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BRIEF REPORT

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Abstract There is growing interest in how perceptual factors such as the spacing between letters within words modulate performance in visual word recognition and reading aloud. Extra-large letter spacing can strongly improve the reading performance of dyslexic children, and a small increase with respect to the standard spacing seems beneficial even for skilled word recognition in adult readers. In the present study we examined the effect of decreased letter spacing on perceptual identification and lexical decision tasks. Identification in the decreased spacing condition was slower than identification of normally spaced strings, thereby confirming that the reciprocal interference among letters located in close proximity (crowding) poses critical constraints on visual word processing. Importantly, the effect of spacing was not modulated by string length, suggesting that the locus of the spacing effect is at the level of letter detectors. Moreover, the processing of crowded letters was facilitated by top-down support from orthographic lexical representation as indicated by the fact that decreased spacing affected pseudowords significantly more than words. Conversely, in the lexical decision task only word responses were affected by the spacing manipulation. Overall, our findings support the hypothesis that increased crowding is particularly harmful for phonological decoding, thereby adversely affecting reading development in dyslexic children.

Keywords Interletter spacing · Orthographic processing · Progressive demasking · Lexical decision

Introduction

The study of how perceptual factors modulate visual word recognition and reading aloud has seen a recent surge of interest. Manipulations in interletter spacing are particularly interesting because the default spacing of letters in printed material is not based on empirical data (Woods, Davis & Scharff, 2005) and it might be suboptimal for many readers. While very large letter spacing impairs performance of skilled adult readers because it disrupts the perceptual integrity of the whole word, up to the point of inducing a sort of letter-by-letter reading that is characteristic of patients with pure alexia (e.g., Cohen Dehaene, Vinckier et al., 2008), Perea, Moret-Tatay and Gómez (2011) observed a benefit in terms of identification latencies for words presented with a slightly wider interletter spacing relative to the default spacing during lexical decision. Perea and colleagues suggested that the wider spacing produces a benefit in lexical access and that the locus of the effect is at an early encoding stage (Perea & Gomez, 2012). The benefit of larger-than-normal spacing appears to be even stronger in dyslexic readers (Perea, Panadero, Moret-Tatay & Gomez, 2012; Zorzi, Barbiero, Facoetti et al., 2012). In a large-scale study on Italian and French dyslexic children, Zorzi and colleagues showed that extra-large letter spacing strongly improved reading speed and accuracy in the dyslexic group but not in typically developing children matched for reading level. Moreover, the gain induced by the spacing manipulation was negatively correlated with letter

V. Montani · A. Facoetti · M. Zorzi (✉)
Department of General Psychology, University of Padova, via Venezia 8, 35131 Padova, Italy
e-mail: marco.zorzi@unipd.it

A. Facoetti
Neuropsychology Unit, "E. Medea" Scientific Institute, Bosisio Parini, LC, Italy

M. Zorzi
Center for Cognitive Neuroscience, University of Padova, Padova, Italy

M. Zorzi
IRCCS San Camillo Neurorehabilitation Hospital, Venice-Lido, Italy

identification accuracy in a task in which the target letter had to be identified within a string of consonants.

