University of Groningen

Effects of number, complexity, and familiarity of flankers on crowded letter identification

Chanceaux, Myriam; Mathot, Sebastiaan; Grainger, Jonathan

Published in:
JOURNAL OF VISION

DOI:
10.1167/14.6.7

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2014

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Chanceaux, M., Mathot, S., & Grainger, J. (2014). Effects of number, complexity, and familiarity of flankers on crowded letter identification. *JOURNAL OF VISION*, *14*(6), [7]. https://doi.org/10.1167/14.6.7

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 28-03-2023

Effects of number, complexity, and familiarity of flankers on crowded letter identification

Myriam Chanceaux
University Grenoble Alpes and Centre National de la Recherche Scientifique, Grenoble, France

Sebastiaan Mathôt
Aix-Marseille University and Centre National de la Recherche Scientifique, Marseille, France

Jonathan Grainger
Aix-Marseille University and Centre National de la Recherche Scientifique, Marseille, France

We tested identification of target letters surrounded by a varying number (2, 4, 6) of horizontally aligned flanking elements. Strings were presented left or right of a central fixation dot, and targets were always at the center of the string. Flankers could be other letters, digits, symbols, simple shapes, or false fonts, and thus varied both in terms of visual complexity and familiarity. Two-alternative forced choice (2AFC) speed and accuracy was measured for choosing the target letter versus an alternative letter that was not present in the string. Letter identification became harder as the number of flankers increased. Greater flanker complexity led to more interference in target identification, whereas more complex targets were easier to identify. Effects of flanker complexity were found to depend on visual field and position of flankers, with the strongest effects seen for leftward flankers in the left visual field. Visual complexity predicted flanker interference better than familiarity, and better than target-flanker similarity. These results provide further support for an excessive feature-integration account of the interfering effects of both adjacent and nonadjacent flanking elements in horizontally aligned strings.

Introduction

Everyday reading in languages that use an alphabetic script requires parallel processing of letter-identity information (see Grainger & Dufau, 2012, for a summary of the arguments), and it has been argued that one of the keys to becoming a skilled reader is to optimize crowded letter-identification processes (Tydgat & Grainger, 2009). That is, given the spatially compact nature of printed words, the parallel processing of multiple letter identities imposes unusually high levels of crowding that the beginning reader must adapt to. Crowding refers to the decrease in our ability to identify a given object due to the spatial proximity of other stimuli (for reviews see Levi, 2008; Pelli & Tillman, 2008; D. Whitney & Levi, 2011). Any reduction in crowding would therefore be beneficial for processing the component letters of words, and for subsequent word recognition and reading. We would therefore argue that a better understanding of skilled reading behavior requires a better understanding of crowded letter identification, the factors that modulate such crowding effects, and how crowding impacts on the parallel processing of letter identity and position. By examining how letter-in-string identification depends on the number, type, familiarity, and visual complexity of flankers, the present study represents one further step towards this goal.

Particularly relevant for the present study are experiments that have examined the influence of the number of flanking elements in horizontally aligned strings of letters (Butler & Currie, 1986; Chanceaux & Grainger, 2013; Huckauf & Heller, 2002a, 2002b). The results of these studies showed a systematic drop in performance as the number of flankers was increased from zero to four (see Strasburger, Harvey, & Rentschler, 1991, for a similar effect with digit stimuli). It has been suggested that different mechanisms are involved in nonadjacent flanking effects (i.e., the effect of A and D on the identification of T in ABTCD) compared with the effects of adjacent flankers (i.e., the effect of B and C). Whereas effects of adjacent flankers would mostly reflect excessive feature-integration or spatial pooling (e.g., Levi, 2008; Pelli, Palomares, & Majaj, 2004), interference from nonadjacent flankers

Citation: Chanceaux, M., Mathôt, S., & Grainger, J. (2014). Effects of number, complexity, and familiarity of flankers on crowded letter identification. *Journal of Vision*, *14*(6):7, 1–17, http://www.journalofvision.org/content/14/6/7, doi:10.1167/14.6.7.

doi: 10.1167/14.6.7 Received March 28, 2014; published November 10, 2014 ISSN 1534-7362

would mainly reflect an increase in positional uncertainty with longer strings (e.g., Butler & Currie, 1986; Huckauf & Heller, 2002a). In other words, processing of target identity might not be harmed so much by nonadjacent flankers, but performance would drop because of a loss of information about target position induced by the increase in the number of elements in the display. While effects of excessive feature-integration would be spatially limited in extent, respecting Bouma's (1973) law, effects of positional uncertainty could operate over greater target-flanker distances, and would be particularly large when several flankers are present.

Another factor known to modulate effects of number of flankers, is grouping. When flankers group together separately from the target, then increasing the number of flankers can augment the effect of grouping. This can result in a canceling or even reversal of the typically negative influence of number of flankers (e.g., Banks, Larson, & Prinzmetal, 1979; Banks & White, 1984; Levi & Carney, 2009; Livne & Sagi, 2007; Malania, Herzog, & Westheimer, 2007; Manassi, Sayim, & Herzog, 2012, 2013; Saarela, Sayim, Westheimer, & Herzog, 2009; Wolford & Chambers, 1983). For example, in the Manassi et al. (2012) study, the threshold elevation for vernier offset acuity was measured for the middle two line segments of four vertically aligned segments presented to the right of a central fixation cross. Flanker line segments were presented left and right of the target configuration, and the number, size, and spatial arrangement of flankers were manipulated. When flankers were horizontally aligned and distinct from the target, then increasing the number of flankers from 2 to 16 caused a drop in crowding. On the other hand, when flankers were not aligned (by adding vertical jitter), then increasing the number of flankers caused an increase in crowding. These, and other results, suggest that configural information can modulate the effects of bottom-up integration processes. However, it is unknown exactly how such grouping processes might affect within-word letter identification processes.

Evidence against the positional uncertainty account of nonadjacent flanking effects seen with letter and digit stimuli was provided by Chanceaux and Grainger (2013), who reported that effects of nonadjacent flankers can be obtained using a two-alternative forced-choice (2AFC) procedure where the response alternative was never present in the stimulus (see Parkes, Lund, Angelucci, Solomon, & Morgan, 2001, for further evidence for crowding in the absence of positional uncertainty). Nevertheless, the results obtained with this procedure do not rule out a related but different interpretation of nonadjacent flanking effects, according to which it is harder to focus attention on the target location in longer strings (Strasburger et al., 1991). A decrease in attentional focus would induce a cost in the processing of target identity as well as target position (but see Greenwood, Bex, & Dakin, 2010, for evidence against a role for such a mechanism in determining the effects of adjacent flankers). Furthermore, the target eccentricities and target-flanker distances tested in this prior work would appear to rule out an excessive feature-integration account of nonadjacent flanking effects when applying Bouma's (1973) law to determine the theoretical extent of the crowding zone, because flankers outside of the crowding zone still induced crowding. However, Chanceaux and Grainger (2013) demonstrated the viability of the feature-integration account by introducing an inward-outward asymmetry as determined theoretically in the work of Nandy and Tjan (2012). Chanceaux and Grainger (2013) demonstrated that, based on the parameters provided by Nandy and Tjan (2012), the crowding zone encompassed one complete outward flanker in the four-flanker condition of the Chanceaux and Grainger study. A single mechanism, that is, excessive feature-integration resulting from the spatial pooling of information present in the crowding zone, can therefore account for the effects of adjacent and nonadjacent flanking elements seen with letter stimuli.

Indeed, one key characteristic of crowding found with very different types of stimuli is inward-outward asymmetry, with outward flankers having a greater impact than inward flankers (Bouma, 1973; Legge, Mansfield, & Chung, 2001; Manassi et al., 2012; Petrov & Meleshkevich, 2011; Petrov, Popple, & McKee, 2007; D. Whitney & Levi, 2011). Furthermore, and crucial for the present study, Grainger and colleagues (Chanceaux & Grainger, 2012; Grainger, Tydgat, & Isselé, 2010; Tydgat & Grainger, 2009) have proposed that the inward-outward asymmetry differs between letter stimuli and other kinds of visual objects, a proposal referred to as the "modified receptive field" (MRF) hypothesis in Chanceaux and Grainger (2012). According to the MRF hypothesis, a word-beginning bias is added to a generic inward-outward asymmetry, leading to a greater leftward elongation of the crowding zone in the left visual field (LVF) for languages that are read from left-to-right. For a constant receptive-field size, this modification leads to an increase in interference from leftward flankers and a reduced interference from rightward flankers for targets in the LVF, thus enhancing the visibility of a word's initial letter when it falls to the left of fixation. Initial evidence in support of this hypothesis was provided by Grainger et al. (2010), who reported that with single flanker stimuli, interference was greater for leftward flankers than rightward flankers when targets were letters presented in the LVF. On the other hand, there was no such asymmetry when letter targets were presented in the right visual field (RVF), and no asymmetry for symbol targets in either

Figure 1. The different types of flanker stimuli used in the experiment. From top to bottom: shapes, symbols, letters, false fonts, digits. The target was always a letter drawn from the nine letters shown here.

visual field. Further evidence in support of the MRF hypothesis was provided by Chanceaux, Mathôt, and Grainger (2013), who manipulated the number of leftward and rightward flankers for letters and simple shapes in peripheral vision. As predicted by the MRF hypothesis, the greatest flanker interference was found for leftward flankers associated with letter targets in the LVF.

