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### Flank to the left, flank to the right: Testing the modified receptive field hypothesis of letter-specific crowding

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# Flank to the left, flank to the right: Testing the modified receptive field hypothesis of letter-specific crowding

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The present study tested for effects of number of flankers positioned to the left and to the right of target characters as a function of visual field and stimulus type (letters or shapes). On the basis of the modified receptive field hypothesis (Chanceaux & Grainger, 2012), we predicted that the greatest effects of flanker interference would occur for leftward flankers with letter targets in the left visual field. Target letters and simple shape stimuli were briefly presented and accompanied by either 1, 2, or 3 flankers of the same category either to the left or to the right of the target, and in all conditions with a single flanker on the opposite side. Targets were presented in the left or right visual field at a fixed eccentricity, such that targets and flankers always fell into the same visual field. Results showed greatest interference for leftward flankers associated with letter targets in the left visual field, as predicted by the modified receptive field hypothesis.

**Keywords:** Letter strings; Crowding; Flanker position; Letter-specific processing.

Research using functional magnetic resonance imaging (fMRI) has shown that a small portion of left ventral occipito-temporal cortex, referred to as the visual word form area (VWFA) plays a key role in visual word recognition (Cohen et al., 2000; see Dehaene & Cohen, 2011, for a review). More precisely, it is thought that the VWFA's main task is the processing of orthographic information—that is, information about which letters are where in the word. In order to explain the precise location of the VWFA amidst cortical structures involved in processing other kinds of visual objects, Dehaene and colleagues proposed what they referred to as “neuronal recycling theory” (e.g., Dehaene, 2005). The general idea is that when children learn to read, neural structures involved in basic object identification, and located in ventral occipito-temporal cortex, are “recycled” for the specific job of printed-word recognition.

Building on this general principle, Tydgate and Grainger (2009) suggested that one key part of the process of recycling or adaptation might involve modifications in the size of receptive fields of location-specific letter detectors, a proposal referred to as the “modified receptive field” (MRF) hypothesis by Chanceaux and Grainger (2012). The driving force behind this hypothesised adaptation would be the excessively crowded conditions to which letter-identification processes must adjust in order to achieve fluent parallel processing of the component letters of printed words. Indeed, the beginning reader has knowledge about individual letter identities, whereby each letter is processed as an individual object. When learning to process several letters together, each individual letter object is crowded by the presence of surrounding letter objects, thereby limiting the visibility of each of these letters. Implementing parallel independent letter

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processing, a hallmark of skilled reading (see Grainger, 2008 for a review of the evidence), requires a shift from processing letters as individual objects to processing them as object parts, and in doing so reducing the crowding associated with the close proximity of letters to each other. In Tydgate and Grainger's (2009) proposal, reduced crowding is achieved by reducing the size of the receptive field of location-specific letter detectors. Following Grainger and Van Heuven (2003), location-specific letter detectors are thought to be aligned horizontally (for languages read horizontally), and signal the presence of a given letter identity at a given location relative to eye fixation (the same mechanism is thought to also operate for parallel processing of digits during number processing). Reducing the spatial extent of the receptive fields of such letter detectors reduces the interference generated by neighbouring stimuli. In support of this proposal, Grainger, Tydgate, and Isselé (2010) reported lower levels of crowding with letter stimuli than symbol stimuli in adult participants.

Crowding is a general phenomenon associated with impaired visual object identification in cluttered scenes (for reviews, see Levi, 2008; Whitney & Levi, 2011). Although the underlying mechanisms are still not completely understood, one popular account is that crowding results from excessive pooling of featural information such that the visual features associated with a given target at a given location are mixed with the features associated with nearby flanking stimuli (e.g., Freeman & Pelli, 2007; Pelli, Palomares, & Majaj, 2004). The size of the region of such excessive feature integration increases linearly with eccentricity (Bouma, 1970) and this integration region has an elliptical shape, characterised by an inward-outward asymmetry with an elongation toward the periphery. Specific proposals as to possible mechanisms driving such excessive pooling vary from purely bottom-up accounts appealing to cortical receptive field structure (e.g., Levi, 2008; Nandy & Tjan, 2012) to top-down accounts, according to which the region of excessive feature integration is determined by spatial attention (Intriligator & Cavanagh, 2001). The MRF hypothesis builds on this general approach to crowding, with the key additional proposal that the region of excessive feature integration associated with letter stimuli is modified during reading acquisition in order to optimise parallel letter processing. More precisely, we hypothesise that, unlike other kinds of

visual objects, location-specific letter detectors are used to process multiple letters in parallel, and the integration region associated with such retinotopic letter detectors differs in size and shape from the integration region associated with the identification of other kinds of objects.