The effect of spacing on reading performance is readily interpreted in terms of visual crowding, that is the reciprocal interference between stimuli located in close proximity (for reviews see Pelli & Tillman, 2008; Whitney & Levi, 2011). Indeed, letter recognition is impaired when letters are closer than a critical spacing (Bouma, 1970). Furthermore, letter spacing influences the size of the visual span (Yu, Cheung, Legge, & Chung, 2007), which is the number of letters acquired at each fixation (see Rayner, 1998, for review). The size of the visual span is strongly correlated with reading rate (Legge, Cheung, Yu et al., 2007; also see Bosse et al., 2007, for the role of the visual-attentional span in dyslexia) and the causality of this link is formalized in the model of Legge, Mansfield, and Chung (2001), which takes the spatial profile of letter accuracy as input and returns reading speed as output. Though crowding is usually discussed in the context of peripheral vision, there is evidence that it also occurs in fovea (e.g., Chicherov & Herzog, 2013; Danilova & Bondarko, 2007). This suggests that crowding, in addition to constraining the number of letters acquired with each fixation (visual span), might also influence foveal recognition of letters (Moll & Jones, 2013). The benefit of wider letter spacing for dyslexics fits well with the finding that they are abnormally affected by crowding (e.g., Martelli, Di Filippo, Spinelli & Zoccolotti, 2009; Moll & Jones, 2013; Moores, Cassim & Talcott, 2011; Spinelli, De Luca, Judica, & Zoccolotti, 2002). Tydgat and Grainger (2009) proposed that learning to read demands the optimization of the parallel processing of letter stimuli, which would involve the reduction of receptive field size for retinotopic letter detectors. Successful adaptation would effectively reduce the effect of letter crowding.

The “modified receptive field hypothesis” of Grainger and colleagues (Tydgat & Grainger, 2009; also see Chanceaux & Grainger, 2012; Chanceaux, Mathôt & Grainger, 2013; Grainger, Tydgat & Isselé, 2010) predicts that smaller-than-normal spacing should be sub-optimal because adaptation of the receptive fields is attuned to the “standard” letter spacing. A decreased spacing condition was previously employed by Perea and Gomez (2012) in a lexical decision task, but its effect was not directly contrasted with normal spacing (the effect of spacing was evaluated in terms of linear trend through five increasing levels of spacing, where only the first level represented smaller-than-normal spacing). A reduction of reading speed for smaller-than-normal letter spacing was observed by Chung (2002; also see Yu et al., 2007) during oral reading of sentences (word-by-word RSVP), but her manipulation produced medium-to-strong perceptual overlap between adjacent letters, thereby disrupting the integrity of letters as separated units. To further investigate the hypothesis that lateral interactions among letters pose critical constraints on visual word processing, we specifically asked whether decreased spacing would hinder the processing of letter strings presented at fixation. Note that this issue is also relevant for better understanding the effect of spacing in dyslexia, because the effect of smaller-than-normal spacing in skilled readers might provide a model of the increased letter crowding observed in dyslexic readers.

Since the standard spacing between letters in printed text is rather small (thereby preventing a large reduction of spacing when avoiding letter overlap) and, in foveal normal vision, lateral interactions between adjacent objects occur only at the resolution limit of the visual system (e.g., Danilova & Bondarko, 2007), in Experiment 1 the spacing manipulation was implemented in the context of the ‘progressive demasking’ (PDM) task (Grainger & Segui, 1990) in order to magnify its effect. In the PDM task, presentation of the target string is interspersed with a masking stimulus; through successive display changes, the duration of the stimulus is increased and the duration of the mask decreased, giving the impression that the word emerges from the mask. The PDM paradigm slows down word recognition and it provides a more sensitive measure of ongoing perceptual processing (Dufau, Stevens & Grainger, 2008).

We jointly manipulated two orthographic properties of the target stimuli, i.e., lexicality (word vs. pseudoword) and length (short vs. long). These two properties can be diagnostic for the distinction between lexical and sublexical processing pathways subserving visual word recognition and reading aloud (for a computational account see Perry, Ziegler, & Zorzi, 2007; Zorzi, 2010). The interaction (or lack thereof) between these orthographic properties and the spacing manipulation can provide important information about the architecture and processing dynamics of visual word recognition (for a similar logic applied to a different manipulation of stimulus quality, see Besner & Roberts, 2003; O’Malley & Besner, 2008; Ziegler, Perry & Zorzi, 2009). In particular, we predicted that decreased letter spacing would hinder pseudowords more than words, because the identification of each letter is critical for successful pseudoword processing (Perry et al., 2007), whereas word processing can be successful even when the letter input is noisy or partial (for computational evidence see McClelland & Rumelhart, 1981; Zorzi, Testolin & Stoianov, 2013). Moreover, an interaction between spacing and string length would reveal that spacing affects a processing stage that is specifically concerned with the sublexical route (e.g., letter parsing for the identification of graphemes; Perry, Ziegler, & Zorzi, 2013), whereas the lack of interaction would point to an earlier processing stage that is shared by the two reading pathways (i.e., letter detectors).