In the present study we provide a further test of alternative accounts of nonadjacent flanker effects by varying flanker familiarity and flanker complexity as well as the number of flankers. First let us summarize what we already know about the effects of these two additional variables. Bernard and Chung (2011) varied the visual complexity of target and flanking stimuli in trigram strings and found that increasing flanker complexity reduced target identification accuracy. Wang, He, and Legge (2014) reported a similar increase in crowding with increasing complexity in a study measuring the visual span of Chinese characters and uppercase and lowercase Latin letters. These results are in line with the excessive-feature-integration account of crowding, since more complex flankers contain more features that have the potential to interfere with target identification. Bernard and Chung (2011) also reported that more complex targets were less impacted by crowding. This again fits with the excessive-feature-integration account, since the more features the target has, the better the target features can compete with flanker features during target identification.

Concerning possible effects of flanker familiarity, at least one prior study points to a role for this factor in crowded letter identification (Huckauf, Heller, & Nazir, 1999). In a trigram crowding paradigm with centrally located target letters, Huckauf et al. (1999) found more interference in target letter identification with rotated letter flankers or pseudoletter flankers compared with upright letter flankers. This finding would appear to rule-out an account of crowding in terms of positional uncertainty, since this would predict greater crowding with real letter flankers. Attentional factors are also an unlikely source of this finding, since different types of flanker should, if anything, facilitate target letter identification via ungrouping of the target from the flankers. In order to account for their findings, Huckauf et al. (1999) proposed that letter flankers access a "higher-level code" (i.e., an object name or label) that reduces interference at the feature level via top-down constraints. They then conjectured that flankers that access a higher level code but are not from the same category as targets (e.g., digit flankers for letter targets) should produce less crowding. This was indeed what they found when comparing the effects of letter and digit flankers on the identification of letter targets.

In the present work we contrasted the effects of different types of flankers (letters, digits, shapes, symbols, and false fonts; see Figure 1) that varied both in terms of their familiarity as individual items, and in terms of how often they are used to form horizontally aligned strings. To confirm our intuitions we measured item familiarity using subjective frequency ratings, to be reported in Experiment 2. Item-in-string frequency was defined as follows: very frequent (letters, digits) to very rare (shapes, false fonts), with symbols lying somewhere between these two extremes. In Experiment 1, targets were presented accompanied by either two, four, or six flankers aligned horizontally and placed symmetrically to the left and to the right of the target. Targets were always letter stimuli and flankers were always from the same flanker category. According to Huckauf et al.'s (1999) higher-level code hypothesis, we should see an effect of flanker type in our experiment, with false fonts flanking more than symbols, which in turn should flank more than letters, and with digits and shapes crowding less than letters. Compared with false fonts, our symbol stimuli were more familiar, and could be associated with a higher level code (i.e., labeled), but arguably less readily so than the letter, digit, or shape stimuli. Flanker complexity was varied both within flanker category and across categories in the present study. According to the excessive-feature-integration account of effects of adjacent and nonadjacent flankers, we expect to observe effects of flanker complexity for both adjacent and nonadjacent flanking elements. Most important, however, is that we chose to investigate the unique influence of each flanking element in a multielement display by estimating the size of the flanker complexity effect separately for each flanker position. This possibility is critical with respect to testing the MRF hypothesis (Chanceaux & Grainger, 2012), according to which, for letter stimuli, the crowding zone presents a stronger inward-outward asymmetry in the LVF than the RVF. This hypothesis predicts a greater influence of flanker complexity for leftward flankers than rightward flankers when targets and flankers appear in the LVF.

Experiment 1: Flanker study

Methods

Participants

Nineteen students at Aix-Marseille University participated in the experiment in exchange for monetary compensation. All participants provided written informed consent, and all reported being native speakers of French.

Stimuli and design

Nine consonant letters (B, D, G, H, K, M, N, R, S) were used as targets in the experiment. The letters were presented in uppercase Courier New font. Flanking stimuli were letters from the same set of consonants (never the target), digits, symbols, simple shapes, or false fonts. Figure 1 provides the complete set of flanking stimuli, grouped by flanker type. The different types of flankers enabled an analysis of the effects of flanker familiarity, both in terms of familiarity of the individual flankers and whether or not the flanking elements typically appear in horizontally aligned strings or not. Number of flankers was varied (two, four, or six flankers) with one, two, or three flankers positioned on each side of the target (i.e., FTF, FFTFF, or FFFTFFF, where T represents the target letter and F a flanking stimulus). Thus, visual field (LVF vs. RVF) was crossed with number of flankers (two, four, or six) and type of flanker (letters, digits, symbols, shapes, or false fonts) in a 2 × 3 × 5 factorial design. Each letter served as the target on 90 trials, three times in each of the 30 conditions formed by the factorial combination of the three factors, giving a total of 810 trials per participant.

Apparatus and procedure

An EyeLink 1000 eyetracker (SR Research, Mississauga, Ontario, Canada) was used to control for eye movements. Participants rested their heads on a chin rest, at 80 cm from the monitor. The eye tracker recorded right eye movements (sampling frequency of 1000 Hz), in the configuration recommended for cognitive research (saccadic detection based on a velocity threshold of 30°/s and an acceleration threshold of $8000°/s^2$). Stimuli were presented on a ViewSonic P227f monitor (refresh rate 100 Hz, screen size 1024 × 768 px; ViewSonic, Brea, CA) using Experiment Builder software (SR Research). Stimuli were presented in black 21-point Courier New font on a gray background. The center-to-center separation between neighboring characters was 0.6° horizontally, and the center of the string was at an eccentricity of 2.7°. Targets always appeared at the center of the string. To calibrate the eye tracker, a nine-point calibration-validation routine was performed at the beginning of the session and then every 50 trials. On each trial, participants had first to gaze at the fixation cross at the center of the screen. This fixation cross disappeared after a period of 200 ms during which there were no eye movements greater than 0.7° left or right of the central fixation (50 × 120 px around the fixation cross). Then the string of target and flankers appeared either to the left or to the right of the fixation cross for 300 ms. Participants had to maintain central fixation during stimulus presentation; otherwise the trial was canceled. After presentation of target and flankers, a masking stimulus was presented accompanied by a postcue indicating the position of the target character that had to be identified. Two letters were also displayed above and below the fixation cross, one of them was the target and the other was another letter randomly selected from the set of nine target letters, but that was not present in the stimulus. This final display remained until participants responded by choosing one of the alternatives (see Figure 2 for a schematic of the procedure). Participants were instructed to respond as accurately as possible and without hesitation by pressing either the upward arrow key (for the alternative above) or the downward key (for the alternative below), following standard 2AFC procedure, in order to designate the identity of the central target letter. An audio tone signaled a correct response. After participants' responses a blank screen was displayed and the next trial began. Visual field, number of flankers, and type of flanker varied randomly across all trials. The experiment lasted about 1 hr.

Results

Effects of flanker type, number of flankers, and visual field

We conducted a linear mixed-effects (LME) analysis with percent error rate as dependent measure (0 for correct trials, 100 for incorrect trials), number of flankers (two, four, or six), visual field (LVF or RVF), and flanker type (digits, letters, false font, shapes, or symbols) as fixed effects, and participant and target letter as random effects on the intercept. The same analysis was conducted with response time as dependent measure. Here and for subsequent analyses, *p*-values and confidence intervals were estimated using

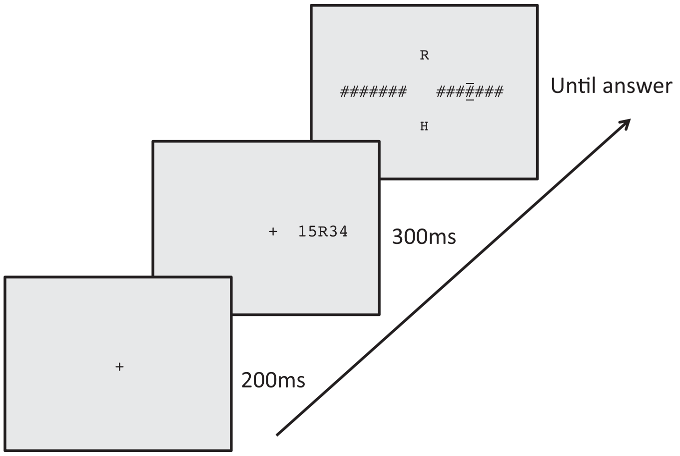

Figure 2. A typical trial. Fixation cross for 200 ms, followed by a string composed of target and flankers presented to the left or right of fixation for 300 ms, and finally a backward mask accompanied by a postcue and two alternatives for the 2AFC procedure. When flankers were letters, the alternative given for 2AFC was never a flanker on that trial.