The MRF hypothesis was further developed by Grainger et al. (2010) on the basis of one key finding in that study. Grainger et al. (2010) compared the identification of isolated letter and symbol targets in the left visual field (LVF) and right visual field (RVF) with that of targets flanked by either a single character to the left or to the right, or with two flankers, one on each side of the target. They found that in the single-flanker condition, flankers located to the left of targets interfered more than flankers on the right, but only for letter stimuli located in the LVF. On the basis of this finding, Grainger et al. (2010) proposed a selective leftward elongation of the receptive fields of letter detectors in the LVF. That is, for a constant size, these receptive fields would capture more information to the left of the target than to the right.<sup>1</sup> This modification of the shape of receptive fields provides a simple mechanism for giving priority to the initial letters of words during visual word recognition. Enabling fast, accurate processing of the initial letter would be particularly beneficial for reading aloud, an activity that is important for beginning readers. Furthermore, as demonstrated by Dandurand, Grainger, Duñabeitia, and Granier (2011), initial letters provide more information with respect to word identity than any other letter position. Finally, another reason why a boost in initial letter processing might be important for efficient word recognition is that letters falling in the LVF are initially processed by neural structures in the right hemisphere, and therefore require more time to reach neural structures for orthographic processing in the left hemisphere (Ellis & Brysbaert, 2010).

The SERIOL model (Whitney, 2001) employs an alternative mechanism for endowing a word-beginning advantage in orthographic processing. The mechanism in question is unidirectional (beginning-to-end) lateral inhibition operating on retinotopic features, which, when accompanied by cross-hemispheric inhibition, transforms acuity-dependent activation levels into a monotonically

<sup>1</sup> This can be seen as an exaggeration of the typical inward-outward asymmetry that characterises the crowding zone of object identification (Bouma, 1978; Nandy & Tjan, 2012).

decreasing activation gradient (greatest activation at the beginning of words) in order to achieve a strictly serial encoding of letter order. However, the observation of distinct serial-position functions for letters compared with other kinds of visual stimuli (e.g., Tydgate & Grainger, 2009) has since motivated the introduction of retinotopic letters in a new version of the SERIOL model (SERIOL2; Whitney & Marton, 2013), such that unidirectional inhibition now operates on retinotopic letters rather than features. The idea now is that the monotonically decreasing activation gradient is learned during reading acquisition, and therefore would more naturally operate at the level of letter representations rather than visual features.

Returning to the main focus of the present study, the two essential ingredients of the MRF hypothesis to be tested here are: 1) a reduction in the size of receptive fields for location-specific letter detectors in order to reduce effects of crowding during parallel letter identification; and 2) a change in the shape of receptive fields for letter detectors in the left visual field, with an elongation of the receptive field to the left accompanied by a decrease in the extent of the receptive field to the right (for a change in shape with size held constant). The latter modification provides a simple mechanism for giving priority to initial letter processing. After specifying the MRF hypothesis as such, Chanceaux and Grainger (2012) sought further evidence in its favour by measuring identification accuracy of characters embedded in strings of 5 characters that could either be letters, digits, symbols, or shapes. Target location was post-cued, and could randomly be at any one of the 5 possible positions in the string, and strings were presented completely to the left or to the right of a central fixation mark. The MRF hypothesis predicted an advantage for letter and digit stimuli compared with symbol and shape stimuli that should be particularly strong at the initial position of strings presented in the LVF. The results of Chanceaux and Grainger (2012) were in line with this prediction. However, as Chanceaux and Grainger note in the discussion of their results, one key prediction of the MRF hypothesis still needs to be put to test. The prediction is that the number of leftward flankers associated with letter targets in the LVF should have a stronger impact on target identification than rightward flankers for the same targets, even if the rightward flankers are more

Structure	Letters	Shapes
FTF	RBK	○□◇
FTFF	RBKM	○□◇△
FFTF	MKBR	△◇□○
FTFFF	RBKMN	○□◇△☆
FFFTF	NMKBR	☆△◇□○

**Figure 1.** Description of the different types of flanker structure (F=flanker, T=target) tested in the experiment, and examples of the stimuli tested. In the examples, the target is always the letter B and the square shape, and flankers are different letters and shapes.

visible (being closer to fixation). Most critical is that this inward-outward asymmetry in flanker interference with letter targets in the LVF should be greater than the asymmetry for shape stimuli in the LVF. Performance in the RVF, on the other hand, should mostly reveal reduced crowding for letter stimuli relative to shape stimuli. Finally, it should be noted that the SERIOL2 model also predicts letter-specific and visual-field-specific processing differences driven by the hypothesised greater amounts of lateral inhibition between retinotopic letter detectors receiving input from the LVF than between retinotopic letter detectors for information falling in the RVF.

