 3.0°, 3.6°). Contrary to Experiment 1, the main effect of Stimulus Type was not significant, $F(1,17)=.14$, $p=.7$. The average accuracy for letter stimuli (61.51%) was only slightly higher than for the shape stimuli (60.96%). The main effect of Eccentricity was significant, $F(4,68)=12.63$, $p<.001$, with variation in performance with Eccentricity following a U-shaped function, and the main effect of Visual Field was only marginally significant ($p=.09$). Most important, and in line with the results of Experiment 1, the three-way interaction between Stimulus Type × Visual Field × Eccentricity was significant, $F(4,68)=3.45$, $p<.05$. This triple interaction reflects a qualitatively different influence of Visual Field on the processing of strings of letters and strings of shapes. As shown in Fig. 7, there was a significant Visual Field × Eccentricity interaction for letter stimuli, $F(4,68)=12.67$, $p<.001$, but not for shape stimuli, $F(4,68)=1.06$, $p=.38$. Pairwise comparisons revealed that the only condition to show a significant LVF advantage was the letter targets at the greatest eccentricity, $t(17)=5.42$, $p<.001$. All other conditions either showed a RVF advantage or no visual field differences.

3.3. Discussion

Our attempt to match letter and non-letter stimuli in terms of familiarity was successful in that performance to letters and shape stimuli did not significantly differ in Experiment 2. This renders the different serial position functions obtained to these two types of stimuli all the more interesting, and indeed we found the same triple interaction between Stimulus Type, Eccentricity, and Visual Field as was seen in Experiment 1. Once again, the effects of stimulus eccentricity

Fig. 5. The 9 shapes and 9 letters tested in Experiment 2.

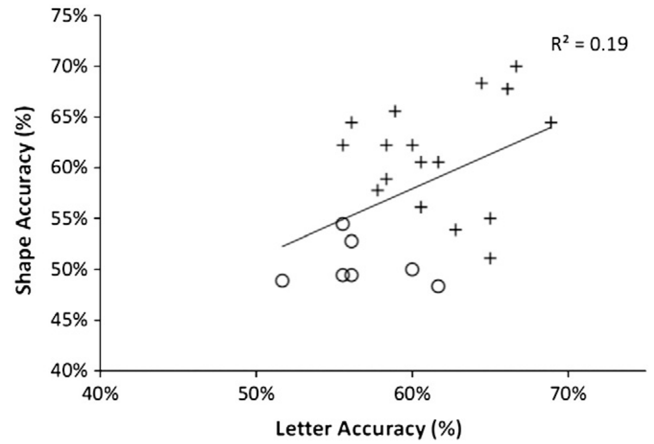

Fig. 6. Average performance on letter stimuli and shape stimuli for the 25 participants tested in Experiment 2. Crosses represent the 18 participants retained for further analysis.

differed in the LVF and RVF for letter stimuli, but not for the non-letter shape stimuli tested in Experiment 2 (see Fig. 7), and once again the principal factor behind this pattern is that the only condition to generate a significant LVF advantage is the condition where letter stimuli are presented at the greatest eccentricity (i.e., the initial position in the LVF and the final position in the RVF).

4. Experiment 3

In Experiment 3 we examined a more commonly used set of symbol stimuli compared with the ones tested in Experiment 1, which were mostly Greek letters. Experiment 3 tests the same keyboard symbol stimuli as used by Tydgat and Grainger (2009). We expect to obtain the same pattern with these keyboard characters as was seen with the symbol stimuli tested in Experiment 1. Experiment 3 also tests digit stimuli, which according to both the MRF hypothesis and the SERIOL2 model should behave just like letter stimuli.

4.1. Method

4.1.1. Participants

Twenty students from Aix-Marseille University participated in the experiment and received 5 €. All of them reported normal or corrected-to-normal vision and were native speakers of French.

4.1.2. Stimuli and design

Nine digits (1 to 9) were used to construct random combinations of 5 different digits, and 9 familiar keyboard symbols (%, /, ?, @,), <, £, §, and µ as in Tydgat & Grainger, 2009) were used to construct random combinations of 5 different symbols. For each string of 5 characters, one character served as the target on a given trial. Each digit and symbol served as the target on 20 trials, half in the Right Visual Field (RVF) and half in the Left Visual Field (LVF), and for each position of the 5 positions in the string. Thus, Stimulus Type (digits vs. symbols) was crossed with Visual Field (LVF vs. RVF) and Eccentricity (1.2°, 1.8°, 2.4°, 3.0°, 3.6°) in a $2\times2\times5$ factorial design.