In Experiment 2 the manipulation of letter spacing was implemented in the context of a lexical decision task in order to extend our investigation to a different paradigm. We also included an increased spacing condition to reassess (in a different language) the facilitation observed by Perea and colleagues (Perea & Gomez, 2012; Perea et al., 2012) on word latencies in lexical decision.

Experiment 1

Method

Eighteen university students participated in the experiments (mean age 23 years). Participants were Italian native speakers and they had normal or corrected-to-normal vision. The experiment was performed using E-Prime 1.1 software (Schneider, Eschman, & Zuccolotto, 2002). Participants sat in front of a computer screen (17-inch, 75 Hz LCD monitor) with their head positioned on a headrest. They were instructed to keep their fixation on the screen centre throughout the task.

The session started with a brief practice block and continued with two experimental blocks of 192 trials each. The experimental block sequence was counterbalanced between participants while the target string sequence was randomized for each subject. Each trial started with a fixation point (white cross on black screen). After 1000 ms, the stimulus was displayed in the screen centre. The stimulus consisted of several cycles, each made up of the successive presentation of a mask (a string of hash marks with the same length of the target) followed by the target. On successive cycles within a trial, the signal-to-noise ratio was increasing. At the first cycle, mask duration was set to 14 screen refreshes (182 ms) and target duration to one screen refresh (13 ms). Then, mask duration decreased and target duration increased progressively at each cycle, while keeping the duration of the overall cycle fixed to 15 refreshes (about 195 ms). At the last cycle the mask was not presented (i.e., mask duration was zero refresh long) and target duration was 15 refreshes. Each trial consisted of 14 cycles (about 2700 ms). Participants had to press the space bar on the keyboard as soon as they could identify the target string. After pressing the space bar, the stimulus disappeared and a response window prompted participants to type the target string within the window.

The letter strings were printed in white on black screen using the Sloan font (Pelli, Robson, & Wilkins, 1988). Sloan letters are equally well identified (they are commonly used to test visual acuity) and their shape allows optimal control of interletter spacing. The letter strings were centrally displayed and they subtended no more than 5° of visual angle. The 192 letter strings were either familiar (96), medium-high frequency Italian words (Burani, Barca, & Arduino, 2001) or pronounceable pseudowords (96) obtained by replacing three letters of the same words but keeping the same syllabic structure. Words and pseudowords were either short (four or five, 48 for each type) or long (seven or eight letters, 48 for each type). We manipulated inter-letter spacing, using either standard letter spacing (1.1 × letter size) or decreased letter spacing (1.03 × letter size). Note that adjacent letters did not overlap in any condition and they were separated by at least one pixel of blank space. The strings were randomly assigned to the spacing condition but so that each string type was equally distributed across the conditions (96 trials for each spacing condition, 24 trials per cell).

Results

Data were analysed employing mixed-effect multiple regression models (Baayen, Davidson & Bates, 2008) using lme4 package (Bates, Maechler, Bolker & Walker, 2013) and afex package (Singmann, 2013) in the R environment (R Core Team, 2013). The model included three fixed effects and their interactions: *string type* (*word* vs. *pseudoword*), *length* (*short* vs. *long*), *spacing* (*standard* vs. *decreased*), two-way interactions *type* by *length*, *type* by *spacing*, *length* by *spacing*, and the three-way interaction *type* by *length* by *spacing*. Barr, Levy, Scheepers et al. (2013) suggested that linear mixed-effects models generalize best when they include maximal random effects structure justified by the design. In our study, this implies by-subject random intercepts and by-subject random slopes for each manipulated factor (which were assumed to be independent from each other). At the item level, only the random intercepts were included because our manipulations of string type and string length imply different items for each level of the type factor and for each level of the length factor. The random slopes for spacing were not included because they did not improve the fit of the model.