These predictions were put to test in the present study by manipulating the number of rightward and leftward flankers (flanker structure) for letter and shape targets (stimulus type) presented in the LVF and RVF (visual field) at a fixed eccentricity. Figure 1 provides examples of the different flanker structure conditions for the letter and shape stimuli. Overall we expect to observe an interaction between visual field and stimulus type, with performance for letters being higher than performance for shapes in the RVF, and this pattern possibly being reversed in the LVF, and particularly in the conditions with more leftward flankers, where performance for letters should be worse than for shapes.

## METHOD

### Participants

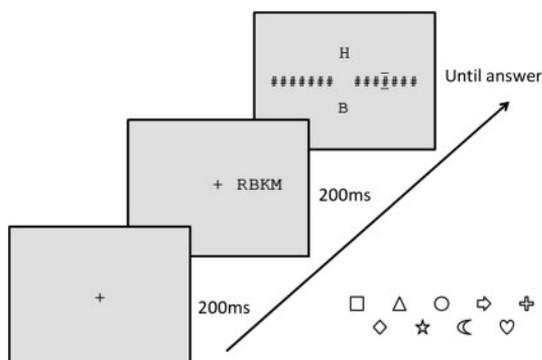
Twenty students from Aix-Marseille University participated in the experiment and received 5€. All of them reported normal or corrected-to-normal vision and were native speakers of French.

## Stimuli and design

Nine consonant letters (B, D, G, H, K, M, N, R, S) were used to construct random combinations of different consonants, and nine visually simple and highly familiar shapes (see Figure 2) were used to construct random combinations of different shapes. For each string of characters, one character served as the target on a given trial. The eccentricity of the target was fixed (at 3° left or right from fixation), and the number of flankers surrounding the target varied from trial to trial: one on each side (FTF, where ‘F’ represents a flanker and ‘T’ represents the target), one flanker on one side and two on the other side (FTFF or FFTF), or one flanker on one side and three on the other side (FTFFF or FFTTF). This defined the five levels of the factor Flanker Structure. Each letter and shape served as the target on 24 trials, half in the right visual field (RVF) and half in the left visual field (LVF), and for each of the five different flanker structures. Thus, Stimulus Type (letters vs. shapes) was crossed with Visual Field (LVF vs. RVF) and Flanker Structure (FTF, FTFF, FFTF, FTFFF, FFTTF) in a 2 × 2 × 5 factorial design. On a given trial, target and flanker stimuli were all different letters, or all different shapes.

## Apparatus and procedure

An EyeLink 1000 eye tracker (SR Research) was used to control for eye movements. Participants rested their forehead and chin on a chin rest at



**Figure 2.** A typical trial. Fixation cross for 200 ms, followed by a stimulus string presented to the left or right of fixation for 200 ms, and finally a backward mask accompanied by a post-cue and two alternatives for the 2AFC procedure. The shape

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°/sec and an acceleration threshold of 8000°/sec<sup>2</sup>). Stimuli were presented on a ViewSonic P227 monitor (refresh rate 100 Hz, screen size 1024 × 768) using Experiment Builder software (SR Research). Letters were presented in black 21-point Courier New font on a grey background. A character subtended about 0.6° horizontally and the target was at an eccentricity of 3°. The flankers could appear at between 1.2° and 4.8°. 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 nine-point calibration grid used to validate calibration accuracy.

On each trial, participants had first to gaze at the fixation cross at the centre of the screen. This fixation cross disappeared after a period of 200 ms, during which there were no eye movements outside an area of 50 × 120 around the cross (0.7° left or right). Then the letter/symbol string appeared either to the left or to the right of the fixation cross for 200 ms. Participants had to maintain central fixation during stimulus presentation, otherwise the trial was cancelled. After presentation of the string, a mask was presented, and a post-cue showed the position of the target character within the string 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 string. This final display remained until participants responded by choosing one of the alternatives, see Figure 2. 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 standard 2-alternative forced-choice (2AFC) procedure. An audio tone signalled a correct response. After participants' response, a blank screen was displayed and the next trial began.

Letters and symbols were presented in separate sessions, the order of which was balanced across participants. Visual Field and Flanker Structure varied randomly across all trials within each session. The experiment lasted about half an hour.

stimuli tested in the present study are shown bottom right.