4.1.3. Apparatus and procedure

These were the same as in the previous experiments. The experiment was divided in two sessions corresponding to the two types of stimuli. Half of the participants started with the digit stimuli (180 trials) followed by the symbol stimuli (180 trials), and the remaining participants received the stimuli in the opposite order. Visual Field and Eccentricity varied randomly across all trials within each session. The experiment lasted about 30 min.

4.2. Results

Six participants were removed from further analyses because they failed to reach above chance-level accuracy in the experiment (Chi-squared test, $p>.01$, circles in Fig. 8).

A repeated measures ANOVA was performed on the data for identification accuracy per condition and participant. The within-participant variables were Stimulus Type (digits or symbols), Visual Field (LVF or RVF) and Eccentricity (1.2°, 1.8°, 2.4°, 3.0°, 3.6°). As in Experiment 1, the main effect of Stimulus Type was significant, $F(1,13)=68.56$, $p<.001$. The average accuracy for digit stimuli (68.60%) was higher than for the symbol stimuli (58.31%). The main effect of Eccentricity was significant, $F(4,52)=8.27$, $p<.001$, with variation in performance with Eccentricity following a U-shaped function. The main effect of Visual Field was not significant ($p=.55$). Most important, and in line with the results of Experiment 1 and 2, the three-way interaction between Stimulus Type × Visual Field × Eccentricity was significant, $F(4,52)=3.32$, $p<.05$. This triple interaction reflects a qualitatively different influence of Visual Field on the processing of strings of digits and strings of symbols. As shown in Fig. 9, there was a significant Visual Field × Eccentricity interaction for digit stimuli, $F(4,52)=4.32$, $p<.01$, but not for symbol stimuli, $F(4,52)=.49$, $p=.74$.

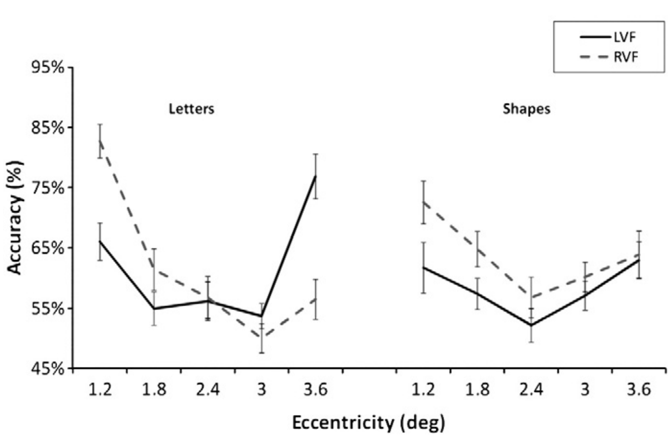

Fig. 7. Mean 2AFC accuracy as a function of Stimulus Type (letters vs. shapes), Visual Field (LVF vs. RVF), and the 5 levels of Eccentricity in Experiment 2, showing the significant Visual Field × Eccentricity interaction for letter stimuli but not for shape stimuli. Error bars are standard errors of the mean.

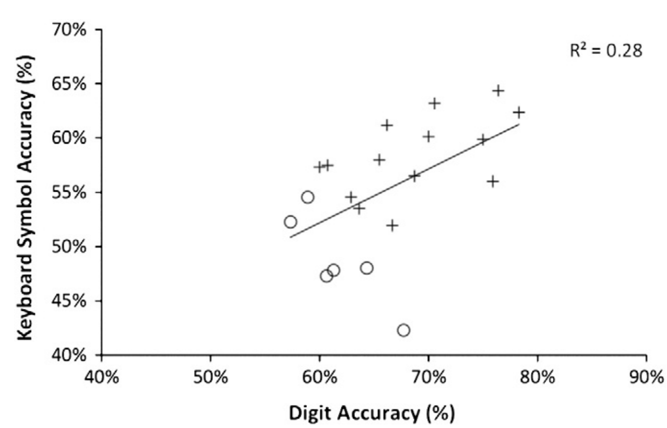

Fig. 8. Average performance on digit stimuli and symbol stimuli for the 20 participants tested in Experiment 3. Crosses represent the 14 participants retained for further analysis.

