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Side flankers produce less crowding, but only for letters

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ABSTRACT

Identification of isolated and crowded letter (B, D, F, G, K, N, L, S, T) and symbol stimuli (%, /, ?, @, }, <, £, §, µ) was examined across the visual field in a two-alternative forced-choice match-to-sample task (2AFC-MTS). During isolated presentation, identification accuracy did not differ between the two stimulus types. Identification rates for the central characters within the three-character strings were higher for letters than for symbols at the horizontal and vertical meridian (Experiment 1), and at diagonal locations (Experiment 2). However, this reduction of parafoveal letter crowding was present in horizontally but not in vertically oriented strings of stimuli. The same pattern of results was replicated in the periphery of the visual field (Experiment 3). The obtained results are in agreement with the proposition that the receptive fields of letter detectors are modified during reading acquisition, in order to support efficient letter identification (Tydgat & Grainger, 2009). However, the pervasive presence of the effect across the visual field suggests that it could originate from a non-retinotopic stage of visual processing.

1. Introduction

Reading is an essential skill in contemporary society. It enables a literate person to convert complex line patterns into meaning, effortlessly and within a fraction of a second. In the earliest phases of reading, representations of growing complexity are achieved through a series of processing stages. Since Selfridge's seminal *Pandemonium* model (Selfridge, 1959), it is commonly accepted that the recognition of visually presented words (at least in the languages that use alphabetic scripts) is based on the identification of their constituent letters, which in turn are identified on the basis of the visual processing of their features (for reviews, see Carreiras, Armstrong, Perea, & Frost, 2014; Grainger, 2008; Grainger & Dufau, 2012).

The perceptual basis of reading mirrors more general visual processing: the visual system performs the identification of letter features and their subsequent integration into individual letters much in the same way as with any other type of object (Dehaene & Cohen, 2007; Szwed, Cohen, Qiao, & Dehaene, 2009). However, unlike most other types of object, letters are typically presented in strings. This makes their identification particularly vulnerable to crowding – a detrimental influence of the surrounding objects (flankers) on target object identification (for reviews, see Levi, 2008; Whitney & Levi, 2011).

Crowding is a ubiquitous phenomenon of extrafoveal vision argued to present a bottleneck for both object recognition (Levi, 2008; Pelli & Tillman, 2008; Whitney & Levi, 2011) and reading (Legge et al., 2007; Pelli et al., 2007). The exact nature of the mechanism(s) responsible for crowding is still debated. It is often claimed to be a behavioral consequence of purely bottom-up processing (presumably exaggerated feature pooling) in early visual cortex (Pelli, 2008; Pelli & Tillman, 2008). By this account, crowding should be exclusively determined by a fixed-size critical spacing (the distance between the target and the flanker). Nevertheless, results of numerous studies show that it can be altered by factors other than critical spacing. Opposite contrast polarity of target and flankers (Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi, Toet, Tripathy, & Levi, 1994) and different colors of target and flankers (Kennedy & Whitaker, 2010; Kooi et al., 1994; Nazir, 1992; Põder, 2007) were shown to reduce crowding. Similarly, crowding can also be reduced by the grouping of multiple flankers (Livne & Sagi, 2007, 2010; Malania, Herzog, & Westheimer, 2007; Saarela & Herzog, 2009; Saarela, Sayim, Westheimer, & Herzog, 2009; Yeotikar, Khuu, Asper, & Suttle, 2011), by directing attention to the target locations ("precueing"; Felisberti, Solomon, & Morgan, 2005; Huckauf & Heller, 2002; Morgan, Ward, & Castet, 1998; Strasburger, 2005; Van der Lubbe & Keuss, 2001; Yeshurun & Rashal, 2010; but see also Freeman & Pelli, 2007), or when

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flankers and targets substantially differ in complexity (Zhang, Zhang, Xue, Liu, & Yu, 2009). Herzog and Manassi (2015) in a recent overview of these studies have offered a strong argument against the conventional, exclusively bottom-up account of crowding.

Among the many findings of different factors that can influence crowding, of particular interest for our study is the report that letters are less prone to crowding than other types of objects (Grainger, Tydgat, & Isselé, 2010). This effect is explained by the "modified receptive field" (MRF) hypothesis (Chanceaux & Grainger, 2012; Chanceaux, Mathôt, & Grainger, 2013; Grainger et al., 2010) that was originally put forward in Tydgat and Grainger (2009). The MRF hypothesis is built upon the "neuronal recycling" theory according to which a part of the object recognition system is modified during reading acquisition in order to make fluent reading possible (Dehaene, 2005; Dehaene & Cohen, 2007). The MRF account hypothesizes the modification would be instigated in order to ensure the efficient parallel identification of each letter within a fixated word in a highly cluttered environment (parallel letter processing is assumed by the contemporary models of word recognition, e.g. Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger & van Heuven, 2003; McClelland & Rumelhart, 1981; but for serial accounts see also Davis, 2010; Whitney, 2011). Specifically, it hypothesizes that the reduced crowding is caused by the decrease in size of the receptive fields of a bank of location specific letter detectors placed along the horizontal meridian ("alphabetic array"; Grainger & van Heuven, 2003).[1] Grainger and colleagues accept the view of crowding as compulsory pooling of all the features that fall within the receptive field of a neuron (Freeman & Pelli, 2007; Pelli, Palomares, & Majaj, 2004) and argue that the proposed shrinking of the receptive fields of letter detectors would decrease the negative influence of the surrounding letters on the identification of each particular letter presented within a string through the reduction of the undesired, compulsory pooling of features that do not belong to the target. This facilitation of parallel identification of letters presented within strings would aid successful reading.

The impairment of successful reading, dyslexia, is lately also linked to crowding. In particular, in developmental dyslexia, crowding disrupts acquisition of reading. Reading rate that drops in the periphery of the visual filed of skilled readers, is significantly more damaged in dyslexia and the dyslexic reading loss has a structure similar to the normal peripheral reading loss (Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009). Dyslexic children tend to avoid highly unpleasant reading training, which in return decreases the amount of practice. This might be very similar to the lack of practice in regular readers for the peripheral visual field, making peripheral reading "acquisition" and disadvantages a good model of dyslexia. This effect of practice seems to be key, as dyslexics show a reading skill difference when it comes to letters vs. symbols (Ziegler, Pech-Georgel, Dufau, & Grainger, 2010) and longer letter strings present an extreme problem in dyslexia, providing further similarity with crowding and peripheral reading in regular readers (De Luca, Burani, Paizi, Spinelli, & Zoccolotti, 2010). Clearly, determining the role of practice in the elimination of crowding effects might aid our understanding of some aspects of reading problems in developmental dyslexia.

The MRF account hypothesizes that the reduced letter crowding effect is a consequence of visual experience during reading acquisition. Support for such a notion can be found in the results of several studies in which a reduction in crowding was obtained through training (Chung, 2007; He, Legge, & Yu, 2013; Huckauf & Nazir, 2007; Hussain, Webb, Astle, & McGraw, 2012; Sun, Chung, & Tjan, 2010). In the two studies where a lower level of crowding for letters was found (Chanceaux & Grainger, 2012; Grainger et al., 2010), the stimuli were presented in the part of the visual field where reading normally takes place (the horizontal meridian in the parafovea) and in the standard text format (horizontal strings). Thus, the question of whether reduced letter crowding is conditioned by the characteristics of the experience that the visual system receives during reading acquisition was not previously examined. Endorsing the suggestion that such an effect is a result of visual experience, in this paper we present three experiments to more fully scrutinize reduced letter crowding.