## RESULTS

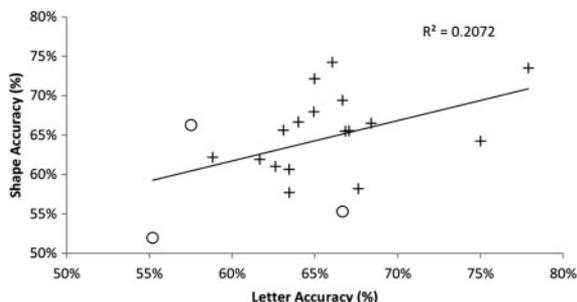
Three participants were removed from further analyses because they failed to reach above chance-level accuracy in one or both sessions of the experiment (Chi-squared test,  $p > .05$ , circles in Figure 3).

A repeated measures ANOVA was performed on the data for identification accuracy per condition and participant. The variables were Stimulus Type (letters or shapes), Visual Field (LVF or RVF) and Flanker Structure (FFFTF, FFTF, FTF, FTFF, FTFFF). The main effect of Stimulus Type was not significant ( $F(1, 16) = .08, p = .78$ ). There was a main effect of Flanker Structure ( $F(4, 64) = 25.17, p < .001$ ), with variation in performance following an inverted U-shaped function (see Figure 4) determined mostly by the total number of flankers in the display. The main effect of Visual Field was also significant ( $F(1, 16) = 4.73, p < .05$ ), with targets in the RVF being better identified than targets in the LVF (66.8% vs.

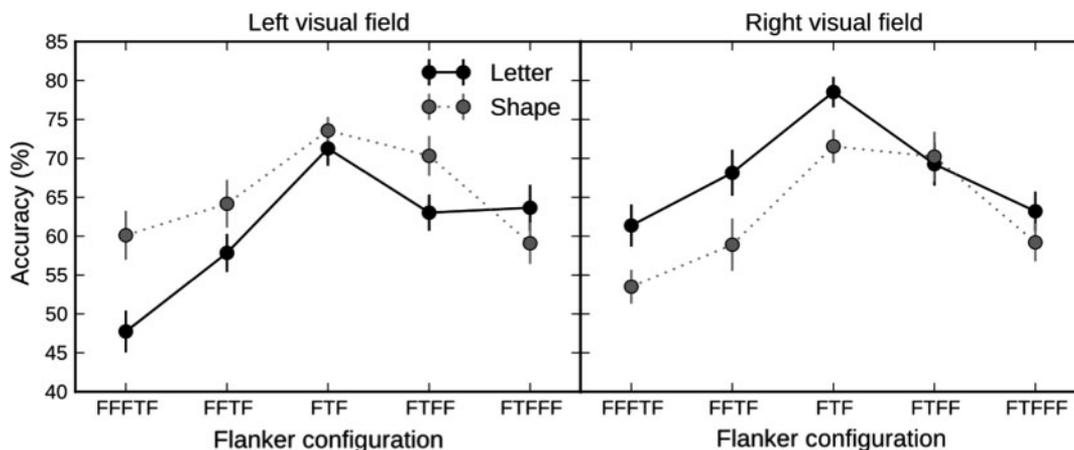
64.7%). Critically, there was a significant two-way interaction between Stimulus Type and Visual Field ( $F(1, 16) = 33.26, p < .001$ ). As can be seen in Figure 4, this two-way interaction is driven by the fact that accuracy is overall higher in the RVF for letters (69.6% vs. 62.5%,  $t(16) = 4.88, p < .001$ ), while in the LVF accuracy is overall higher for shapes (66.8% vs. 64.1%,  $t(16) = 2.21, p < .05$ ).

There was also a marginal three-way Stimulus Type  $\times$  Visual Field  $\times$  Flanker Structure interaction ( $F(4, 64) = 2.24, p = .074$ ). In the LVF, the critical interaction between Flanker Structure and Stimulus Type was significant ( $F(4, 64) = 3.09, p < .05$ ), but was not significant in the RVF ( $F(4, 64) = 1.10, p = .36$ ). The interaction between Stimulus Type and Flanker Structure in the LVF is driven by the asymmetrical effect of Flanker Structure seen with letter targets compared with the more symmetrical pattern seen with shapes. This is clearly due to the greater interference from leftward flankers compared with rightward targets for letter targets in the LVF.