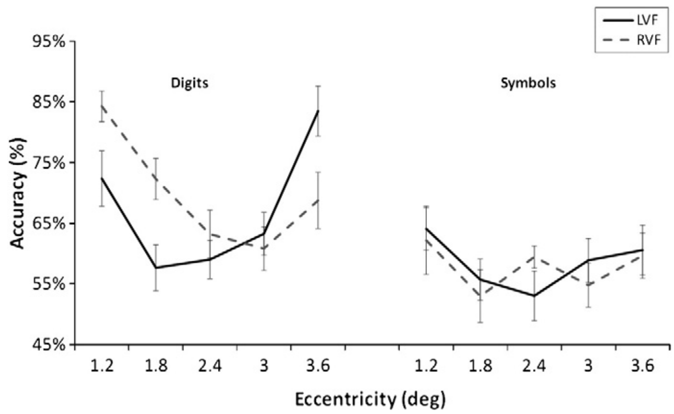

Fig. 9. Mean 2AFC accuracy as a function of Stimulus Type (digits vs. keyboard symbols), Visual Field (LVF vs. RVF), and the 5 levels of Eccentricity in Experiment 3, showing the significant Visual Field × Eccentricity interaction for digit stimuli but not for symbol stimuli. Error bars are standard errors of the mean.

4.3. Discussion

The results of Experiment 3 are exactly as predicted. Digit stimuli showed the same advantage for processing targets at the first position in the string in the left visual field as we had seen for letter stimuli in Experiments 1 and 2. Although the performance to keyboard symbols was overall lower compared with the symbol and shape stimuli tested in Experiments 1 and 2, the same absence of interaction between Visual Field and Eccentricity was found. Most important is that there was no sign of a selective first position advantage for symbol targets in the left visual field.

5. General discussion

In the present study we asked participants to identify a single target character in a string containing 5 characters, while varying the target position in the string and with the entire string presented either in the Left Visual Field (LVF) or Right Visual Field (RVF). The strings were either a random combination of consonants or a random combination of symbol stimuli (mostly Greek letters) in Experiment 1, consonants or a random combination of simple shapes in Experiment 2, and digits or keyboard symbols in Experiment 3. The most important result of the present study is the triple interaction that was found between Eccentricity, Stimulus Type, and Visual Field in all three experiments. The significant triple interaction reflected the presence of a significant interaction between Eccentricity and Visual Field only for letter or digit stimuli. Symbol and shape stimuli showed similar effects of eccentricity in the two visual fields, whereas the performance to letter and digit stimuli was more determined by the left-to-right position in the string, leading to a high level of performance for targets at the most eccentric position in the LVF (i.e., the initial position of the string).

The observed selective advantage for letter and digit targets at the most eccentric position in the LVF was predicted by the modified receptive field (MRF) hypothesis put forward by Tydgat and Grainger (2009) in order to account for differences in the serial position functions for letters and digits compared with symbol stimuli when presented in central vision. Tydgat and Grainger proposed that during the course of learning to read there is an adaptation of elementary visual object recognition processes in order to optimize the processing of strings of letters (for reading) and strings of digits (for number processing). They specifically proposed that not only does this adaptation involve a reduction in the size of receptive fields for retinotopic letter and digit detectors, but also that the shapes of receptive fields are modified in order to give priority to the initial letters of words and the initial digit of numbers.[5] The key prediction of the MRF hypothesis with respect to the present study was that only letter/digit stimuli should show a strong LVF advantage for targets located at the greatest eccentricity. The results of all three Experiments were clear-cut in this respect, since the only condition to generate a significant LVF advantage was the letter/digit target condition at the greatest eccentricity.

5.1. Initial letter superiority

Superior performance to letters that occupy the first position in a string of letters is a well-established finding. This pattern is seen in the target search paradigm (Hammond & Green, 1982; Ktori & Pitchford, 2008; Mason, 1975, 1982; Mason & Katz, 1976; Pitchford et al., 2009) as well as tachistoscopic identification paradigms with either full-report (e.g., Averbach & Coriell, 1961; Butler & Merikle, 1973; Haber & Standing, 1969; Mewhort & Campbell, 1978; Wolford & Hollingsworth, 1974) or post-cued partial report, as in the present study (Tydgat & Grainger, 2009; Ziegler et al., 2010). Initial letter superiority is also reflected in the finding that changes involving the first letter of words interfere more with normal text reading than changes involving inner letters (e.g., Jordan, Thomas, et al., 2003; White, Johnson, Liversedge, & Rayner, 2008).[6] Tydgat and Grainger's (2009) MRF hypothesis provided a precise mechanism for this initial letter superiority effect, while clearly predicting that it should be exaggerated in the LVF. Note, however, that this exaggeration has to be measured with respect to the effects of other factors contributing to edge effects, as discussed below. It is because of this that the comparison with performance to non-letter stimuli is critical in interpreting the results of the present study.