Markov-Chain Monte Carlo (MCMC) simulation (Baayen, 2008). The full models are listed in the Appendix as Tables A1 and A2. In brief we observed the following effects (see Figure 3): Performance decreased with increasing number of flankers; performance varied for the different flanker types, such that Symbols > Digits > Shapes > False Font > Letters (see also Table 1); and performance was better in the RVF than in the LVF.

Effects of visual complexity

The first aim of these analyses was to investigate whether the differences between flanker types are due to differences in the visual complexity of the different types of flanker (Bernard & Chung, 2011). The second aim was to exploit the effect of visual complexity in order to test which positions in a multiflanker string contribute most to the overall flanker effect. The rationale is that the strength of the relationship between behavioral performance and the visual complexity of a particular flanker indicates how strongly that flanker interferes with target letter identification.

We quantified visual complexity as the average "edginess" of a stimulus. More specifically, we took the mean luminance of the image after applying a Sobel operator. The Sobel operator performs a two-dimensional (2-D) spatial gradient measurement on an image and so emphasizes regions of high spatial frequency that correspond to edges. It is a standard 2-D edge-detection algorithm that is sensitive to pixel-to-pixel changes in luminosity. This method is straightforward and has the advantage that it relies on local contrast, albeit in a rudimentary way, which is known to be a crucial feature for the visual system (Itti, Koch, & Niebur, 1998). We do not claim that our measure of visual complexity is superior to other measures that have been used. However, different measures of visual complexity are generally in fairly good agreement, and the results presented here likely generalize to other measures of visual complexity.

We then determined the relationship between the flankers' visual complexity and behavioral performance, using an LME with error rate as dependent measure, visual complexity as fixed effect, and participant as random effect on the intercept. (The target item is omitted as random effect from this and subsequent analyses, because we will include the target's visual complexity as fixed effect.) The same analysis was performed with response time as dependent measure. These analyses were performed separately for each stimulus configuration and flanker position, and revealed a highly robust relationship in all cases (all ts$>$ 2; see Figure 4 for the error rate data). Strikingly, the differences between flanker types (see Figure 3) appear to be largely, if not fully, attributable to systematic differences in visual complexity.

Effects of flanker position

On a given trial, a single type of flanker was used, that is, all flankers were drawn from the same category. As can be seen in Figure 4, there are systematic differences in visual complexity between flanker types. Therefore, visual complexities of different flanker positions are interdependent: If the left-most flanker is visually complex, the right-most flanker is usually also visually complex. The analysis shown in Figure 4 does not take this interdependence into account, and therefore gives the appearance that the effect of visual complexity is roughly equal across flanker positions.

In order to analyze effects of visual complexity separately for each flanker position, we entered the visual complexity for each flanker position as a separate fixed effect into an LME, which was otherwise the same as before. We also entered the visual complexity of the target as a fixed effect. This allowed us to estimate the unique effect of visual complexity for each stimulus position separately. This analysis was done for each visual field and stimulus configuration separately, and separately for error rate and response time as dependent measures. We also conducted the analysis across all stimulus configurations (number of flankers), in which case empty flanker positions were assigned a visual complexity of 0. The results are summarized in Figure 5. For clarity, we do not present the full models, but indicate 95% confidence intervals (CIs) as error bands in the figure, such that $p < 0.05$ where the CI does not include 0.

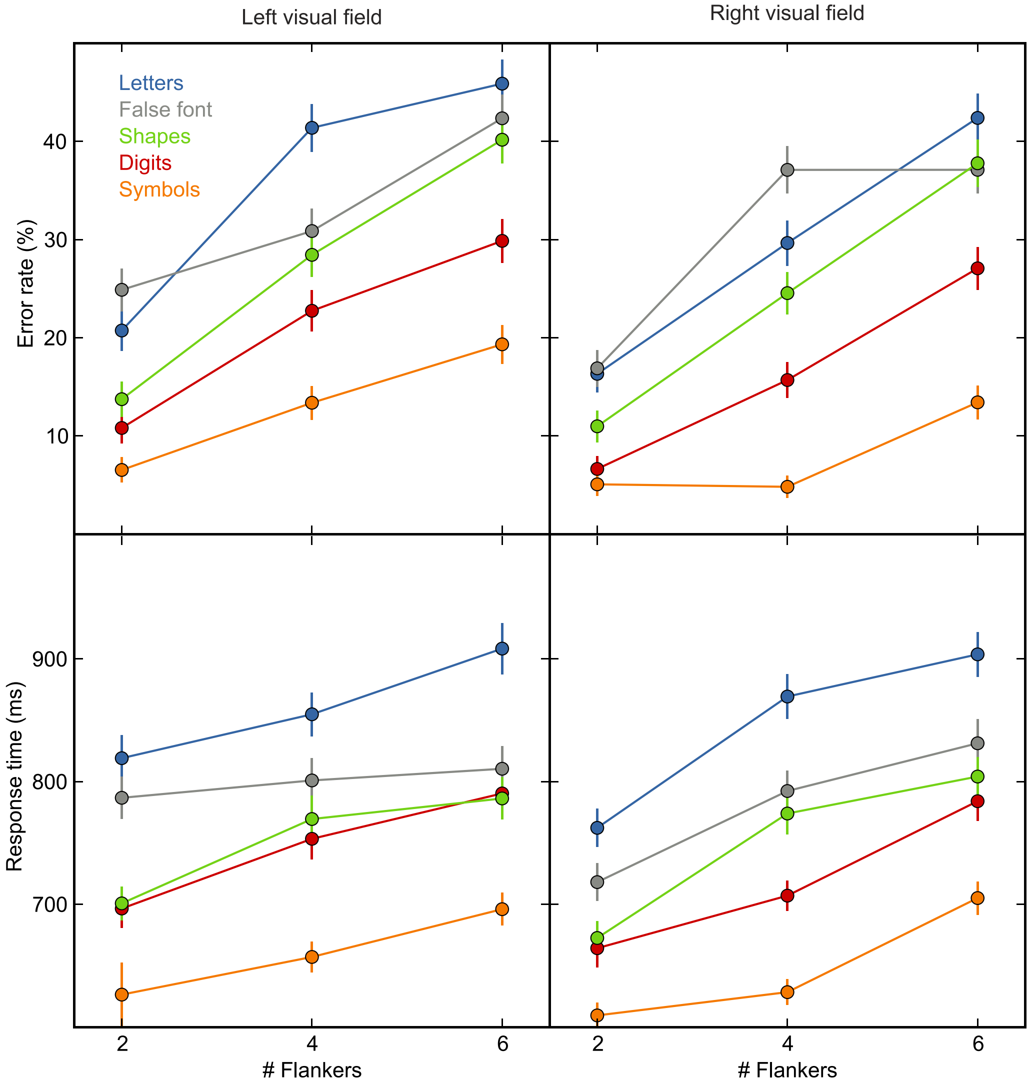

Figure 3. The effects of visual field, flanker type, and number of flankers on error rate (top row) and response time (bottom row). Error bars correspond to the standard error of the mean.

The pattern of results shown in Figure 5 can be summarized as follows. Firstly, flankers directly next to the target interfere strongly. Secondly, peripheral flankers, especially left-most flankers in the LVF, also interfere strongly. Thirdly, flanker visual complexity *impairs* performance (positive slopes), whereas target visual complexity *improves* performance (negative slopes).

Figure 5 suggests that performance is affected disproportionally by leftward flankers in the LVF. To test this more rigorously, we performed an LME with error rate as dependent variable and subject as random effect on the intercept. The summed visual complexity

Type	Error rate (%)	Response time (ms)	Obj. vis. comp.	Obj. sim. ×10,000	Rated vis. comp.	Rated freq.	Rated sim.
Symbol	10.48	654	19.69	4.78	1.51	2.78	1.86
Digit	18.95	733	27.93	5.16	0.97	3.76	1.60
Shape	26.28	753	37.45	4.37	1.21	2.85	1.42
False font	31.58	790	38.46	4.43	2.72	0.26	1.68
Letter	32.87	853	39.47	5.55	1.28	3.76	2.56

Table 1. The average rating values (1 = Low; 5 = High) obtained in Experiment 2 for the five categories of flanker stimuli, for visual complexity (vis. comp.), frequency (freq.), and similarity (sim.) to (other) letters (see Methods). *Notes*: Average performance per flanker category (Response time, Error rate) and objective edge-based flanker complexity (Obj. vis. comp.) and target flanker similarity (Obj. sim.) means are given for comparison (both in arbitrary units). Flanker categories are listed by decreasing performance.