The ANOVA was followed up with planned comparisons contrasting the effects of leftward (collapsed over FFFTF and FFTF) vs. rightward flankers (collapsed over FTFF and FTFFF) for letters in the LVF, where we expect to observe robust differences, compared with the same contrast for letters in the RVF and shapes in the LVF, where we expect to observe reduced effects. Leftward flankers caused a significant decrease in accuracy compared with rightward flankers for letter stimuli in the LVF ( $t(16) = 3.31, p < .005$ ). There was no significant difference between the leftward and rightward flanker conditions for



**Figure 3.** Average performance on letter stimuli and shape stimuli for the 20 participants tested in Experiment 1. Crosses represent the 17 participants retained for further analysis.



**Figure 4.** Mean 2AFC accuracy as a function of Stimulus Type (letters vs. shapes), Visual Field (LVF vs. RVF), and Flanker

letters in the RVF ( $t(16)=0.36, p=.72$ ), or for shape stimuli in the LVF ( $t(16)=0.93, p=.37$ ). Although this comparison falls beyond the scope of the MRF hypothesis, there was an effect of flanker condition for shape stimuli in the RVF ( $t(16)=3.22, p<.01$ ) such that there was increased interference for leftwards flankers. This intriguing effect and its relation to the MRF hypothesis remains to be further explored.

## DISCUSSION

The present study was designed to provide a further test of the MRF hypothesis first proposed by Tydgate and Grainger (2009) and refined by Grainger et al. (2010) and Chanceaux and Grainger (2012). The MRF hypothesis was introduced by Tydgate and Grainger (2009) as an explanation for the different patterns of serial-position functions seen for letter stimuli, compared with other kinds of visual stimuli (e.g., Hammond & Green, 1982; Mason, 1982; Pitchford, Ledgeway, & Masterson, 2008). The key idea behind the MRF hypothesis is that learning to read requires setting up a specialised system for parallel letter processing in the form of a horizontally aligned bank of location-specific letter detectors (Grainger & Van Heuven, 2003), accompanied by an adaptation of the size and shape of the receptive fields of these letter detectors in order to optimise orthographic processing. The two central ingredients of the MRF hypothesis are a reduction in the spatial extent of receptive fields for letters compared with other kinds of visual object, and the leftward elongation of receptive fields for letter detectors that receive information from the LVF. Maintaining a constant size, the leftward elongation causes a reduction in the rightward extent of the receptive field, thus reducing interference from rightward flankers and giving priority to the leftmost letter in the string (for languages that are written from left to right).

The MRF hypothesis predicted a selectively greater effect of leftward flankers for letter stimuli located in the LVF compared with both shape stimuli in the LVF and letter stimuli in the RVF. This was expected to diminish or even reverse the typical superiority for letter stimuli, which should be observable in the RVF due to the hypothesised reduced crowding for letters. In line with these predictions we observed a significant interaction between stimulus type and visual field, with greater accuracy to letters compared with

shapes in the RVF, and the opposite pattern in the LVF. Crucially, and as predicted by the MRF hypothesis, the lower accuracy to letters in the LVF was most evident in the conditions with more than one flanker to the left of targets (see Figure 4). Furthermore, the critical interaction between stimulus type and flanker structure was significant in the LVF and not in the RVF. This interaction seen with letter stimuli is clearly driven by the greater interference from leftward than rightward flankers. Shape stimuli, on the other hand, showed a similar drop in accuracy for leftward and rightward flankers in the LVF.

As noted in the Introduction, the SERIOL2 model of orthographic processing (Whitney & Marton, 2013) also correctly predicted a greater interference for letter stimuli in the LVF. Only simulations run with this complex model will tell whether it can accommodate the full pattern of results of the present study, but our understanding of the core mechanisms of the model suggests that this is certainly a possibility. The key difference between Whitney and Marton's (2013) approach and ours is that adaptation of basic visual object processing during reading acquisition is driven by very different goals: serial processing of letters in Whitney and Marton's approach, and parallel processing of letters in ours. Although maintaining a strictly serial letter processing mechanism would appear untenable in the face of certain empirical results (e.g., Adelman, Marquis, & Sabatos-DeVito, 2010), we agree that future research is necessary in order to tease apart these different accounts of letter-specific processing.

In conclusion, the present study provided a direct test of one clear prediction of the MRF hypothesis (Chanceaux & Grainger, 2012), whereby leftward flankers should generate more interference than rightward flankers when stimuli are letters presented in the LVF, compared with both letter stimuli presented in the RVF and shape stimuli presented in the LVF. The results are in line with the predictions, and therefore lend support to the hypothesis that learning to read causes an adaptation of relatively low-level visual processes aimed at optimising the uptake of orthographic information during reading.

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