2. Experiment 1

In Experiment 1 we tested isolated (Experiment 1a) and crowded (Experiment 1b) identification of letters and symbols at the horizontal and the vertical meridian of the parafovea. Since the procedure that we used was similar to Grainger et al. (2010), we expected to replicate their original findings of comparable levels of correct identification for individual letters and symbols, and the superior identification of letters than symbols in the circumstances of horizontal crowding. Given the MRF hypothesis (Chanceaux & Grainger, 2012; Grainger et al., 2010) proposed that the shrinking of the receptive fields takes place in retinotopic letter-shape detectors placed along the horizontal meridian in the vicinity of fixation, this account would predict that the decreased crowding for letters should not be observable at other locations in the visual field. On the other hand, one recent study (He et al., 2013) showed that the training induced reduction of letter crowding transfers almost completely to untrained peripheral locations, thus suggesting that the relief from crowding might be driven by a nonretinotopic mechanism. In Experiment 1 we examined these two predictions.

In this experiment we also examined whether the effects of crowding are dependent on string orientation. The MRF hypothesis is not explicit in this respect, but it does not specifically predict different letter crowding effects depending on the orientation of letter strings. However, if the reduced crowding of letters is indeed driven by the readers' visual experience it could be anticipated that the effect shall remain limited to horizontally oriented strings only, since all our participants have had extensive experience in processing horizontal but not vertical strings of letters. Such a prediction is in accordance with several findings of superior processing of text in the standard, horizontal orientations: Byrne (2002) showed that horizontally oriented text is read faster than vertically oriented text,[2] whereas Yu, Park, Gerold, and Legge (2010) and Babkoff, Faust, and Lavidor (1997) showed that this horizontal orientation advantage is present even when the influence of oculomotor factors is experimentally eliminated. The Yu et al. study demonstrated that faster processing of horizontal text is probably caused by a larger horizontal visual span, which in turn is believed to be crucially (Legge et al., 2007) or uniquely (Pelli et al., 2007) determined by crowding. Thus, even though the Yu et al. study examined visual span and not directly crowding, its findings suggest that lower levels of crowding could be expected for the horizontally in contrast to the vertically oriented strings of letters. Finally, in a visual short-term memory task superior performance with letters in comparison to symbols was conditional on horizontal string orientation (Ktori, Grainger, & Dufau, 2012).

Drawing upon and extending the work of Grainger et al. (2010) we sought to follow the methods used in their study as closely as

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[1] The MRF hypothesis also postulates the change in the shape of the receptive fields of letter detectors. In this study, however, we do not test this assumption but rather focus on the proposed shrinking of the receptive field size only.

[2] Experience with vertical formats can cancel out the horizontal orientation advantage. For example, no effect of text orientation was found in the study of Oda, Fujita, Mansfield, and Legge (1997) in which the participants were Japanese readers who had experience with text processing in both orientations.

possible. In effect, the same combination of crowding and a backward masking paradigm was employed in our experiments, where the function of the latter was to prevent ceiling effects (in the isolated presentation conditions). The use of backward masking is obviously not a prerequisite for the investigation of crowding or the experience-driven attenuation of letter crowding in particular, but we believe that the application of this particular paradigm should not negatively affect the outcome of the current experiments.

2.1. Method

2.1.1. Participants

Twenty psychology students from the University of Novi Sad, Serbia, with normal or corrected to normal vision took part in the experiment. All participants were right-handed and native Serbian readers, accustomed to common, everyday reading of both the Roman and the Cyrillic alphabet (i.e. literate Serbians are typically fluent bi-alphabets).

2.1.2. Apparatus

Experiments were run in MATLAB environment (The Mathworks Inc., Natick, MA, 2010) with Psychtoolbox 3 extensions (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). The stimuli were presented on a 19″ CRT (Viewsonic G90FB) monitor with a resolution of 1152 × 864 pixels and a refresh rate set at 75 Hz. A chin rest was used to ensure that the stimuli were viewed from a fixed position at a distance of 60 cm.

2.1.3. Stimuli and design

As in Grainger et al. (2010), the stimuli were made up of nine letters (B, D, F, G, K, N, L, S, T) and nine keyboard symbols (%, /, ?, @, }, <, £, §, µ) presented in the Courier New font. A single (isolated) target character was presented in Experiment 1a, whereas the central character within a string of three different characters of the same type (i.e. three letters or three symbols) was the target in Experiment 1b. Black stimuli (luminance: 0.27 cd/m^2) were presented on a white background (luminance: 90 cd/m^2). The stimuli were presented at the horizontal meridian (half the trials to the left and half the trials to the right of the fixation point), and at the vertical meridian (half the trials above and half the trials bellow the fixation point). Target eccentricity was 1.5° of visual angle from the fixation point. Characters subtended 0.44° of visual angle and the center-to-center spacing between the characters that were presented in strings was 0.6°.

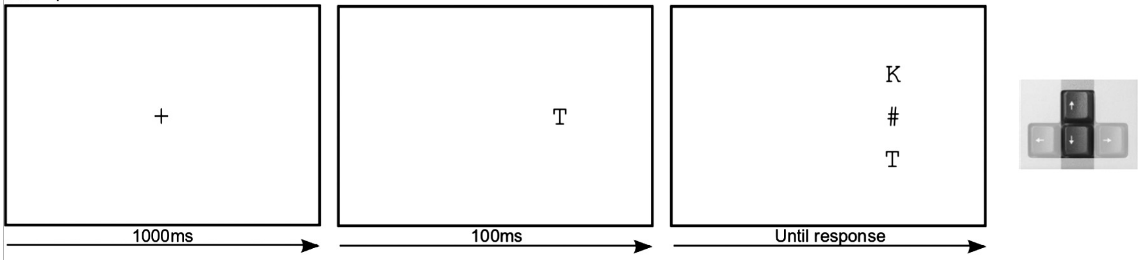
In Experiment 1a, the two tested factors were Stimulus Type (letter vs. symbol) and Location (horizontal meridian vs. vertical meridian). A total of 144 trials were presented in a random order, given that each character was presented eight times (two times into the left, to the right, above and below fixation; i.e. four times at the horizontal meridian and four times at the vertical meridian). Three factors were tested in Experiment 1b: Stimulus Type (letter vs. symbol), Location (horizontal meridian vs. vertical meridian) and String Orientation (horizontal string vs. vertical string). The addition of the third factor resulted in a total of 288 trials for Experiment 1b.