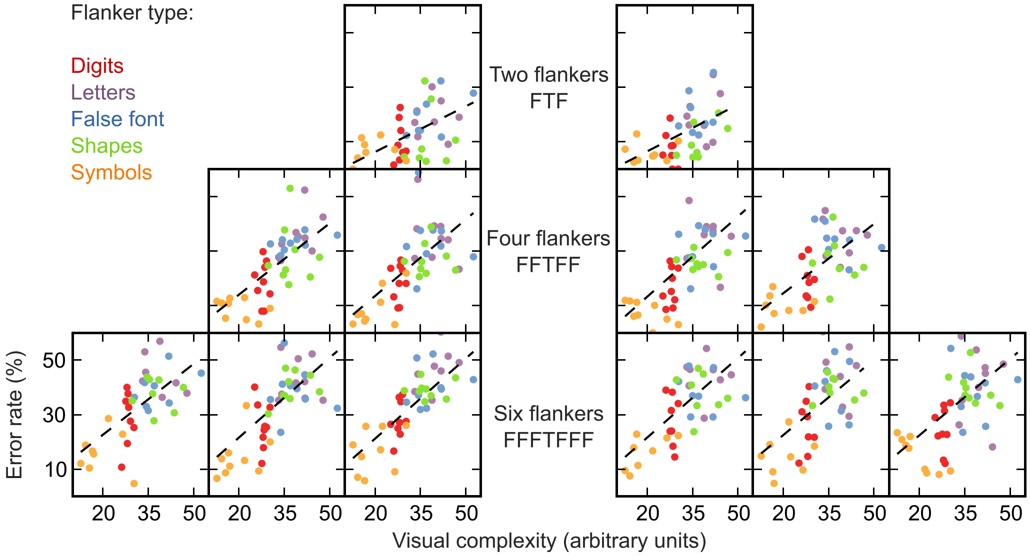

Figure 4. The relationship between visual complexity of the flanker (on the *x*-axis) and error rate (on the *y*-axis) for each stimulus configuration (different rows) and flanker position (different columns). Dots correspond to the nine target letters combined with the five types of flanker shown in different colors. Dashed lines correspond to mixed-effects model slopes.

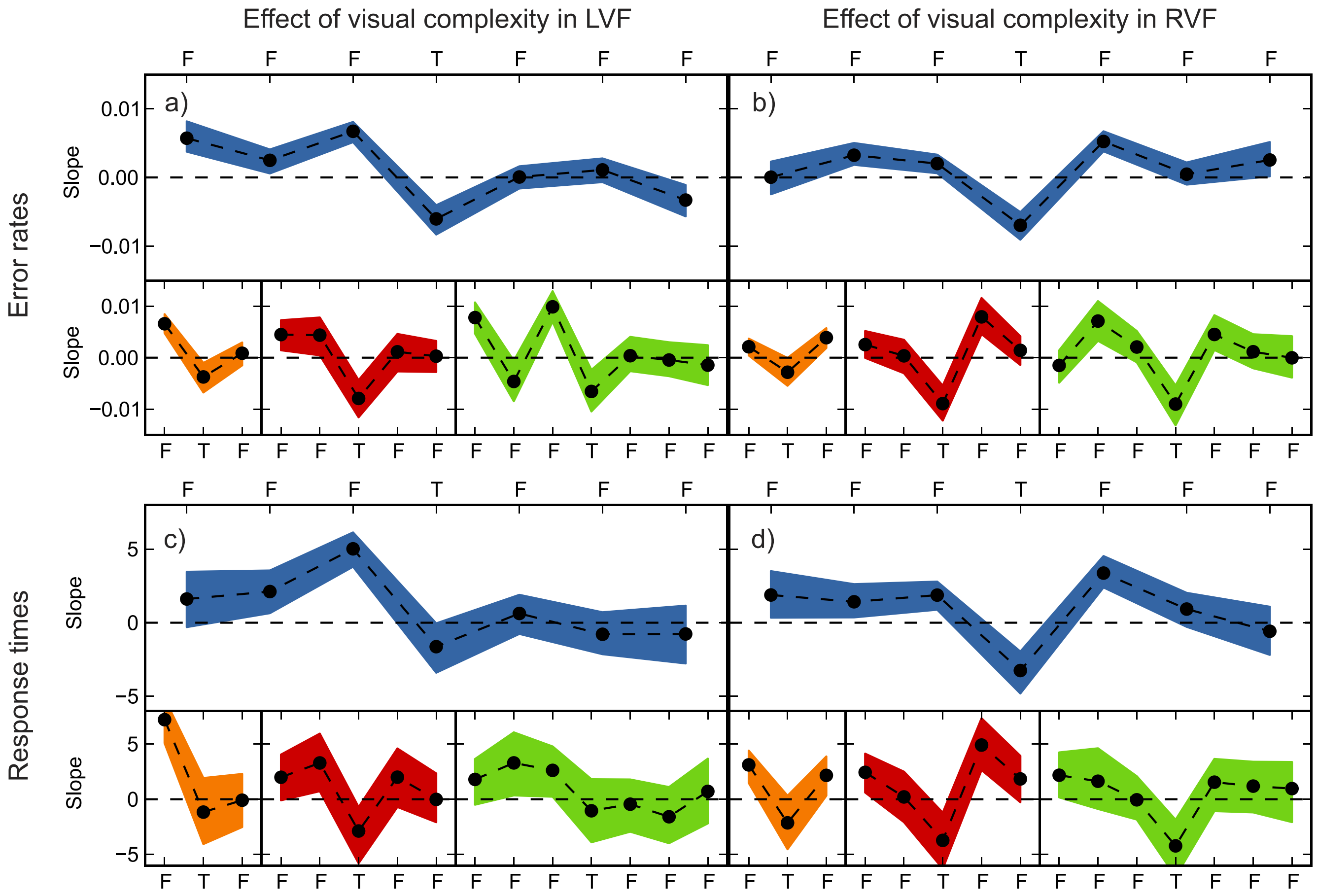

Figure 5. The effect of visual complexity on error rates (a–b) and response times (c–d) in the LVF (a, c) and RVF (b, d). Each dot corresponds to the slope of the partial effect of visual complexity for a specific stimulus position on behavioral performance. The large panes (blue) correspond to the model across all stimulus configurations. The small panes correspond to configurations with two (orange), four (red), or six (green) flankers. The middle stimulus, marked T, corresponds to the target, the remaining stimuli, marked F, correspond to flankers. Error bands indicate 95% confidence intervals.

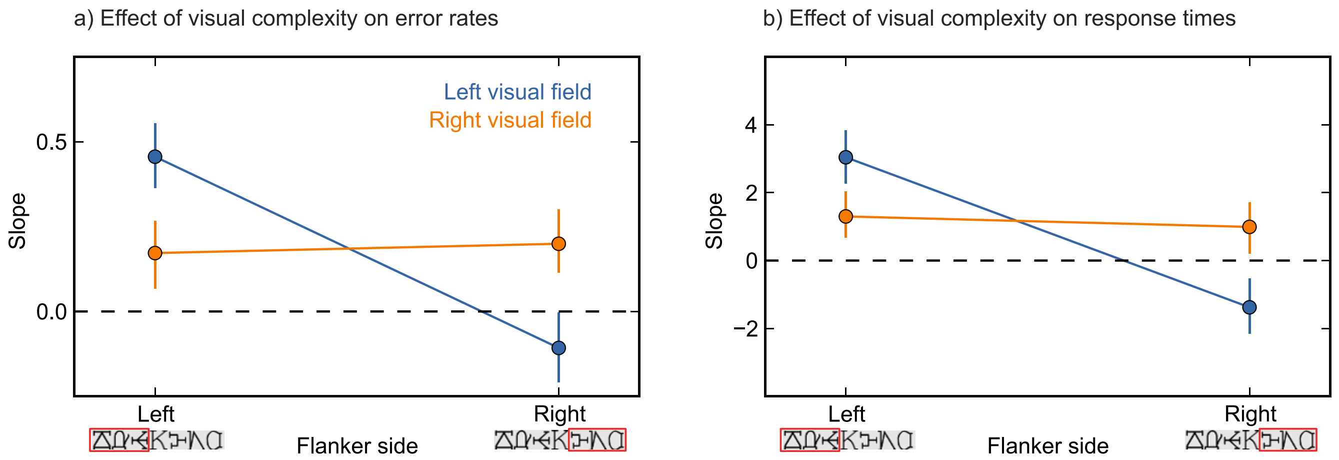

Figure 6. The effect of visual complexity on error rate (a) and response time (b) for rightward and leftward flankers in the right and left visual fields. The red outlines in the example stimuli below the *x*-axis indicate which flanker positions were combined to determine leftward and rightward visual complexity. Error bars indicate 95% confidence intervals.

of leftmost flankers (FFF——), the summed visual complexity of rightward flankers (——FFF), and visual field were entered as fixed effect. We also included the interaction terms between visual field and leftward visual complexity and the interaction between visual field and rightward visual complexity. The same analysis was conducted using response time as dependent measure. The full models are shown in the Appendix in Tables A3 and A4, but the main result is that the effect of leftward visual complexity is reduced in the RVF, compared to the LVF (error rate: $t = 4.108$, $p < 0.001$; response time: $t = 3.235$, $p = 0.001$), whereas the effect of rightwards visual complexity is increased in the RVF, compared to the LVF (error rate: $t = 4.284$, $p = < 0.001$; response time: $t = 4.238$, $p < 0.001$). This pattern of results can be summarized as follows: In the LVF there is an asymmetry, such that leftward flankers interfere more than rightward flankers, but in the RVF there is no such asymmetry (see Figures 5 and 6). Note that the reversed effect for rightward flankers in the LVF seen in Figure 6 is likely a repellent statistical artifact that arises because we estimate partial effects for strongly correlated predictors. In reality, as can be seen in Figure 5, the effect of rightward flankers in the RVF is reduced, perhaps absent, but not reversed.