The results of the present study allow us to rule-out alternative explanations of the superior processing of the initial letters in a string. Basically, any account of initial letter superiority that appeals to language-specific processing mechanisms cannot account for the present results. The reason is because, if anything, language-specific effects should be stronger in the RVF than the LVF, and therefore any effects of this factor should have been exaggerated under RVF presentation. In the present study we found exactly the opposite pattern. This result is all the stronger given that in the RVF, initial letters are the closest to fixation, whereas in the LVF they are the furthest from fixation.

One explicit language-specific account of edge effects was tentatively put forward by Pitchford et al. (2009). According to these authors, the serial position function found in studies using the letter search paradigm might be partly due to top-down influences from partially activated lexical representations. The key finding in this respect was that letter detection times for targets appearing at the initial and final position in a random string of letters were found to be negatively correlated with positional letter frequency (i.e., the more frequently a letter occurs at a given position in words across a given corpus, the faster the letter is detected at that position). The correlation was not significant for inner letters, thus pointing to a frequency-based explanation of edge effects, such as via top-down lexical influences on letter identification. Without wishing to exclude a possible role for such lexical influences on letter-in-string, it is important to note that we found no significant correlations between letter frequency and letter identification performance at any position

[5] One reviewer wondered about the plausibility of having retinotopic digit detectors operating at the largest eccentricities used in the present study. We would argue that it is distance from fixation measured in letter/digit units, not in visual angle, that is important, and that a distance of 6 letter/digit units from fixation is not an unusually large distance.

[6] Winskel, Perea, and Ratitamkul (2012) have recently shown that such differences between initial letters and inner letters are not seen when reading without interword spaces in Thai, a language that typically does not introduce spaces between words. Clearly, it would be interesting to test Thai readers, who have limited experience with other scripts, in the paradigm used in the present study.

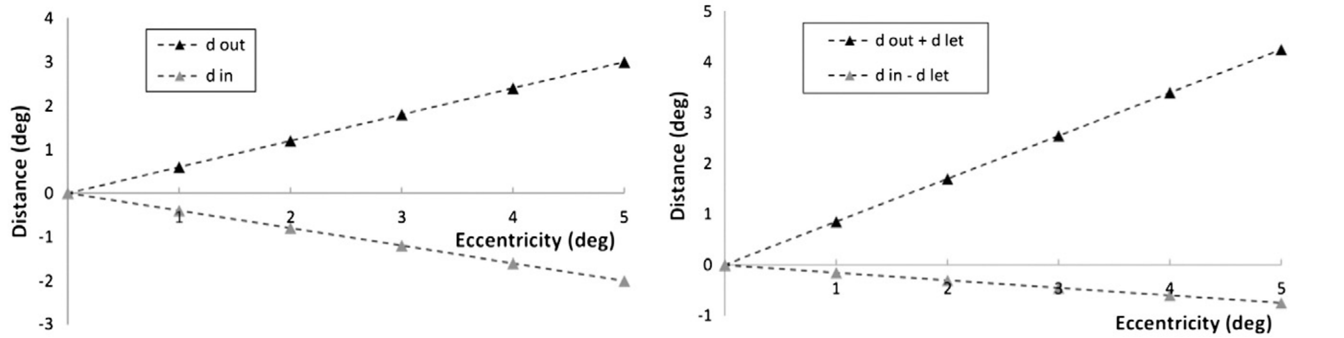

Fig. 10. Inward–outward asymmetry in Nandy and Tjan's (2012) model of crowding used to simulate the size and shape of receptive fields for the eccentricities tested in the present study (left panel). Modification of this asymmetry for letter and digit stimuli appearing in LVF according to the MRF hypothesis (right panel).

in the string in either the LVF or the RVF in Experiments 1 and 2 (all p values > .08 in Experiment 1, and > .2 in Experiment 2).[7]

Hellige et al. (1995) argued that different serial position functions found for letter stimuli in the LVF and RVF are due to differences in the way spatial attention influences processing in the two hemispheres. As noted in the Introduction section, in the Hellige et al. study participants had to report the identity of the three letters that formed a CVC syllable that was briefly presented to the right or to the left of fixation, or centered on fixation. The key finding was an overall superiority in the accuracy of report for the first letters of target strings, and the fact that this initial letter advantage was found to be much larger when the strings were presented in the LVF or with fixation on the center of the string. It is interesting to note that Hellige et al. referred to this specific finding as being “counterintuitive”, since they expected the central fixation condition to produce a pattern that resembled RVF presentation rather than LVF presentation. Of course, this pattern is perfectly compatible with the MRF hypothesis.