2.1.4. Procedure

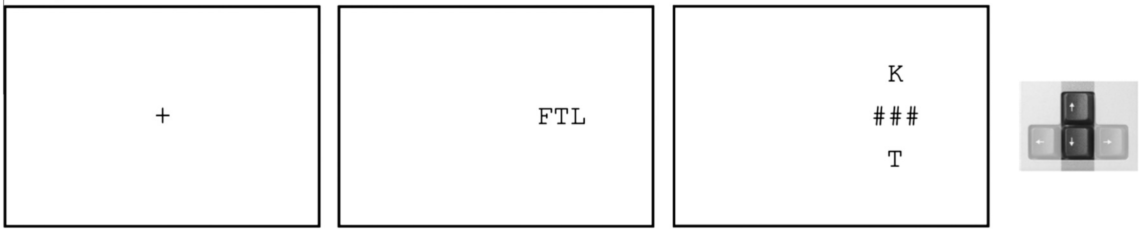
Within a single experimental session, participants first took part in Experiment 1a and then in Experiment 1b.

A two-alternative forced-choice match-to-sample (2AFC-MTS) task was used in Experiment 1a. Participants were given written and oral instructions, as well as twelve practice trials before each part of the experiment started. Fig. 1 illustrates the sequence of events in a trial. Each trial commenced with a fixation mark that

(a) Experiment 1a



(b) Experiment 1b: horizontal orientation block



(c) Experiment 1b: vertical orientation block

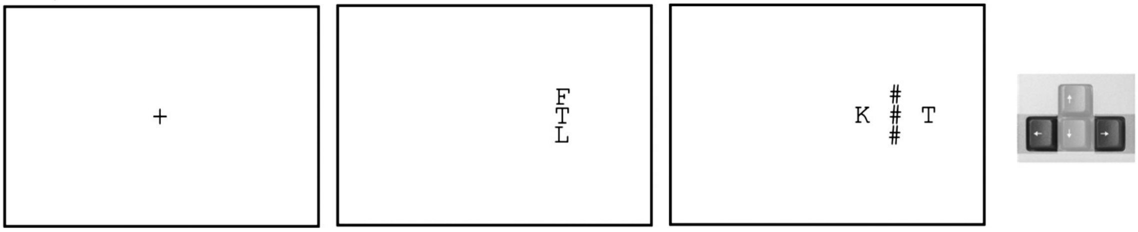


Fig. 1. Illustration of the three screens (fixation mark, stimulus, response) presented in a trial and response keys in Experiment 1. (a) Procedure and stimuli used in Experiment 1a, (b) horizontal orientation block of Experiment 1b, (c) vertical orientation block of Experiment 1b. The horizontal meridian letter condition is used here for illustration.

appeared at the center of the screen for 1000 ms. After the fixation mark disappeared, the stimulus (a single character) was presented for 100 ms, and was followed by a backward mask – a hash symbol (#) at the location of the previous stimulus. Two other characters (of the same stimulus type as the previously presented stimulus) were also presented together with the mask. One of these two characters was located above the mask and the other below it. The task was to decide which of the two characters matched the stimulus. Participants responded by pressing the upward arrow key or downward arrow key on the computer keyboard. After the response, the screen was cleared, and a new trial began with the onset of the fixation mark. Participants could make one short break after responding to half the trials in Experiment 1a.

The procedure used in Experiment 1b was similar, except for two differences. The first difference was that the stimuli consisted of three different characters of the same type (letters or symbols), rather than a single character as in the case of Experiment 1a. The central character within the string was the target, and the outer two (randomly chosen from the remaining eight characters of the same type) were the flankers. The backward mask accordingly consisted of three hash marks (###). As in Experiment 1a, the participant had to decide which of two offered alternatives was the target. The presentation of the stimuli in two different string orientations was the cause of the second procedural difference in Experiment 1b. For the horizontal string trials, the position of the two alternative answers on the screen (above and below the central hash mark) and the response keys that the participants used (upward arrow and downward arrow) were the same as in Experiment 1a (Fig. 1; panel b). Conversely, in the vertical string trials, the vertically oriented string of three hash marks (the backward mask) were used while the two alternative answers were placed to the left and the right of the central hash mark in that string. The participants would accordingly answer by pressing leftward or rightward arrow key (Fig. 1; panel c). Horizontal and vertical string trials were presented in separate blocks, with the order counterbalanced across participants. The string orientation blocking was employed in order to preserve the two-alternative nature of the task (i.e. in order to ensure that the participants always knew that there were only two response keys that were available to them). Participants were offered two short breaks during Experiment 1b. In total, the duration of the experimental session was approximately 25 min.

2.1.5. Data analysis

In all reported experiments, binomial accuracy data was analyzed by modeling the generalized linear mixed effects (GLME; Baayen, 2008; Baayen, Davidson, & Bates, 2008; Jaeger, 2008). The mixed logit model analyses were carried out in the R environment (R-Core Development Team, 2013), using the *glmer* function of the *lme4* package (Bates, Maechler, & Bolker, 2013) and the *ggplot2* package (Wickham, 2009) was used for visualizations. The factors of interest, specified in the design section of each experiment, were modeled as fixed effects. In order to minimize their collinearity and make the interpretation of the computed coefficients straightforward (Baayen, 2008), factor labels were transformed into numerical values and centered as to have a mean of 0 and a range of 1. For each experiment a model with the maximum random effect structure justified by the data (intercepts and slopes for the random effects of participants and targets) is reported.

2.2. Results

2.2.1. Experiment 1a

Mean response accuracy in Experiment 1a was 89.66%. Response accuracy in the four experimental conditions is shown in Fig. 2.

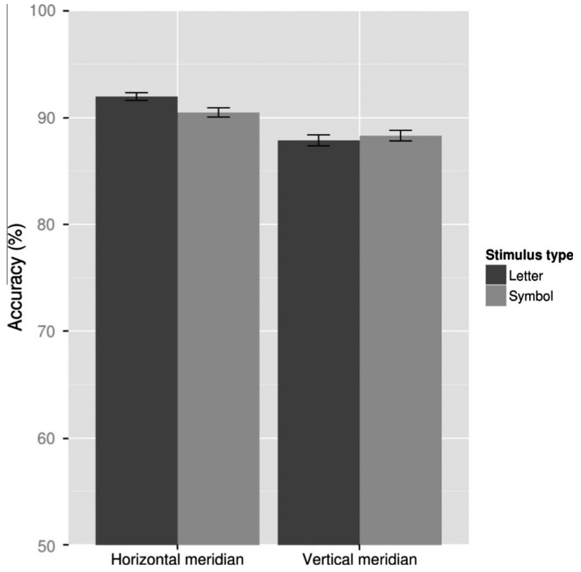


Fig. 2. Mean response accuracy in four experimental conditions of Experiment 1a. Error bars indicate ±1SEM.

Table 1
Summary of GLME results for Experiment 1a.

Parameter	Estimate	*SE*	Wald *z*	*p*
(Intercept)	2.307	0.153	15.077	<0.001
Stimulus Type	−0.072	0.129	−0.561	0.575
Location	−0.355	0.129	−2.752	0.006
Stimulus Type × Location	0.231	0.258	0.896	0.370

Table 1 shows the results of the GLME model of Experiment 1a. The only random parameter included in the model was the random intercept for participants, since model comparisons did not justify the inclusion of random slopes for participants nor the random intercepts and slopes for targets. There was a significant main effect of Location, produced by somewhat higher performance at the horizontal meridian. No significant difference in identification accuracy for letters and symbols was observed, and the interaction between the two factors was not significant either.

2.2.2. Experiment 1b

Mean response accuracy in Experiment 1b was 65.99% and the percentage of correct responses in the eight conditions of Experiment 1b is shown in Fig. 3.