Effects of target letter frequency

We obtained the frequency of each target letter from a French book corpus (New, Pallier, Brysbaert, & Ferrand, 2004), counting occurrences of uppercase letters (token frequency) independently of their position in words. We conducted an LME with the target's visual complexity and frequency as fixed effects and participant as random effect on the intercept. This analysis was conducted with error rate as well as response time as dependent variable. This analysis showed a clear positive relationship between target letter frequency and performance in terms of error rate ($t = 5.380$, $p < 0.001$) as well as response time ($t = 7.996$, $p < 0.001$). In other words, it is easier to discriminate high-frequency letters, and this effect is independent of visual complexity.

Effects of target-flanker similarity

As shown in Table 1, letter stimuli were more visually complex than other stimulus categories. Therefore, because we used only letter targets in our experiment, more visually complex flankers may have been more similar to the target. In others words, it is possible that the effects of visual complexity that we report above are fully driven by target-flanker similarity, known to modulate crowding (Andriessen & Bouma, 1976; Bernard & Chung, 2011; Freeman, Chakravarthi, & Pelli, 2012; Kooi, Toet, Tripathy, & Levi, 1994; Nazir, 1992). To test this possibility, we first determined target-flanker similarity for each flanker on a given trial.

We quantified similarity using template matching (or template overlap), a simple algorithm that has been shown to predict behavioral confusion matrices (e.g., Gervais, Harvey, & Roberts, 1984). In this measure, the similarity between two characters (A and B) is expressed as:

$$S_{\mathrm{AB}} = \left(\sum (\mathrm{X}_{ij\mathrm{A}} - \mathrm{X}_{ij\mathrm{B}})^2\right)^{-0.5}$$

Here, $\mathrm{X}_{ij\mathrm{A}}$ is the brightness of the pixel at position i,j of character A; $\mathrm{X}_{ij\mathrm{B}}$ is the brightness of the pixel at position i,j of character B; S_{AB} is the similarity between A and B.

Next, we compared two LME models, both using participant as random effect on the intercept, and error rate as dependent measure. The visual-complexity model had one fixed effect for the visual complexity of each flanker position, plus the target position (cf. Figure 5). The target-flanker similarity model had one fixed effect for the target-flanker similarity of each flanker position. Then, we compared the two models based on the Aikaike Information Criterion (AIC; low values are better, taking into account the number of free parameters in the model, such that simpler models are preferred). This revealed that the visual-complexity model (AIC = 13,853) was superior to the target-flanker-similarity model (AIC = 14,504). Strikingly, the combined model, containing both visual complexity and target-flanker similarity as fixed effects, performed about equally well (AIC = 13,850) as the visual-complexity only model. This demonstrates that target-flanker similarity explained very little variance that was not already accounted for by visual complexity. In sum, although visual complexity and target-flanker similarity may be related in our experiment, visual complexity is the better predictor of behavioral performance.

Experiment 2: Normative ratings

With the exception of the false fonts, we used relatively familiar stimuli that differ in many respects other than visual complexity. It is therefore possible that the flanker interference observed in Experiment 1 is not primarily related to visual complexity, but to other stimulus properties that correlate with visual complexity. To investigate this, we collected normative ratings for all flanker stimuli.

Methods

Twenty-one students at Aix-Marseille University participated in the experiment in exchange for monetary compensation. All participants provided written informed consent, and all reported being native speakers of French. All 45 flanker stimuli used in Experiment 1 were presented in random order. Participants rated the following properties of each stimulus on a 5-point scale: frequency (very rare to very common), complexity (very simple to very complex), and overall similarity to (other) letters (very different to very similar). Nonletter stimuli were rated in terms of overall how similar they looked to letters, and letter stimuli were rated in terms of how similar they looked to other letters. In other words, we did not use a pairwise similarity judgment. Stimulus color and size were the same as in Experiment 1. Ratings were entered using three rating scales presented on a single digital form. Participants validated their response by pressing an "OK" button. If the form was incomplete, the participant was notified, and the stimulus was presented again at a random point during the remainder of the experiment. Stimulus presentation was controlled with OpenSesame (Mathôt, Schreij, & Theeuwes, 2012). An overview of all stimuli, including their visual complexity and normative ratings, is shown in Table A5 of the Appendix. A summarized overview by stimulus type is shown in Table 1. The experiment, stimuli, and normative ratings can be downloaded from http://dx.doi.org/10.6084/m9.figshare.977864.

Results

In order to test whether any of the normative ratings obtained in Experiment 2 predict performance in Experiment 1 better than the edge-based visual-complexity measure, we compared four LME models. Each model used participant as random effect on the intercept, and error rate as dependent measure. Each model had one fixed effect for each flanker position. In the edge-based visual-complexity model, the fixed effects corresponded to the edge-based visual complexity of the stimuli. In the rated-frequency model, the fixed effects correspond to the stimuli's rated frequency and analogously for rated complexity and rated letter similarity. Next, we compared the four models based on the AIC. This showed that the edge-based visual-complexity model (AIC = 13,853) was superior to models based on rated frequency (AIC = 14,504), rated similarity to (other) letters (AIC = 14,425), and rated visual complexity (AIC = 14,545). This was confirmed by the same model comparison using response time, which also showed that visual complexity (AIC = 191,442) performed better than rated frequency (AIC = 191,900), rated similarity (AIC = 191,684), and rated complexity (AIC = 191,930). In summary, flanker interference is related more to edge-based visual complexity, which is an objective measure, than to the three subjective stimulus properties that we collected through normative ratings.

Discussion

We measured 2AFC letter identification-speed and accuracy for target letters accompanied by horizontally aligned flanking characters, with target and flankers presented to the left or to the right of fixation. Flankers could be other letters, digits, symbols, simple shapes, or false fonts. Number of flankers also varied, with either one, two, or three flankers placed symmetrically to the left and right of the target, giving a total of two, four, or six flankers. Increasing the number of flankers led to a decrease in target identification accuracy, thus replicating our prior work investigating effects of number of flankers in similar conditions (Chanceaux & Grainger, 2013). Performance also varied significantly as a function of flanker category. As can be seen in Table 1 and Figure 4, the effects of flanker type are almost perfectly accounted for by the average flanker complexity for each category of flanker type. On the other hand, and contrary to Huckauf et al.'s (1999) higher-level code hypothesis, it is clear from Table 1 that the effects of flanker type were not driven by flanker familiarity. Furthermore, our own estimation of the frequency with which flankers could form horizontally aligned strings (letters/digits > symbols > false fonts/shapes) did not predict the amount of flanker interference, since digit flankers interfered less than shape flankers but more than symbol flankers. We also found a positive relation between target letter frequency and performance, with letters that occur more frequently in print having lower response times and error rates, independently of flanker condition. This finding corroborates prior research on isolated letter identification in central vision (see Grainger, Rey, & Dufau, 2008, for a review), and shows that letter-frequency effects can be found when target letters are surrounded by flanking elements in peripheral vision (see New & Grainger, 2011, for a comparison of frequency effects for isolated letters and letters embedded in strings, in central vision).

Effects of number of flankers

The effect of number of flankers observed in the present study partly replicates the results obtained in the unilateral presentation conditions in our prior work (Chanceaux & Grainger, 2013). As in our prior work, the number-of-flankers effect was obtained using a 2AFC task where the alternative response was never present as a flanker. This is thought to limit the influence of positional uncertainty in driving any effect of flanker interference, with results mainly reflecting participants' difficulty in identifying targets rather than localizing them. Chanceaux and Grainger (2013) calculated the extent of the crowding zone for the conditions tested in their study (identical to the present study) using the parameters of Nandy and Tjan's (2012) model of inward-outward asymmetries in the crowding zone. This model was able to account for continuing interference in the four-flanker condition (two to each side of the target) compared with two flankers, but predicted no further decrement in performance in the six-flanker condition. This was in line with the results obtained using homogeneous X flankers (e.g., XXXTXXX) in Chanceaux and Grainger's study, but is not in line with the results of the present study. In the present work we found a significant decrease in performance as the number of flankers was increased from four to six (see Figure 3). This discrepancy with respect to our prior work is likely due to the lesser interference generated by homogeneous flankers compared with different flanking stimuli, as already demonstrated by Chanceaux and Grainger (2013). This is likely due to grouping of homogenous flankers (the X flankers in Chanceaux & Grainger's study), and therefore constitutes further evidence for reduced crowding by flankers being grouped separately from targets (e.g., Manassi et al., 2012; Zhang, Zhang, Xue, Liu, & Yu, 2009). Could grouping have had an influence in the present study? According to grouping accounts of crowding, more visually distinct targets should stand out from flankers and would be subject to less crowding (Malania et al., 2007; Manassi et al., 2012). This is one possible basis of the effects of target-flanker similarity seen in the present study. In Table 1 it can be seen that more similar flankers generated greater crowding, in line with prior research on effects of target-flanker similarity (e.g., Andriessen & Bouma, 1976; Bernard & Chung, 2011; Freeman et al., 2012; Kooi et al., 1994; Nazir, 1992). However, regression analyses revealed that most of the influence of target-flanker similarity was driven by flanker complexity in the present study.