The SERIOL model (Whitney, 2001, 2008), correctly predicts that there should be a distinct processing advantage for initial letters in the LVF. This advantage is generated by a LVF-specific left-to-right directional inhibition operating at the level of visual features, and designed to generate a monotonic activation gradient on letter representations such that the first letter fires first, followed by the second, until the end of the string. The hemisphere-specific directional inhibition is necessary in order to reverse the acuity gradient in the LVF, and given that this mechanism operates at the level of visual features, it incorrectly predicts similar serial position functions for letters and other kinds of visual object. However, as noted in the Introduction section, Whitney has since developed a new version of the SERIOL model (SERIOL2: Whitney, 2011; Whitney & Marton, submitted for publication), which rectifies this problem. It does so by incorporating the notion of retinotopic letter detectors (Grainger & Van Heuven, 2003); the sizes of which vary as a function of eccentricity and visual field. SERIOL2 therefore accounts for the results of the present study much in the same way as the MRF hypothesis. However, unlike our MRF hypothesis, SERIOL2 is a full-blown model of orthographic processing that provides a detailed account of the mechanisms that enable the transformation of retinotopic letter information into location-invariant, word-centered orthographic representations. It is the precise mechanisms involved in this transformation that distinguish Whitney's approach from our own. A more detailed comparison of these two approaches must await implementation of the MRF hypothesis within the general framework of Grainger and Van Heuven's (2003) model of orthographic processing.

[7] Letter frequencies were calculated from a corpus of 7087 five-letter French words (Lexique 3.7: New, Pallier, Ferrand, & Matos, 2001), using a position-specific token count.

5.2. Crowding, letter string processing, and the MRF hypothesis

The present results would appear to be best accounted for by a combination of generic (i.e., stimulus-independent) edge effects supplemented with a letter-specific first position advantage in the LVF. The generic edge effects would be captured by Bouma's (1978) proposed elongation of receptive fields toward the periphery (i.e., an inward–outward asymmetry). Indeed this proposal has been integrated into a recent model of crowding (Nandy & Tjan, 2012). This model predicts the size and shape of the crowding zone, that is the empirically defined region of lateral interactions, as a function of eccentricity on the basis of three fundamental properties of crowding: 1) Bouma's law; 2) inward–outward asymmetry; 3) radial–tangential anisotropy (e.g., Toet & Levi, 1992). The last factor determines the elliptical shape of receptive fields, and since it is irrelevant for accounting for the present results, it will not be considered further.

Here we provide an implementation of the MRF hypothesis using Nandy and Tjan's (2012) model. For the present purposes, there are two key parameters that define the size and shape of the crowding zone in this model: 1) D_{radial} — which defines the radial extent of the crowding zone according to Bouma's law ($0.5 \times D_{radial} = 0.5 \times$ Eccentricity); and 2) D_{in}–D_{out} — which defines the inward–outward asymmetry of the crowding zone. On the basis of Nandy and Tjan's results, we estimated the value of D_{in}–D_{out} as .2, meaning that 60% of the crowding zone is outward and 40% is inward (see Fig. 11).

In order to predict accuracy in letter and non-letter identification in the different conditions tested in the present study, we counted the number of flanking characters that fell in the theoretically defined receptive field of the target character. In order to simplify this process, and as a first approximation, we counted in half-letters, such that if the target's receptive field covered more than 50% of the radial extent of a flanker this is counted as 0.5, and if the receptive field completely encompassed the flanker this is counted as 1.0 (a calculation based only on complete letters yielded very similar results). This calculation provided a good fit to the results of the non-letter stimuli tested in Experiments 1 and 2 ($R^2 = .73$, $F = 21.96$, $p < .001$). For predictions concerning the letter and digit stimuli, following the MRF hypothesis we added a new parameter to the model (D_{let}), which increases the inward–outward asymmetry in the LVF for letter and digit stimuli only. The value of this parameter that provided the best fit to the data was .5, which means that 85% of the receptive field is on the left (outward side, see Fig. 10) of the target in the LVF ($R^2 = .69$, $F = 17.16$, $p < .001$). Fig. 11 shows the performance predicted by this model on the basis of the number of flanking elements that fall in the target's receptive field, alongside the empirical results of the present study. It is clear that the model does a good job in capturing the varying forms of the serial position functions as a function of target type and visual field (note that the difference in height of the empirical and theoretical curves is irrelevant).