Table 2 shows the results of the GLME model of Experiment 1b. A significant Stimulus Type × String Orientation interaction was registered. As Fig. 3 illustrates, the interaction was produced by the superior identification of the horizontal letter strings (in comparison both to the vertical letter strings and the symbol strings in either orientation). In accordance, separate analyses that were conducted for letters and symbols showed a significant main effect of String Orientation for letters ($\beta = -0.485$, $SE = 0.086$, $z = -5.618$, $p < 0.001$), but not for symbols ($\beta = -0.032$, $SE = 0.081$, $z = -0.398$, $p > 0.1$). Secondly, a significant Location × String Orientation interaction was also registered in the model. Separate analyses for horizontal and vertical meridian locations confirm the pattern presented in Fig. 3. Main effect of String Orientation for the stimuli presented at the horizontal meridian was not significant ($\beta = -0.046$, $SE = 0.084$, $z = -0.549$, $p > 0.1$), whereas the identification on the vertical meridian was more successful for the targets presented within horizontal strings than for the targets presented within vertical strings ($\beta = -0.549$, $SE = 0.083$, $z = -6.648$,

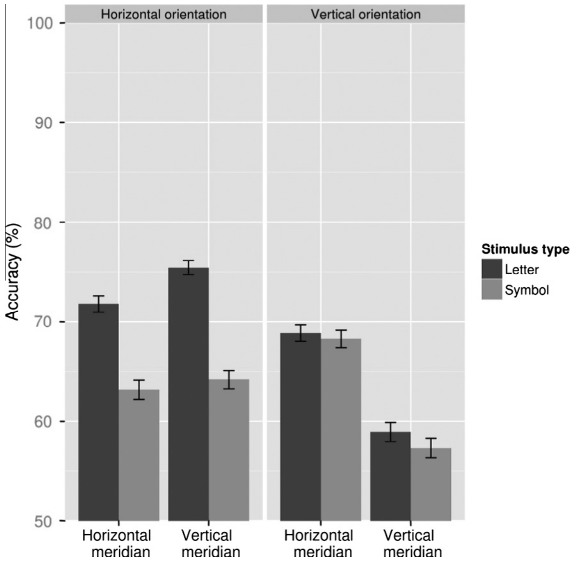


Fig. 3. Mean response accuracy in eight experimental conditions of Experiment 1b. Error bars indicate ±1SEM.

Table 2
Summary of GLME results for Experiment 1b. Random intercepts were modeled for participants and targets, and the "Slope" column indicates if the random slope corrections for the fixed effect parameters (p – participant, t – target) were also included in the model.

Parameter	Estimate	*SE*	Wald *z*	*p*	Slope
(Intercept)	0.746	0.135	5.547	<0.001	
Stimulus Type	−0.321	0.168	−1.914	0.056	p
Location	−0.172	0.060	−2.883	0.004	
String Orientation	−0.270	0.060	−4.536	<0.001	
Stimulus Type × Location	−0.132	0.119	−1.111	0.267	
Stimulus Type × String Orientation	0.525	0.159	3.314	<0.001	p
Location × String Orientation	−0.723	0.202	−3.581	<0.001	p
Stimulus Type × Location × String Orientation	0.197	0.238	0.825	0.409	

$p < 0.001$). A non-significant three-way interaction between the factors examined in Experiment 1b shows that the effect of Location × String Orientation was not different for letters and symbols.

Finally, a large drop in performance in Experiment 1b in comparison to Experiment 1a (23.67%[3]), is reflected as the significant main effect of Experiment in the joint analysis of the two parts of Experiment 1 ($\beta = -1.554$, $SE = 0.071$, $z = -21.984$, $p < 0.001$).

2.3. Discussion

The success rates for the identification of single characters (Experiment 1a) were high, similar for letters and symbols, and comparable to the results of Grainger et al. (2010). Matching levels of correct identification for isolated letters and symbols contradict the possibility that the processing of letters is inherently easier than the processing of some other symbols. Thus, the eventual effects in the processing of strings (Experiment 1b) can indeed be attributed to crowding.

The results of Experiment 1a revealed a slight advantage for identification at the horizontal meridian in comparison to the vertical meridian, irrespectively of the stimulus type. Such an outcome is not surprising, since the general advantage of the visual processing at the horizontal meridian had been established in numerous studies (Altpeter, MacKeben, & Trauzettel-Klosinski, 2000; Anderson, Wilkinson, & Thibos, 1992; Cameron, Tai, & Carrasco, 2002; Carrasco, Talgar, & Cameron, 2001; Carrasco, Williams, & Yeshurun, 2002; Pointer & Hess, 1989; Regan & Beverley, 1983; Seiple, Holopigian, Szlyk, & Wu, 2004; Silva et al., 2010; Weymouth, Hines, Acres, Raaf, & Wheeler, 1928), and is probably caused by the anatomic organization of the visual system (Abrams, Nizam, & Carrasco, 2011; Connolly & Van Essen, 1984; Curcio & Allen, 1990; Curcio, Sloan, Kalina, & Hendrickson, 1990; Tootell, Switkes, Silverman, & Hamilton, 1988).

Correct identification of the characters presented in strings (Experiment 1b) dropped substantially in comparison to the presentation of single characters as a consequence of crowding. In these circumstances, the identification of letters was superior to symbols, but only when the stimuli were presented in horizontal strings. In contrast, vertically crowded letters were identified with equal success as the vertically oriented symbols. Thus, the results of Experiment 1b replicated the findings of reduced crowding of letters (Grainger et al., 2010), but only if the letters were presented in the format to which the participants had been accustomed in normal reading. Furthermore, the same pattern of results was established both on the horizontal and the vertical meridian in the parafovea. Such a generalization of the effect to untrained locations is unexpected by the MRF account (Chanceaux & Grainger, 2012; Grainger et al., 2010), but is in agreement with the findings of He et al. (2013) that show practically complete transfer of the training induced reduction of letter crowding to untrained locations in the visual field.

Whereas the single characters (both letters and symbols) were somewhat better identified when they were presented at horizontal locations, in the presentation of strings the performance at horizontal and vertical locations depended on string orientation (i.e. position of flankers). At the vertical meridian the identification of letters and symbols was higher when they were presented in horizontal strings, while at the horizontal meridian the performance was slightly (though not significantly) higher for the vertical strings. This pattern of results reflects the radial–tangential anisotropy of crowding – a phenomenon of a more exaggerated interference of target identification by radially than tangentially positioned flankers (Toet & Levi, 1992).