Therefore, given current estimates of the spatial extent of the crowding zone, the finding that six flankers generate more interference than four flankers, in the present study, could be taken as evidence against a feature-integration account, and in favor of an attentional account of the effects of nonadjacent flankers. According to the attentional account, an increase in the number of flankers causes a spread in spatial attention, and results in less attention being allocated to target processing (Strasburger, 2005; Strasburger et al., 1991). However, we would argue that the fact that visual complexity had a strong impact on the amount of interference generated by the outermost flankers in certain conditions is further evidence in favor of an excessive feature-integration account of the effects of nonadjacent flanking elements. The basic idea here is that processing of the target letter is perturbed by visual information extracted from all flanking elements that fall within the crowding zone. This perturbation could take the form of irrelevant features providing negative evidence toward the target letter identity (e.g., Grainger et al., 2010; McClelland & Rumelhart, 1981). As noted by Balas, Nakano, and Rosenholtz, (2009), the general form of such a mechanism of excessive feature-integration is well adapted to the hypothesized structure of the ventral visual stream for visual object identification, as described in certain computational models (e.g., Fukushima, 1980; Riesenhuber & Poggio, 1999). Of course, this does not exclude a role for other forms of pooling, such as low-level averaging of visual information as part of the processing of texture (e.g., Greenwood et al., 2010; Parkes et al., 2001) in order to account for crowding phenomena in spatial vision.

Effects of flanker complexity and flanker position

The effects of flanker complexity nicely replicate the findings of Bernard and Chung (2011). These authors varied the visual complexity of letter targets and flankers in a trigram crowding paradigm by using different fonts. They found that identification of central targets was impaired by increasing flanker complexity, whereas target letter complexity had a positive influence on performance. We also found a positive relation between target letter complexity and performance, and we agree with Bernard and Chung (2011) that, overall, this pattern fits well with an excessive feature-integration account of crowding (e.g., Pelli et al., 2004). The general idea is that more complex flankers will have more features that compete with the target's own features during target identification. More complex targets have more features that can better compete with flanker features, hence reducing crowding. Furthermore, we also demonstrated that although there was some evidence for effects of target-flanker similarity, effects of flanker complexity were the better predictor of letter-identification performance.

Perhaps the key contribution of the present work is our evaluation of the independent effect of flanker complexity at each flanker position, and for the different flanker configurations. The results of these analyses, shown in Figures 5 and 6, revealed different patterns in the influence of flanker complexity as a function of visual field and the position of the flanking stimuli. In the RVF the effects of flanker complexity were equivalent for flankers located to the left and to the right of targets. On the other hand, in the LVF, a very different pattern of effects was seen for flankers to the left and right of the target. In the LVF, flanker complexity had a strong interfering effect for flankers located to the left of targets, which disappeared with flankers located to the right of targets. The overall pattern of effects of flanker complexity therefore demonstrates a greater sensitivity to flanker interference for flankers located to the left of the target when target and flankers are located in the LVF, and this is accompanied by a reduced sensitivity to flankers located to the right of targets in the LVF. Figure 5 shows that the increased sensitivity to flanker complexity for leftward flankers in the LVF is due to the fact that the most distant flankers continue to contribute to this effect in the accuracy data, which is not the case for rightward flankers in the LVF, nor for leftward and rightward flankers in the RVF.

The pattern of flanker complexity effects is precisely the pattern predicted by the MRF hypothesis (Chanceaux & Grainger, 2012), and is in line with the findings reported by Chanceaux et al. (2013) in a study that separately manipulated the number of leftward and rightward flankers. In that study, horizontally aligned strings of letters and simple shapes were presented in peripheral vision to the left or to the right of fixation, with targets occupying the central position in the string and at the same eccentricity as the present study. The number of flankers (one to three) on one side of the target was manipulated, keeping a single flanker on the opposite side, and targets and flankers were from the same category (letters or shapes). The results showed a rapid drop in target-identification accuracy as the number of leftward flankers increased for letter targets in the LVF. Thus, letter targets showed strongly asymmetrical effects of flanking letters in the LVF, which was neither the case for letter stimuli in the RVF, nor for shape stimuli in either visual field.

According to the MRF hypothesis, learning to read causes an adaptation in elementary visual processes freshly recruited for the new job of mapping print-to-sound and print-to-meaning. The primary goal of this adaptation is to optimize parallel independent letter processing, thought to be the key to skilled reading behavior (see Grainger, 2008, for a review). This optimization is hypothesized to have two main ingredients: a reduction in size of the integration zone of location-specific letter detectors (Grainger & van Heuven, 2003), and a change in the shape of the integration zone for letter detectors receiving information from the LVF (for languages with an alphabetic script read from left-to-right). More precisely, the hypothesized change in shape involves a leftward elongation of the integration zone for a constant surface, thus exaggerating the inward-outward asymmetry in the LVF. The hypothesized change in size of the integration zone reduces the amount of interletter crowding during word reading, and the change in shape boosts processing of the initial letter of words. We would therefore argue that the strong influence of visual complexity seen for the outermost leftward flankers in the LVF in the present study is the result of this increase in the inward-outward asymmetry of the crowding zone for letter stimuli processed in the LVF.

This interpretation of the present results generates two clear predictions. First, target stimuli that are neither letters nor digits should not exhibit the observed interaction between visual field and inward-outward asymmetry of crowding. Note that it is the nature of the target stimuli, not the flanker stimuli, that is critical in this respect. Second, letter stimuli in a script read from right to left, as is the case for Semitic languages, should exhibit a reversed asymmetry, with stronger effects for outward flankers in the RVF, at least for skilled monoscriptal readers of the language in question. Concerning this second prediction however, the evidence at present suggests that the asymmetry would be more likely cancelled rather than reversed. Nazir, Ben-Boutayab, Decoppet, Deutsch, and Frost (2004) measured letter identification at the five positions of five-letter strings with fixation either on the first or the last letter of the string, with native English speakers tested with Roman letters, and native Hebrew speakers tested with Hebrew letters. Although the English speakers showed a RVF advantage that was largest for inner letters (which we interpret as reflecting greater crowding of these letters in the LVF), there were no significant effects of visual field in the Hebrew readers (but see C. Whitney & Marton, 2013, for unpublished research revealing a stronger trend toward a reversed asymmetry in Hebrew). The difficulty in finding a clear reversed asymmetry for Hebrew readers could be due to the fact that they were also skilled readers of English in these studies. On the other hand, this pattern could point to a role for other factors, such as hemispheric specialization, in determining visual hemifield differences in the processing of linguistic stimuli (Brysbaert & Nazir, 2005). This clearly remains an important avenue for future research.

Conclusions

We found a strong negative impact of increasing the number of horizontally arranged flanking elements (two, four, or six) on target letter identification across a large variety of flanker types. We measured the rated familiarity of the different types of flanker, and contrary to Huckauf et al.'s (1999) higher-level code hypothesis, found that this variable was not the best predictor of performance. On the other hand, an objective measure of flanker complexity was found to capture most of the variance of flanker interference across the different flanking stimuli. Most important is that, when effects of flanker complexity were evaluated independently for each flanker position and flanker configuration, the position of flanking elements strongly influenced performance in the LVF but not the RVF. More specifically, in the LVF we found a strong negative influence of flanker complexity for leftward flankers but not for rightward flankers, in line with Chanceaux and Grainger's (2012) MRF hypothesis of letter-specific crowding.

Keywords: letter-in-string identification, crowding, flanker complexity, flanker type

Acknowledgments

This research was funded by ERC grant 230313.

Commercial relationships: none.

Corresponding author: Jonathan Grainger.
Email: jonathan.grainger@univ-amu.fr.
Address: Laboratoire de Psychologie Cognitive, Aix-Marseille University, Marseille, France.

References

Andriessen, J. J., & Bouma, H. (1976). Eccentric vision: Adverse interactions between line segments. *Vision Research*, *16*, 71–78.

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. Cambridge, UK: Cambridge University Press.

Balas, B., Nakano, L., & Rosenholtz, R. (2009). A summary-statistic representation in peripheral vision explains visual crowding. *Journal of Vision*, *9*(12):13, 1–18, http://www.journalofvision.org/content/9/12/13/, doi:10.1167/9.12.13. [PubMed] [Article]

Banks, W. P., Larson, D.W., & Prinzmetal, W. (1979). Asymmetry of visual interference. *Perception & Psychophysics*, *25*, 447–456.