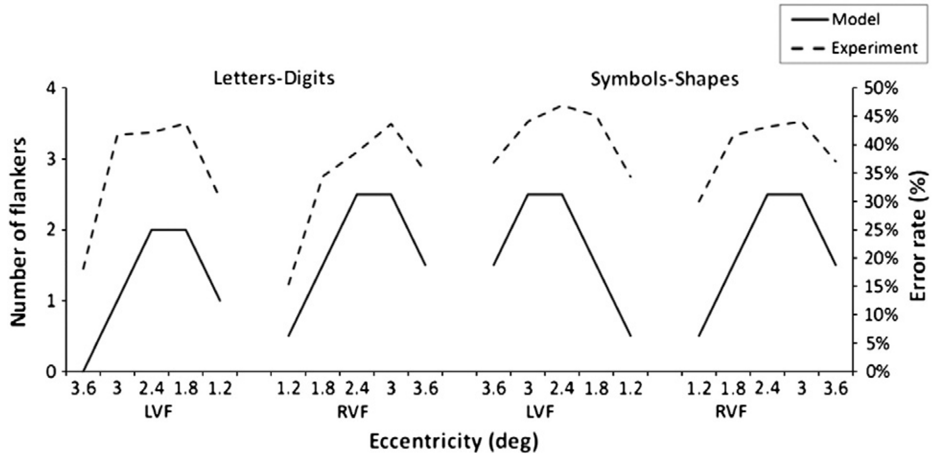

Fig. 11. Observed and simulated data. For the model (solid lines) the values are the number of complete flankers that fall in the theoretically defined receptive field. For the observed data (dashed lines) the values correspond to the error rate (%) averaged across all three experiments. Letter and digit stimuli in the left panel, and symbol and shape stimuli in the right panel. Note that eccentricity has been reversed in the LVF in order to maintain the left-to-right order of stimuli, and that observed data are errors not accuracy.

By measuring flanker interference by counting the number of flankers that fall in the receptive fields defined by Nandy and Tjan's (2012) model, we were able to provide a good fit to the results obtained with the non-letter stimuli in the present study. In line with the MRF hypothesis, we also obtained a good fit to the results of the letter stimuli by exaggerating the inward–outward symmetry of the basic model in order to simulate the condition where letter targets were presented in the LVF. There are some obvious oversimplifications in the present attempt to model serial position functions for letter and non-letter stimuli in peripheral vision, but the success of this approach suggests that it provides a promising foundational framework for future modeling efforts. One oversimplification is that we have not implemented a change in size of receptive fields for letter stimuli, as proposed by Tydgat and Grainger (2009), only a change in shape, given that this was the key aspect of receptive field modification behind the predictions tested in the present study. Since we did not include an isolated target condition in the present study, we have no means of comparing the size of crowding effects for letter and non-letter stimuli (no baseline condition), which is necessary in order to estimate the required modification in receptive field size. Future theoretical and empirical work is required in order to fully test the MRF hypothesis and its specific implementation using Nandy and Tjan's (2012) model of crowding.

6. Conclusions

According to the MRF hypothesis first proposed by Tydgat and Grainger (2009), and further developed in the present work, learning to read causes an adaptation of basic object processing mechanisms in order to optimize parallel letter processing. A key part of this adaptation is thought to involve a change in the size and shape of receptive fields of retinotopic letter detectors. One very specific modification, which was the focus of the present study, arises in order to optimize the processing of the initial letters of words. This is hypothesized to be accomplished by exaggerating the inward–outward asymmetry of receptive fields for letter stimuli presented in the LVF. The predictions of this MRF hypothesis were tested in three experiments in which strings of five characters (letters, digits, symbols, or shapes) were briefly presented in the LVF or RVF, and participants asked to identify a target character at a post-cued location. The results revealed the expected selective advantage for letter and digit targets at the initial position of strings is presented in the LVF.

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