3. Experiment 2

Experiment 1 showed that there was a significant interaction of Stimulus Type with String Orientation, which was driven by the reduction of letter crowding for the horizontal but not the vertical strings. However, the presence of another interaction – String Orientation × Location – could have obscured this principal finding of Experiment 1 to some extent. In order to provide an additional test of the outcome of the first experiment, in Experiment 2 we shifted the presentation of the stimuli to diagonal parafoveal locations. On the basis of the results of Experiment 1, we expected equal identification of single letters and symbols in Experiment 2, and a significant Stimulus Type × String Orientation interaction when the three character strings were presented. However, since the Location × String Orientation interaction in Experiment 1 was a consequence of the radial–tangential anisotropy of crowding, we expected that it should not be encountered in the results of Experiment 2: when the stimuli are presented at diagonal locations, the horizontal and vertical flankers are not aligned on the

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[3] Multiplication of this value by the factor of two would give a more appropriate assessment of the performance drop, since the chance level performance in the experiments was 50% and therefore the theoretical range of correct responses was 50–100%. Calculated with respect to the theoretical range of responses, the drop in performance between the two parts of the Experiment 1 was 47.34%.

radial or tangential axes relative to the fovea. At the same time, the results of this experiment should complete the picture of reduced letter crowding effects all around the parafovea. As previously discussed, the MRF hypothesis predicts that the effect should be observable along the horizontal meridian of the parafovea only, whereas the results of our Experiment 1 showed that it is generalized to zones of the parafovea where practice in reading normally does not take place (i.e. the vertical meridian). If the conclusion that the decrease of letter crowding is not conditioned on their precise location in the visual field is correct, we expected that it should be observable at diagonal parafoveal locations, too.

3.1. Method

3.1.1. Participants

Twenty psychology students from the University of Novi Sad, different from those that were tested in Experiment 1, took part in Experiment 2. All participants were right-handed, native Serbian readers and had normal or corrected vision.

3.1.2. Apparatus, stimuli, design and procedure

The apparatus and stimuli were the same as in Experiment 1. In contrast to Experiment 1, in which the stimuli were presented at the horizontal and vertical meridians, the stimuli in Experiment 2 were presented at diagonal parafoveal locations (Appendix A). In order to make the results of Experiment 2 directly comparable with the results obtained in Experiment 1, and in the absence of theoretical motivation for separate analyses of performance at each of the four diagonal locations, we examined the upper-left and the lower-right locations jointly and referred to them as diagonal 1, while the joint performance at the lower-left and the upper-right locations is referred to as diagonal 2. In this way, Experiment 2 was essentially a repetition of Experiment 1, albeit with a 45° shift of the location of stimulus presentation. Except for this, the method used in Experiment 2 was identical to the method of Experiment 1. Experiment 2 also consisted of two parts. Isolated characters were presented in Experiment 2a, in which the two tested factors were Stimulus Type (letter vs. symbol) and Location (diagonal 1 vs. diagonal 2). In Experiment 2b, strings of three characters were presented, and the three tested factors were Stimulus Type (letter vs. symbol), Location (diagonal 1 vs. diagonal 2) and String Orientation (horizontal string vs. vertical string).

3.2. Results

3.2.1. Experiment 2a

Mean response accuracy in Experiment 2a was 87.95%. Response accuracy in the four experimental conditions is presented in Fig. 4.

As in Experiment 1a, the only random parameter included in the model was the random intercept for participants, since model comparisons did not justify the inclusion of random slopes for participants nor the random intercepts and slopes for targets. No significant fixed effects were registered in Experiment 2a, as Table 3 illustrates.

3.2.2. Experiment 2b

Mean response accuracy in Experiment 2b was 63.72%. The percentage of correct responses in the eight conditions of Experiment 2b is presented in Fig. 5.

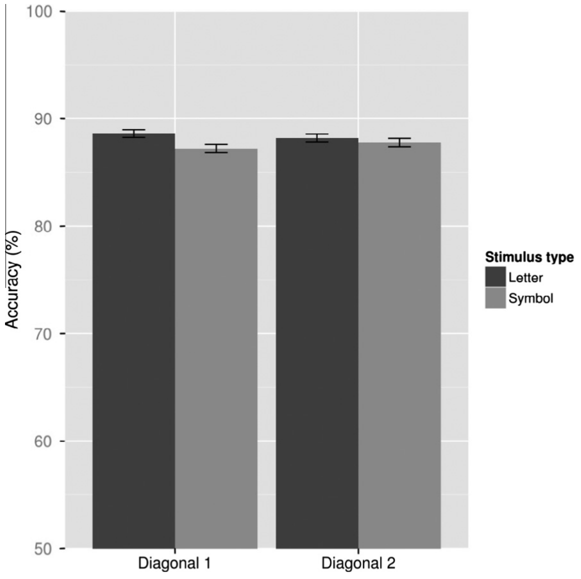

Fig. 4. Mean response accuracy in four experimental conditions of Experiment 2a. Error bars indicate ±1SEM.

Table 3
Summary of GLME results for Experiment 2a.

Parameter	Estimate	*SE*	Wald *z*	*p*
(Intercept)	2.447	0.237	8.937	<0.001
Stimulus Type	−0.098	0.123	−0.800	0.424
Location	−0.006	0.123	−0.049	0.961
Stimulus Type × Location	0.106	0.246	0.430	0.667

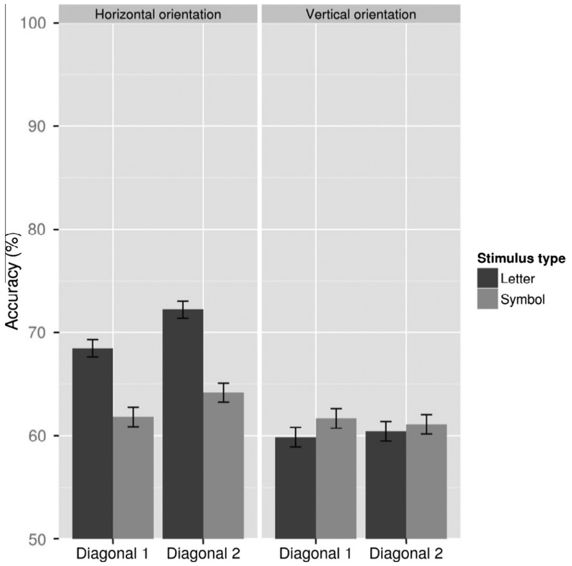

Fig. 5. Mean response accuracy in eight experimental conditions of Experiment 2b. Error bars indicate ±1SEM.

Table 4 shows the results of the GLME model of Experiment 2b, in which a significant Stimulus Type × String Orientation interaction was observed. As Fig. 5 illustrates, the interaction was caused by the superior target identification of the horizontal letter strings than the vertical letter strings or the symbol strings in either orientation. This pattern of results was confirmed in the separate analyses for letter and symbol stimuli: the main effect of String Orientation was significant in the letter analysis ($\beta = -0.473$, $SE = 0.080$, $z = -5.889$, $p < 0.001$), but not in the symbol analysis ($\beta = -0.070$, $SE = 0.078$, $z = -0.904$, $p > 0.1$). No other significant interaction effects were observed.

Table 4
Summary of GLME results for Experiment 2b. Summary of GLME results for Experiment 1b. Random intercepts were modeled for participants and targets, and the "Slope" column indicates if the slope corrections for the fixed effect parameters (p – participant, t – target) were also included in the model.