Banks, W. P., & White, H. (1984). Lateral interference and perceptual grouping in visual detection. *Perception & Psychophysics*, *36*, 285–295.

Bernard, J. B., & Chung, S. T. L. (2011). The dependence of crowding on flanker complexity and target-flanker complexity. *Journal of Vision*, *11*(8): 1, 1–16, http://www.journalofvision.org/content/11/8/1, doi:10.1167/11.8.1. [PubMed] [Article]

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research*, *13*, 767–782.

Brysbaert, M., & Nazir, T. (2005). Visual constraints in written word recognition: Evidence from the optimal viewing-position effect. *Journal of Research in Reading*, *28*, 216–228.

Butler, B. E., & Currie, A. (1986). On the nature of perceptual limits in vision: A new look at lateral masking. *Psychological Research*, *48*, 201–209.

Chanceaux, M., & Grainger, J. (2012). Serial position effects in the identification of letters, digits, symbols, and shapes in peripheral vision. *Acta Psychologica*, *141*, 149–158.

Chanceaux, M., & Grainger, J. (2013). Constraints on letter-in-string identification in peripheral vision: Effects of number of flankers and deployment of attention. *Frontiers in Psychology*, *4*, 119, doi:10.3389/fpsyg.2013.00119.

Chanceaux, M., Mathôt, S., & Grainger, J. (2013). Flank to the left, flank to the right: Testing the modified receptive field hypothesis of letter specific crowding. *Journal of Cognitive Psychology*, *25*, 774–780, doi:10.1080/20445911.2013.823436.

Freeman, J., Chakravarthi, R., & Pelli, D.G. (2012). Substitution and pooling in crowding. *Attention, Perception & Psychophysics*, *74*, 379–396, doi:10.3758/s13414-011-0229-0.

Fukushima, K. (1980). Neocognitron: A self-organizing neural network model for a mechanism of pattern recognition unaffected by shift in position. *Biological Cybernetics*, *36*, 193–202.

Gervais, M. J., Harvey, L. O., & Roberts, J. O. (1984). Identification confusions among letters of the alphabet. *Journal of Experimental Psychology: Human Perception & Performance*, *10*, 655–666.

Grainger, J. (2008). Cracking the orthographic code: An introduction. *Language & Cognitive Processes*, *23*, 1–35.

Grainger, J., & Dufau, S. (2012). The front-end of visual word recognition. In J. S. Adelman (Ed.), *Visual word recognition volume 1: Models and methods, orthography and phonology*. Hove, UK: Psychology Press.

Grainger, J., Rey, A., & Dufau, S. (2008). Letter perception: From pixels to pandemonium! *Trends in Cognitive Sciences*, *12*, 381–387.

Grainger, J., Tydgat, I., & Isselé, J. (2010). Crowding affects letters and symbols differently. *Journal of Experimental Psychology: Human Perception & Performance*, *36*, 673–688.

Grainger, J., & van Heuven, W. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *The mental lexicon* (pp. 1–24). New York: Nova Science Publishers.

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2010). Crowding changes appearance. *Current Biology*, *20*, 496–501.

Huckauf, A., & Heller, D. (2002a). Spatial selection in peripheral letter recognition: In search of boundary conditions. *Acta Psychologica*, *11*, 101–123.

Huckauf, A., & Heller, D. (2002b). What various kinds of errors tell us about lateral masking effects. *Visual Cognition*, *9*, 889–910.

Huckauf, A., Heller, D., & Nazir, T. A. (1999). Lateral masking: Limitations of the feature interaction account. *Perception & Psychophysics*, *61*, 177–189.

Itti, L., Koch, C., & Niebur, E. (1998). A model of saliency-based visual attention for rapid scene analysis. *IEEE Transactions on Pattern Analysis & Machine Intelligence*, *20*, 1254–1259.

Kooi, F. L., Toet, A., Tripathy, S. P., & Levi, D. M. (1994). . The effect of similarity and duration on spatial interaction in peripheral vision. *Spatial Vision*, *8*, 255–279.

Legge, G. E., Mansfield, J. S., & Chung, S. T. L. (2001). Psychophysics of reading: XX linking letter recognition to reading speed in central and peripheral vision. *Vision Research*, *41*, 725–743.

Levi, D. M. (2008). Crowding—An essential bottleneck for object recognition: A mini-review. *Vision Research*, *48*, 635–654.

Levi, D. M., & Carney, T. (2009). Crowding in peripheral vision: Why bigger is better. *Current Biology*, *19*, 1988–1993.

Livne, T., & Sagi, D. (2007). Configuration influence on crowding. *Journal of Vision*, *7*(2):4, 1–12, http://www.journalofvision.org/content/7/2/4, doi:10.1167/7.2.4. [PubMed] [Article]

Malania, M., Herzog, M. H., & Westheimer, G. (2007). Grouping of contextual elements that affect vernier thresholds. *Journal of Vision*, *7*(2):1, 1–7, http://www.journalofvision.org/content/7/2/1, doi:10.1167/7.2.1. [PubMed] [Article]

Manassi, M., Sayim, B., & Herzog, M. H. (2012). Grouping, pooling, and when bigger is better in visual crowding. *Journal of Vision*, *12*(10):13, 1–14, http://www.journalofvision.org/content/12/10/13, doi:10.1167/12.10.13. [PubMed] [Article]

Manassi, M., Sayim, B., & Herzog, M. H. (2013). When crowding of crowding leads to uncrowding. *Journal of Vision*, *13*(13):10, 1–10, http://www.journalofvision.org/content/13/13/10, doi:10.1167/13.13.10. [PubMed] [Article]

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part I. An account of basic findings. *Psychological Review*, *88*, 375–407.

Nandy, A. S., & Tjan, S. T. (2012). Saccade-confounded image statistics explain visual crowding. *Nature Neuroscience*, *15*, 463–469, doi:10.1038/nn.3021.

Nazir, T. A. (1992). Effects of lateral masking and spatial precueing on gap-resolution in central and peripheral vision. *Vision Research*, *32*, 771–777.

Nazir, T. A., Ben-Boutayab, N., Decoppet, N., Deutsch, A., & Frost, R. (2004). Reading habits, perceptual learning, and recognition of printed words. *Brain & Language*, *88*, 294–311.

New, B., & Grainger, J. (2011). On letter frequency effects. *Acta Psychologica*, *138*, 322–328.

New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical database. *Behavior Research Methods, Instruments, & Computers*, *36*, 516–524.

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A., & Morgan, M. (2001). Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience*, *4*(7), 739–744.

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision*, *4*(12):12, 1136–1169, http://www.journalofvision.org/content/4/12/12, doi:10.1167/4.12.12. [PubMed] [Article]

Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window for object recognition. *Nature Neuroscience*, *11*, 1129–1135.

Petrov, Y., & Meleshkevich, O. (2011). Locus of spatial attention determines inward–outward anisotropy in crowding. *Journal of Vision*, *11*(4):1, 1–11, http://www.journalofvision.org/content/11/4/1, doi:10.1167/11.4.1. [PubMed] [Article]

Petrov, Y., Popple, A.V., & McKee, S. P. (2007). Crowding and surround suppression: Not to be confused. *Journal of Vision*, *7*(2):12, 1–9, http://www.journalofvision.org/content/7/2/12, doi:10.1167/7.2.12. [PubMed] [Article]

Riesenhuber, M., & Poggio, T. (1999). Hierarchical models of object recognition in cortex. *Nature Neuroscience*, *2*, 1019–1025.

Saarela, T. P., Sayim, B., Westheimer, G., & Herzog, M. H. (2009). Global stimulus configuration modulates crowding. *Journal of Vision*, *9*(2):5, 1–11, http://www.journalofvision.org/content/9/2/5, doi:10.1167/9.2.5. [PubMed] [Article]

Strasburger, H. (2005). Unfocused spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision*, *5*(11):8, 1024–1037, http://www.journalofvision.org/content/5/11/8, doi:10.1167/5.11.8. [PubMed] [Article]

Strasburger, H. Harvey, L. O., Jr., & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception & Psychophysics*, *49*, 495–508.

Tydgat, I., & Grainger, J. (2009). Serial position effects in the identification of letters, digits, and symbols. *Journal of Experimental Psychology: Human Perception & Performance*, *35*, 480–498.

Wang, H., He, X., & Legge, G. E. (2014). Effect of pattern complexity on the visual span for Chinese and alphabet characters. *Journal of Vision*, *14*(8):6, 1–17, http://www.journalofvision.org/content/14/8/6, doi:10.1167/14.8.6. [PubMed] [Article]

Whitney, C., & Marton, Y. (2013). *The SERIOL2 model of orthographic processing*. Retrieved from https://www.researchgate.net/publication/237065841_The_SERIOL2_Model_of_Orthographic_Processing

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences*, *15*, 160–168.

Wolford, G., & Chambers, L. (1983). Lateral masking as a function of spacing. *Perception & Psychophysics*, *33*, 129–138.