For the main analysis, we performed Type III tests, comparing a model in which only the corresponding effect is missing with the model containing the effect. The *p* values were calculated via the likelihood ratio tests. For the separate models (see below), we report regression coefficients (*b*), t values, and *p* values evaluated using the method suggested by Baayen (2008), which estimates the degrees of freedom by subtracting the number of fixed-effect parameters from the total number of data-points considered. Mean accuracy and reaction times in the different conditions are reported in Table 1.

Reaction times The reaction time (RT) analysis was performed only on correct responses. We log transformed the durational dependent measures to normalize the distribution. The parameters of the random and fixed effects of the final model are reported in Table 2. The main effect of string type was significant, $\chi^2(1) = 51.05$, $p < .0001$, indicating that responses were faster for words than for pseudowords (i.e., lexicality effect). The main effect of length was significant, $\chi^2(1) = 30.32$, $p < .0001$, indicating that responses were faster for short than for long strings (i.e., length effect). The main effect of spacing was also significant $\chi^2(1) = 12.73$, $p < .001$, showing that the identification of strings with decreased letter

Table 1 Experiment 1. Mean accuracies and reaction times (standard deviations in parentheses) for all experimental conditions

	Words		Pseudowords	
	Short	Long	Short	Long
Standard spacing	0.97 (0.06)	0.96 (0.08)	0.92 (0.07)	0.82 (0.11)
	1329 (111)	1483 (107)	1652 (120)	2015 (102)
Decreased spacing	0.97 (0.07)	0.96 (0.05)	0.88 (0.07)	0.81(0.10)
	1363 (91)	1504 (115)	1735 (122)	2143 (157)

spacing was slower than the identification of normally spaced strings (spacing effect). The type by length interaction was significant $\chi^2(1) = 15.70$, $p < .001$; see Fig. 1, left panel), suggesting that the length effect was stronger for pseudowords. Importantly, the type by spacing interaction was also significant $\chi^2(1) = 7.70$, $p < .01$; see Fig. 1, right panel), indicating that, in the decreased spacing condition, pseudoword identification was impaired more than word identification. No other effect was significant. To further investigate the lexical modulation of the spacing effect, the string type by spacing interaction was broken down by fitting separate models on the two types of string. Hence, for this analysis the main effect and the interaction term of the type of string were excluded. The length factor was also excluded because it did not interact with spacing in the full model. The spacing effect turned out to be significant both for pseudowords, $b = 0.05$, $t(1479) = 4.1$, $p < 0.001$ and for words, $b = 0.01$, $t(1663) = 2.24$, $p < 0.05$.

Error rates We applied a multiple regression model with a logistic link function and binomial variance because the dependent variable was dichotomous (Jaeger, 2008). The main effect of string type was significant, $\chi^2(1) = 47.27$, $p < .0001$, indicating higher accuracy for words than pseudowords (i.e., lexicality effect). The main effect of length was also significant, $\chi^2(1) = 9.23$, $p < .001$, indicating that identification accuracy was better for short strings than for long strings (i.e., length effect). No other main effect or interaction was significant.

Experiment 2

The aim of Experiment 2 was to further investigate the effect of decreased letter spacing observed in Experiment 1 using a different experimental paradigm, i.e., the lexical decision task (LDT). We also included an increased spacing condition, which was shown to influence LDT in the studies of Perea and colleagues. In Perea et al. (2011), a joint manipulation of spacing and length yielded a benefit of increased spacing but no effect of length and no interaction for the word stimuli. For pseudowords, increased spacing had no effect on five-letter stimuli and a detrimental effect (rather than a benefit) for eight-letter