Parameter	Estimate	*SE*	Wald *z*	*p*	Slope
(Intercept)	0.597	0.096	6.241	<0.001	
Stimulus Type	−0.150	0.090	−1.672	0.095	
Location	0.074	0.056	1.320	0.187	
String Orientation	−0.298	0.079	−3.776	<0.001	p
Stimulus Type × Location	−0.065	0.111	−0.587	0.563	
Stimulus Type × String Orientation	0.405	0.111	3.616	<0.001	
Location × String Orientation	−0.148	0.111	−1.322	0.186	
Stimulus Type × Location × String Orientation	0.034	0.224	0.154	0.878	

A large, 24.24% drop in performance[4] in Experiment 2b in comparison to the Experiment 2a can be observed from the corresponding figures and is confirmed by the significant main effect of Experiment in the joint analysis of the two parts of Experiment 2 ($\beta = -1.476$, $SE = 0.065$, $z = -22.845$, $p < 0.001$).

3.3. Discussion

Identification of single characters at diagonal locations was high and comparable to the levels registered in Experiment 1a. As in Experiment 1a, the performance for individual letters and symbols was similar, suggesting that the eventual differences in the results for the two types of string stimuli should be attributed to the differences in their crowding. While in Experiment 1a a significant effect of Location was produced by better identification of single characters at the horizontal meridian, no effect of Location was registered in Experiment 2a, suggesting matched levels of performance at the two parafoveal diagonals.

Due to crowding, the performance in the string stimuli was, as expected, lower than in single characters, and was at the level previously registered in Experiment 1b. Rates of correct identification did not differ for letters and symbols presented within vertical strings. In contrast, a significant release from crowding was observed for letters but not symbols presented in horizontal strings. Thus, the results of Experiment 2b confirmed the main finding of Experiment 1 – letters were less crowded than symbols, but only when they were presented in horizontally oriented strings. In accordance with the findings of He et al. (2013), the presence of the effect at the diagonal locations shows that it is generalized to locations where practice in letter identification (i.e. reading) normally does not take place. Such a transfer is not expected by the present version of the MRF hypothesis (Chanceaux & Grainger, 2012; Grainger et al., 2010), as this account places the effect at the level of letter detectors that are presumably location-specific and aligned along the horizontal meridian.

As predicted, placing the string stimuli at diagonal positions did cancel out the interaction of String Orientation and Location. Therefore, the conclusion that the presence of this interaction in the results of Experiment 1b was a consequence of radial–tangential anisotropy in crowding is confirmed by the results of Experiment 2b. In this way, Experiment 2 provided further direct evidence that the reduced letter crowding effect depends on string orientation.

4. Experiment 3

In the first two experiments we found the reduced letter crowding at various parafoveal locations. In the discussion sections of these experiments, we argued that the presence of this effect beyond the horizontal meridian is not in line with the MRF hypothesis, since it assumes that the effect emerges at the level of the location specific letter detectors (placed in the vicinity of fovea and aligned along the horizontal axis). However, the extent to which such detectors should be location specific was not specified by the MRF hypothesis, and the size of receptive fields of neurons in the V4, the zone where the proposed detectors are putatively located in the LCD model of Dehaene et al. (2005), is sufficient to tolerate a moderate deviation in this respect.[5] Thus, in Experiment 3 we present a stronger test for the spatial generalization of the effect that we observed in the previous experiments. In this experiment the stimuli were presented at larger, peripheral eccentricities in the visual field. If the effect of reduced horizontal crowding for letters is indeed independent of the location where the stimuli are presented, its presence should be encountered deep in the periphery of the visual field, too. Such an outcome would demonstrate that the effect is a general characteristic of letter crowding, one that indeed is not restricted to the retinal locations where reading is normally performed and practiced. While this could be expected having in mind the results of the training study of He et al. (2013), this result would clearly contradict the prediction based on the MRF hypothesis in its present form (Chanceaux & Grainger, 2012; Grainger et al., 2010).

4.1. Method

4.1.1. Participants

Twenty-two psychology students of the University of Novi Sad with normal or corrected vision took part in the experiment. All participants were right-handed and native Serbian readers.

4.1.2. Apparatus, stimuli, design and procedure

The stimuli of Experiment 3 were not presented parafoveally but in the periphery of the visual field. Target eccentricity in Experiment 3 was 7° of visual angle. In order to make peripheral identification possible, the size of the characters and the spacing between them (Experiment 3b) was increased in comparison to Experiment 1: characters subtended 2.1° of visual angle, and the center-to-center spacing was 3°. Except for this, the method of Experiment 3 was identical to the method of Experiment 1 (for illustration, see Fig. 1). A single (isolated) target character was presented in Experiment 3a, while the central character within a string of three different characters of the same type (letters or symbols) was the target in Experiment 3b. Two factors were tested in Experiment 3a: Stimulus Type (letter vs. symbol) and Location (horizontal meridian vs. vertical meridian). Three factors were examined in Experiment 3b: Stimulus Type (letter vs. symbol), Location (horizontal meridian vs. vertical meridian) and String Orientation (horizontal string vs. vertical string).

4.2. Results

4.2.1. Experiment 3a

Mean response accuracy in Experiment 3a was 95.39%. Response accuracy in the four experimental conditions is shown in Fig. 6.

Results of the GLME model are presented in Table 5. Model comparisons did not justify the inclusion of random effect of targets, so the intercept correction was modeled only for participants. There was a significant main effect of Location, which was driven

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[4] Or 48.46% if the theoretical range of response accuracy in the experiments is taken into account.

[5] Single-cell recording of rhesus monkey V4 shows that the receptive field size at 1.5° eccentricity does not fall below 2° (Motter, 2009), whereas the estimate of 3° is reported for the human V4 at the same eccentricity (Smith, Singh, Williams, & Greenlee, 2001).

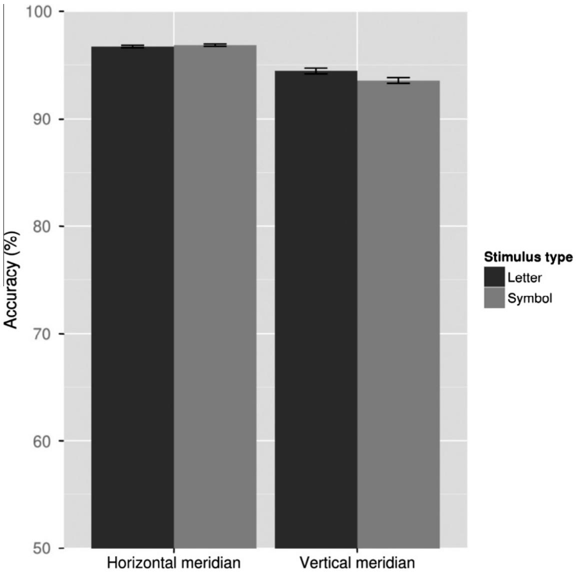

Fig. 6. Mean response accuracy in four experimental conditions of Experiment 3a. Error bars indicate ±1SEM.

Table 5
Summary of GLME results for Experiment 3a. Summary of GLME results for Experiment 1b. Random intercept was modeled for participants and the "Slope" column indicates if random slope corrections for the fixed effect parameters (p – participant, t – target) were also included in the model.

Parameter	Estimate	*SE*	Wald *z*	*p*	Slope
(Intercept)	3.428	0.206	16.62	<0.001	
Stimulus Type	−0.059	0.182	−0.322	0.747	
Location	−1.082	0.239	−4.522	<0.001	p
Stimulus Type × Location	−0.202	0.364	−0.556	0.579	

by the better identification of stimuli at the horizontal meridian than at the vertical meridian. The effects of Stimulus Type and the Stimulus Type × Location interaction were not significant.