Zhang, J. Y., Zhang, T., Xue, F., Liu, L., & Yu, C. (2009). Legibility of Chinese characters in peripheral vision and the top-down influences on crowding. *Vision Research*, *49*, 44–53.

Appendix

Effect	Slope/ intercept	95% upper	95% lower	*p* value	*t* value
Intercept	11.04	3.69	18.38	<0.01	3.06
Flanker type (Digit) [Reference: Letters]	−8.82	−17.30	−0.63	0.03	−2.13
Flanker type (False font)	4.47	−4.06	12.37	0.28	1.08
Flanker type (Shape)	−9.93	−18.51	−2.06	0.02	−2.38
Flanker type (Symbol)	−10.98	−18.56	−2.16	0.01	−2.65
No. of flankers	6.27	4.79	7.43	<0.01	9.30
Visual field (Right) [Reference: Left]	−7.44	−15.14	1.20	0.07	−1.79
Flanker type (Digit) × No. of flankers	−1.49	−3.51	0.29	0.12	−1.57
Flanker type (False font) × No. of flankers	−1.92	−3.86	−0.09	0.04	−2.01
Flanker type (Shape) × No. of flankers	0.36	−1.36	2.48	0.70	0.38
Flanker type (Symbol) × No. of flankers	−3.00	−4.82	−1.05	<0.01	−3.14
Flanker type (Digit) × Visual field (Right)	1.48	−10.37	12.62	0.80	0.25
Flanker type (False font) × Visual field (Right)	2.22	−10.39	13.53	0.71	0.38
Flanker type (Shape) × Visual field (Right)	4.32	−7.85	15.22	0.46	0.73
Flanker type (Symbol) × Visual field (Right)	7.13	−5.26	17.19	0.23	1.21
No. of flankers: Visual field (Right)	0.25	−1.71	2.04	0.79	0.26
Flanker type (Digit) × No. of flankers × Visual field (Right)	0.05	−2.45	2.69	0.97	0.04
Flanker type (False font) × No. of flankers × Visual field (Right)	0.46	−2.45	3.15	0.74	0.34
Flanker type (Shape) × No. of flankers × Visual field (Right)	−0.20	−3.02	2.26	0.88	−0.15
Flanker type (Symbol) × No. of flankers × Visual field (Right)	−1.47	−4.04	1.13	0.28	−1.08

Table A1. The intercept and fixed effects from an LME with error rate as dependent measure and participant and target letter as random effects on the intercept. *Note*: For discrete effects, the reference category is indicated between square brackets.

Effect	Slope/ intercept	95% upper	95% lower	*p* value	*t* value
Intercept	774.72	696.21	857.20	<0.01	19.86
Flanker type (Digit) [Reference: Letters]	−127.00	−192.54	−65.73	<0.01	−3.98
Flanker type (False font)	−7.70	−70.03	58.38	0.81	−0.24
Flanker type (Shape)	−108.74	−169.10	−39.37	<0.01	−3.37
Flanker type (Symbol)	−191.84	−255.80	−127.53	<0.01	−6.00
No. of flankers	21.78	10.95	31.02	<0.01	4.18
Visual field (Right) [Reference: Left]	−68.96	−131.64	−5.89	0.03	−2.15
Flanker type (Digit) × No. of flankers	2.21	−11.42	16.91	0.76	0.30
Flanker type (False font) × No. of flankers	−14.33	−27.89	2.04	0.05	−1.95
Flanker type (Shape) × No. of flankers	−0.64	−15.81	13.79	0.93	−0.09
Flanker type (Symbol) × No. of flankers	−2.88	−17.70	10.37	0.70	−0.39
Flanker type (Digit) × Visual field (Right)	21.99	−68.71	116.57	0.63	0.49
Flanker type (False font) × Visual field (Right)	−31.00	−118.14	57.27	0.49	−0.69
Flanker type (Shape) × Visual field (Right)	16.07	−64.74	119.94	0.72	0.35
Flanker type (Symbol) × Visual field (Right)	40.44	−49.40	125.17	0.37	0.89
No. of flankers: Visual field (Right)	13.47	−2.22	27.44	0.07	1.82
Flanker-type (Digit) × No. of flankers × Visual field (Right)	−7.91	−27.89	14.17	0.45	−0.76
Flanker type (False font) × No. of flankers × Visual field (Right)	7.46	−15.64	26.32	0.47	0.72
Flanker type (Shape) × No. of flankers × Visual field (Right)	−1.03	−21.68	20.93	0.92	−0.10
Flanker type (Symbol) × No. of flankers × Visual field (Right)	−8.99	−28.82	11.19	0.39	−0.86

Table A2. The intercept and fixed effects from an LME with response time as dependent measure and participant and target letter as random effects on the intercept. *Note*: For discrete effects, the reference category is indicated between square brackets.

Effect	Slope/ intercept	95% upper	95% lower	*p* value	*t* value
Intercept	3.34	<0.01	6.83	0.05	1.98
Left-vis-comp	0.46	0.37	0.56	<0.01	9.39
Right-vis-comp	−0.11	−0.21	−0.02	0.03	−2.14
Visual field (Right) [Reference: Left]	−5.56	−8.60	−2.18	<0.01	−3.42
Left-vis-comp × Visual field (Right)	−0.28	−0.43	−0.15	<0.01	−4.11
Right-vis-comp × Visual field (Right)	0.31	0.18	0.46	<0.01	4.28

Table A3. The intercept and fixed effects from an LME with error rate as dependent measure and participant as random effect on the intercept. *Notes*: For discrete effects, the reference category is indicated between square brackets. Left-vis-comp = visual complexity of leftward flankers; Right-vis-comp = visual complexity of rightward flankers.

Effect	Slope/ intercept	95% upper	95% lower	*p* value	*t* value
Intercept	651.56	595.28	711.94	<0.01	21.03
Left-vis-comp	3.04	2.36	3.76	<0.01	8.08
Right-vis-comp	−1.38	−2.09	−0.64	<0.01	−3.51
Visual field (Right) [Reference: Left]	−52.29	−75.08	−27.12	<0.01	−4.15
Left-vis-comp × Visual field (Right)	−1.73	−2.71	−0.69	<0.01	−3.24
Right-vis-comp × Visual field (Right)	2.35	1.23	3.39	<0.01	4.24

Table A4. The intercept and fixed effects from an LME with response time as dependent measure and participant as random effect on the intercept. *Notes*: For discrete effects, the reference category is indicated between square brackets. Left-vis-comp = visual complexity of leftward flankers; Right-vis-comp = visual complexity of rightward flankers.

Stimulus	Type	Edge-based vis. comp.	Rated vis. comp	Rated freq.	Rated sim.
1	digit	30.27	0.62	3.86	1.86
2	digit	26.21	0.71	3.86	1.38
3	digit	25.21	1.05	3.81	2.05
4	digit	27.59	1.43	3.76	1.57
5	digit	28.11	1.33	3.57	1.48
6	digit	28.32	1.10	3.81	1.57
7	digit	28.54	0.43	3.81	0.95
8	digit	29.12	1.19	3.57	1.67
9	digit	27.98	0.90	3.81	1.86
B	letter	44.20	1.19	3.86	2.71
D	letter	34.16	0.67	3.81	2.81
G	letter	33.86	1.38	3.67	2.48
H	letter	41.75	1.19	3.76	2.19
K	letter	39.62	1.62	3.48	2.38
M	letter	47.81	1.33	3.81	2.67
N	letter	41.85	1.14	3.76	2.76
R	letter	38.86	1.81	3.81	2.52
S	letter	33.15	1.14	3.86	2.52
	false font	35.01	3.24	0.19	1.10
	false font	30.42	2.90	0.24	1.19
	false font	39.18	2.86	0.10	2.33
	false font	33.82	3.05	0.33	1.81
	false font	41.78	2.86	0.19	1.38
	false font	37.02	2.48	0.14	1.90
	false font	34.38	1.67	0.52	3.24
	false font	52.55	2.76	0.33	0.95
	false font	41.94	2.67	0.33	1.24
◇	shape	29.68	0.86	2.33	1.19
□	shape	46.64	0.62	2.86	1.19
△	shape	35.12	0.95	2.95	1.86
○	shape	34.65	0.05	3.86	3.24
⇨	shape	35.43	1.71	3.05	0.52
♡	shape	36.46	1.19	3.52	0.71
✚	shape	43.61	1.76	2.71	0.81
☾	shape	38.55	1.38	1.71	2.86
☆	shape	36.91	2.38	2.67	0.43
%	symbol	16.97	1.57	2.67	0.52
}	symbol	15.57	1.33	2.95	0.86
µ	symbol	22.46	1.95	2.05	3.33
§	symbol	26.54	2.43	1.71	3.00
/	symbol	12.70	< 0.01	3.38	1.43
?	symbol	16.56	0.95	3.81	0.62
@	symbol	30.32	2.29	3.29	2.52
<	symbol	14.27	0.43	3.00	1.43
£	symbol	21.84	2.62	2.19	3.00

Table A5. A list of all stimuli used in the experiment.