Table 2 Experiment 1. Details of the final model

Random effects						
Groups	Name	Variance	SD	Correlation		
Item	(Intercept)	0.0081	0.0899			
Subject	(Intercept)	0.0551	0.2347			
	Type: Word	0.0106	0.1027	0.13		
	Length: Long	0.0063	0.0792	−0.79	−0.40	
	Spacing: Standard	0.0013	0.0355	0.21	0.53	0.30
Fixed effects						
	Estimate	SE	t value			
(Intercept)	7.42	0.06	129.07			
Type: Word	−0.23	0.03	−7.19			
Length: Long	0.23	0.03	7.79			
Spacing: Standard	−0.05	0.01	−3.30			
Type × Length	−0.12	0.03	−3.98			
Type × Spacing	0.02	0.02	1.49			
Length × Spacing	−0.01	0.02	−0.47			
Type × Length × Spacing	0.02	0.02	0.72			

Note. Factors were dummy coded with short pseudowords and decreased spacing as reference levels. Parameters of the random effects are reported in the top panel. SD = standard deviation, SE = standard error.. Parameters of the fixed effects are reported in the bottom panel. Note that the b coefficient (Estimate) represents the adjustment with respect to the reference level

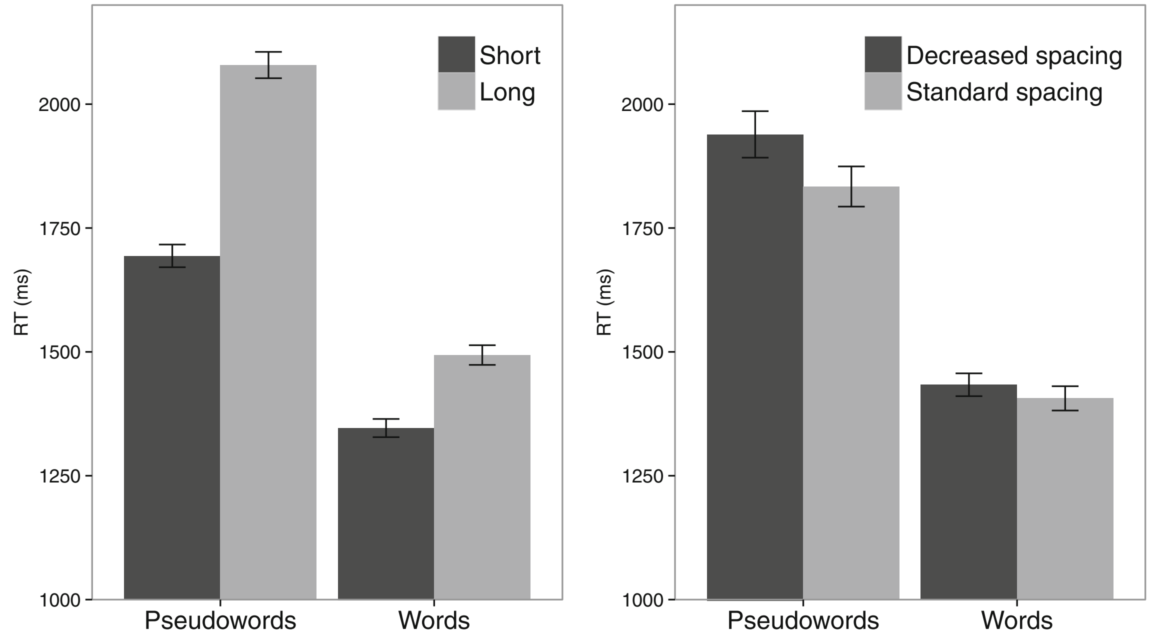

Fig. 1 Progressive demasking task (Experiment 1). Left panel: interactive effects of lexicality (words vs. pseudowords) and length (short vs. long), showing a more marked length effect for pseudowords. Right panel: interactive effects of lexicality and spacing, showing that decreased spacing impaired pseudowords more than words. Error bars represent within-subjects SEMs

stimuli. In Perea and Gomez (2012), responses to pseudowords (five to six letters long) were unaffected by spacing.