4.2.2. Experiment 3b

Mean response accuracy in Experiment 3b was 69.74%. The percentage of correct responses in the eight conditions is presented in Fig. 7.

Table 6 shows the results of the GLME model. A significant Stimulus Type × String Orientation interaction was produced by the higher performance for the horizontal strings of letters than the vertical strings of symbols, and comparable levels of performance for the vertical strings of letters and symbols. This interaction was confirmed in separate analyses on letter and symbol stimuli, which showed a significant main effect of String Orientation for letters ($\beta = -0.389$, $SE = 0.083$, $z = -4.698$, $p < 0.001$), but not for symbols ($\beta = -0.001$, $SE = 0.079$, $z = -0.024$, $p > 0.1$). Furthermore, a significant Location × String Orientation interaction was also registered in the model. Separate analyses for horizontal and vertical meridian locations confirmed the pattern of results presented in Fig. 7. At the horizontal locations, performance was higher for vertical strings than for horizontal strings ($\beta = 0.554$, $SE = 0.082$, $z = 6.759$, $p < 0.001$); the inverse effect was observed at the vertical locations, where performance for horizontal strings was higher than for vertical strings ($\beta = -0.9235$, $SE = 0.080$, $z = -11.601$, $p < 0.001$). A non-significant three-way interaction between the factors examined in Experiment 3b shows that this Location × String Orientation interaction did not substantially differ between letters and symbols.

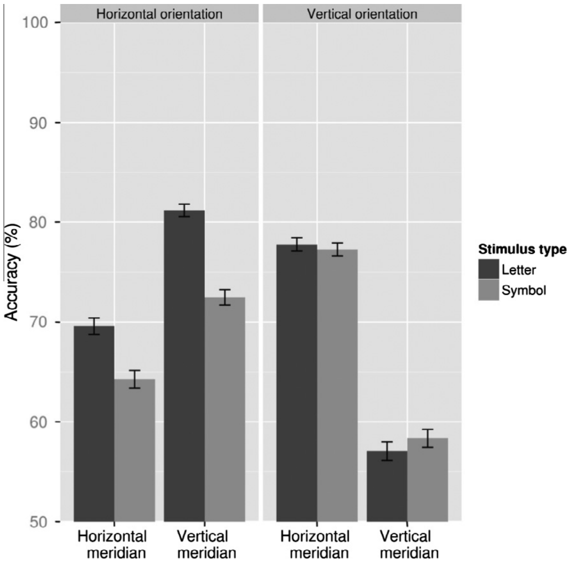

Fig. 7. Mean response accuracy in eight experimental conditions of Experiment 3b. Error bars indicate ±1SEM.

Table 6
Summary of GLME results for Experiment 3b. Random intercepts were modeled for participants and targets, and the "Slope" column indicates if the random slope corrections for the fixed effect parameters (p – participant, t – target) were also included in the model.

Parameter	Estimate	*SE*	Wald *z*	*p*	Slope
(Intercept)	0.934	0.097	9.595	<0.001	
Stimulus Type	−0.183	0.125	−1.461	0.144	
Location	−0.267	0.086	−3.095	0.002	p
String Orientation	−0.139	0.081	−1.712	0.087	p
Stimulus Type × Location	−0.094	0.115	−0.815	0.415	
Stimulus Type × String Orientation	0.391	0.115	3.393	<0.001	
Location × String Orientation	−1.654	0.248	−6.681	<0.001	p
Stimulus Type × Location × String Orientation	0.354	0.230	1.538	0.124	

As in the previous two experiments, a significant main effect of Experiment ($\beta = -0.924$, $SE = 0.080$, $z = -11.601$, $p < 0.001$) in the joint analysis of the two parts of Experiment 3 was caused by the substantially decreased performance in Experiment 3b. This drop in performance was 25.65% (or 51.3%, given the possible range of response accuracy in the experiments).

4.3. Discussion

Identification of single characters in the periphery of the visual field was high and, as in the case of previous experiments, comparable for single letter and symbol stimuli. Similarly to Experiment 1a, isolated identification at the horizontal meridian was significantly superior to the vertical meridian, probably due to the general characteristics of visual processing (Abrams et al., 2011; Connolly & Van Essen, 1984; Curcio & Allen, 1990; Curcio et al., 1990; Tootell et al., 1988).

Crucially, the same Stimulus Type × Orientation interaction that had been previously registered in Experiments 1b and 2b was again encountered when the string stimuli were presented at peripheral locations. Thus, the decreased horizontal crowding of letters was shown to generalize to peripheral locations in the visual field. The presence of the effect deep in the periphery of the visual field (both at the horizontal and vertical meridian) contradicts the assumption that it is produced in the location specific letter detectors aligned along the horizontal meridian and close to the fovea, as predicted by the MRF hypothesis (Chanceaux & Grainger, 2012; Grainger et al., 2010).

Besides this principal finding, the radial–tangential anisotropy effect emerged in Experiment 3b once again: stimuli presented within horizontal strings were better identified at vertical locations, while the identification of vertical strings was superior at horizontal locations in the visual field. In short, the results of Experiment 3 closely resembled those of Experiment 1.

5. General discussion

In the present study we examined individual and crowded identification of letters and symbols at different locations in the visual field in order to more thoroughly explore previous report of decreased crowding for letter stimuli (Grainger et al., 2010).

The decreased letter crowding effect has been explained by the account known as the "modified receptive field" hypothesis (Chanceaux & Grainger, 2012; Grainger et al., 2010; Tydgat & Grainger, 2009). This in turn is based on the proposal that the identification of letters in reading is different from the identification of other types of objects because the letters within words are argued to be processed in parallel (e.g. Dehaene et al., 2005; Grainger & van Heuven, 2003). Due to this simultaneous processing, and due to the extremely crowded circumstances in which letter identification is performed, the MRF account hypothesized that perceptual learning during reading acquisition results in a decrease in the size of the receptive fields of letter detectors that are location specific and aligned along the horizontal meridian next to the fovea (i.e. located in the parts of the visual field that are used for reading). The outcome of our study provides partial support for this account. In all three experiments we did find reduced levels of crowding for letters, whereas no advantage of letter identification was observed when individual characters were tested. This result replicates the findings of Grainger et al. (2010) and supports the claim that the superior processing of letters presented in strings is not a reflection of some general perceptual advantage of individual letters vs. symbols but rather a specific characteristic of letter crowding.

More generally, we take the results of our study as evidence of an experience-based adaptation of the visual system. This adaptation is beneficial for the identification of letters presented within strings and thus aids the early, perceptual phase of reading. In this sense, the results of our study are in agreement with the MRF account, which assumes that the reduced letter crowding is a likely consequence of visual expertise and emerges during the course of reading acquisition. However, the results of our study provide a more detailed picture of the reduced letter crowding effect, one that deviates from the current version of the MRF hypothesis in two important respects.