Method

Eighteen new participants (mean age 24 years) were recruited in Experiment 2. They were all Italian native speakers and had normal or corrected-to-normal vision. The experiment was run using E-Prime 2.0 software (Psychological Software Tools Inc., Pittsburgh, PA, USA). Stimuli and general procedure were the same as in Experiment 1 with the following differences. Three spacing conditions were included: standard (0.0), decreased (−1 pt), and increased (+1 pt). These values of interletter spacing are those provided by Microsoft Word, as also used in the study of Perea and Gomez (2012). Each trial consisted of: (i) a 1000 ms fixation point; (ii) the stimulus presented for 66 ms; (iii) a 33-ms mask[1] (a string of hash marks with the same length of the target); and (iv) a 2000-ms blank inter-trial interval. The letter strings and the mask were presented in Times New Roman, 14 pt font (as in Perea & Gomez, 2012). Each string was presented at the centre of the screen, in black ink on a white background. Participants were instructed to press 'M' on the computer keyboard if the letter string was an existing Italian word and 'Z' if the letter string was not a word.

Results

The data were analyzed with the same methods as in Experiment 1, with the exception that word and pseudoword data were analyzed independently. In addition to the random factors (see Exp. 1), each model included two fixed effects and their interaction: *length* (*short* vs. *long*), *spacing* (*standard* vs. *decreased* vs. *increased*), and the two-way interaction *length* by *spacing*. Mean accuracy and reaction times in the different conditions are reported in Table 3. Incorrect responses (9.3 % of the data) were excluded from the RT analyses.

Table 3 Experiment 2. Mean accuracies and reaction times (standard deviations in parentheses) for all experimental conditions

	Words		Pseudowords	
	Short	Long	Short	Long
Standard spacing	0.95 (0.05)	0.96 (0.06)	0.90 (0.07)	0.84 (0.06)
	594 (39)	588 (27)	708 (51)	723 (45)
Decreased spacing	0.87 (0.10)	0.92 (0.04)	0.89 (0.08)	0.89 (0.09)
	607 (44)	607 (35)	688 (47)	717 (37)
Increased spacing	0.93 (0.05)	0.96 (0.07)	0.90 (0.08)	0.85 (0.07)
	577 (37)	581 (17)	699 (36)	714 (33)

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[1] We used limited stimulus exposure time and post-stimulus masking because the effect of the spacing manipulation was unreliable in a pilot LDT experiment in which the stimulus was presented until response.

Word data

Latencies The main effect of spacing was significant $\chi^2(2) = 14.66$, $p < 0.001$, showing that the manipulation of interletter spacing affected response times. No other effect was significant. To further elucidate what levels of the spacing condition significantly affected responses, we fitted the model excluding the length factor, taking the standard spacing condition (mean: 590 ms) as reference level. Increased spacing (mean: 578 ms) showed a trend towards faster responses than standard spacing, but the effect did not reach statistical significance, $b = -12.97$, $t(1617) = -1.69$, $p = 0.09$. Decreased spacing yielded significantly slower responses than standard spacing, $b = 16.86$, $t(1617) = 2.17$, $p < 0.05$ (see Fig. 2, left panel).

Error rates The main effect of spacing was significant $\chi^2(2) = 16.74$, $p < 0.001$, showing that the manipulation of the interletter spacing affected accuracy. No other effect was significant. As for latencies, we then fitted the model excluding the length factor with standard spacing (mean: 0.96) as reference level. Increased spacing (mean: 0.95) did not differ from standard spacing, $b = -0.18$, $z(1728) = -0.61$, $p = 0.54$. Decreased spacing (mean: 0.90) yielded significantly higher error rates than standard spacing, $b = -0.99$, $z(1728) = -3.74$, $p < 0.001$.