Firstly, in all three experiments the decrease in crowding for letters was conditional on their presentation within horizontal strings. Though the MRF account is not explicit in this respect, it seems to refer to the general advantage of letters in crowding, and does not predict any specific differences depending on the orientation of the stimuli. On the other hand, the reduction of horizontal and not vertical letter crowding provides even stronger support for the claim that the readers' visual experience is the basis of the effect, given that our participants received extensive everyday practice precisely in the identification of horizontally arranged letters, whereas reading of vertically oriented text is likely to be very uncommon for them. As mentioned above, similar experience-driven orientation bias of letter processing has previously been found in reading: whereas horizontal text is read faster by the readers of horizontal scripts (Byrne, 2002), such an advantage is not encountered in readers who are accustomed to both horizontally and vertically oriented text (Oda et al., 1997). Importantly, this horizontal bias is evident even when oculomotor factors are eliminated (Yu et al., 2010), which suggests that the experience impacts the early, perceptual levels of reading process. In this respect, the findings of our study support the notion that reduced horizontal (but not vertical) crowding results in a larger horizontal visual span, which in turn is partly responsible for the faster reading of the familiar, horizontally oriented text (Yu et al., 2010).

Secondly, the reduction of horizontal crowding was present at the horizontal meridian in the parafovea, as predicted by the MRF account, but it was also encountered at the vertical meridian (Experiment 1b) and at diagonal parafoveal locations (Experiment 2b) where such an effect would not be predicted. The generalization of the effect is yet more convincing in the results of Experiment 3b, in which the same advantage of horizontal strings of letters was also found in the periphery of the visual field. These findings clearly demonstrate that the reduction of letter crowding is not a spatially constrained phenomenon, and this is in accordance with the reports of the virtually complete transfer-of-training induced decrease of letter crowding across the visual field (He et al., 2013). Then again, such an outcome is not easily assimilated by the MRF hypothesis, given that the experience-based shrinking of the receptive fields of the location specific letter detectors seems implausible at locations where reading normally does not take place.

On the other hand, the explanation of the described pattern of results could be founded on the view of crowding as a complex phenomenon that does not take place at a single stage of visual processing, but rather at the multiple stages – from the level of features to the level of whole objects (Anderson, Dakin, Schwarzkopf, Rees, & Greenwood, 2012; Whitney, 2009; Whitney & Levi, 2011). Based on this idea, it can be assumed that early stages (or lower levels) of processing are responsible for certain general characteristics of crowding that are common to all crowded object recognition, while the extensive experience with particular type of objects could modulate their crowding at a later stage, possibly through the reduction of object level interference. For example, the effect of radial–tangential anisotropy (Toet & Levi, 1992), which is one of the hallmarks of crowding, was observed in our Experiments 1 and 3 and was evident for both letter and symbol stimuli. Yet the reduced horizontal crowding of letters was observed both in the presence of the radial–tangential anisotropy (Experiments 1b and 3b), and also when the radial–tangential anisotropy was experimentally neutralized (Experiment 2b). This mutual independence of the two effects suggests that their origin might stem from different levels of visual processing. Thus, a general effect of radial–tangential anisotropy, which affects the crowding of objects of any kind, could be ascribed to interference caused by a general mechanism that is at play at the level of features (such an explanation is compatible with the common notion that this mechanism takes the form of excessive pooling of features in early visual zones, but is not incongruent with the top-down accounts either). In contrast, because a distinct effect of reduced letter crowding is encountered independently of the presence of this anisotropy, and because it does not seem to be location specific, it could be assumed that its origin is at a later stage of visual processing. This interpretation echoes recent notions of crowding as a phenomenon that takes place at multiple levels in the visual system (e.g. Anderson et al., 2012; Whitney, 2009; Whitney & Levi, 2011). Two previously mentioned accounts of orthographic processing (Dehaene et al., 2005; Grainger & van Heuven, 2003) propose that the location specific letter detectors feed into the next level of non-retinotopic, abstract letter detectors. A revised version of the MRF hypothesis which would locate the effect of decreased letter crowding at this later stage of visual processing could account for the current results, but further research is required in order to directly test such a proposal.

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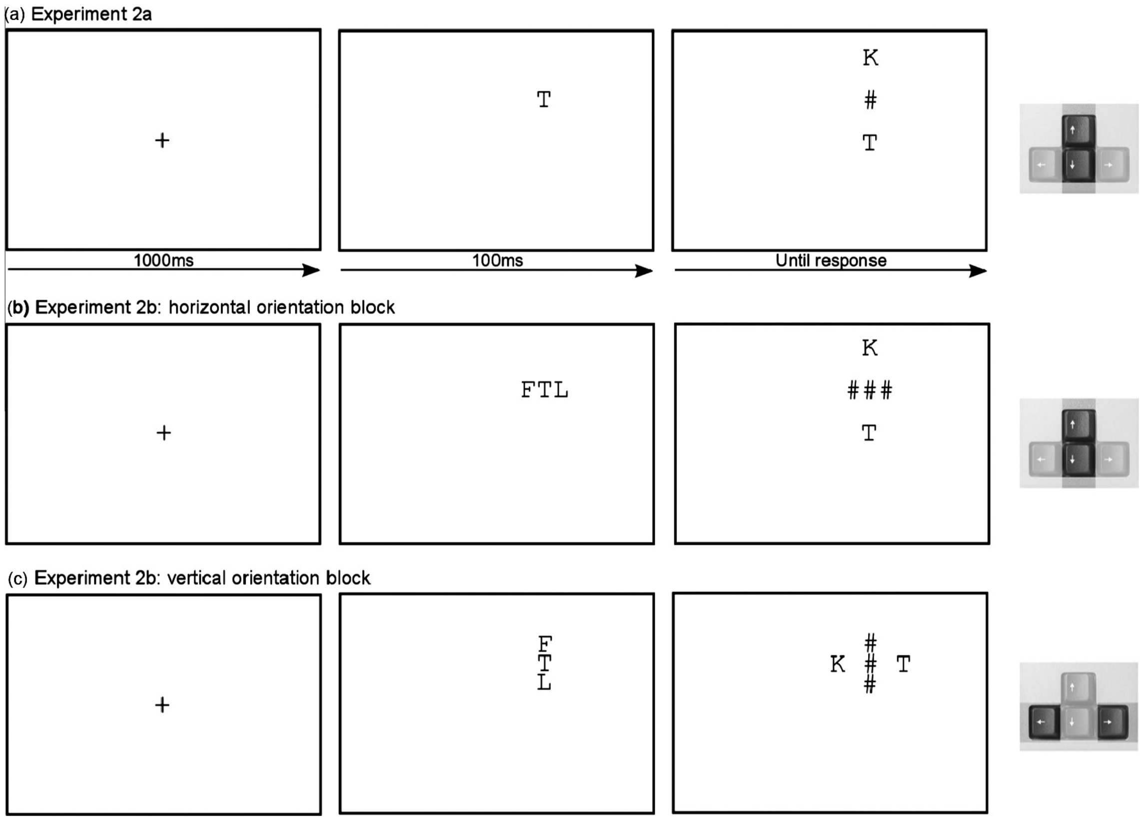
Appendix A

Illustration of the three screens (fixation mark, stimulus, response) presented in a trial and response keys in Experiment 2. (a) Procedure and stimuli used in Experiment 2a, (b) horizontal orientation block of Experiment 2b, (c) vertical orientation block of Experiment 2b. Diagonal 2 (upper-right) letter condition was used for the illustration.



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