Pseudoword data

Latencies The main effect of the length was significant, $\chi^2(1) = 4.65$, $p < 0.05$, indicating that responses were faster for short than for long strings (i.e., length effect). No other effect was significant (for the effect of spacing see Fig. 2, right panel).

Error rates The analysis failed to show any significant effects.

Discussion

Our results with the PDM paradigm (Experiment 1) replicated the classic effects observed with the standard naming paradigm: responses to words were faster than responses to pseudowords (i.e., lexicality effect) and longer strings were responded to slower than shorter strings (i.e., length effect). In addition, the length effect was stronger for pseudowords, consistent with previous naming studies (e.g., Weekes, 1997) as well as with leading computational models of reading (e.g., Perry et al., 2007; Perry, Ziegler, & Zorzi, 2010; see Perry, Ziegler, & Zorzi, 2014, for an Italian version of the CDP++ model).

The manipulation of the spacing between letters affected response times: identification in the decreased spacing condition was slower than identification of normally spaced strings. The detrimental effect of decreased letter spacing in our experiment can be readily explained in terms of increased crowding and it is in line with the hypothesis that skilled readers are tuned to the standard interletter spacing (Tydgat & Grainger, 2009). A large body of evidence shows that reading rate is limited by crowding (e.g. Pelli & Tilman, 2008). Concurrently, there is mounting evidence that abnormal crowding affects reading and it is implicated in dyslexia (e.g., Callens, Whitney, Tops, & Brysbaert, 2013; Martelli et al., 2009; Moll & Jones, 2013; Moores, Cassim & Talcott, 2011; Spinelli et al., 2002; Zorzi et al., 2012).

The effect of spacing did not interact with string length, despite the presence of a robust length effect that was also

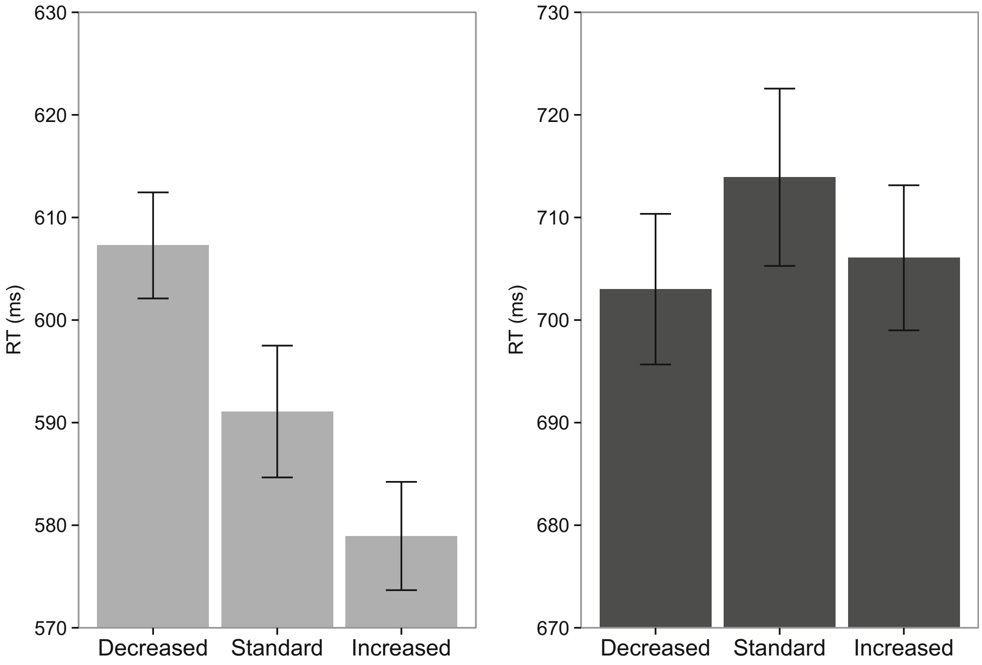

Fig. 2 Lexical decision task (Experiment 2). Effect of the spacing manipulation on response latencies for words (left panel) and pseudowords (right panel). Error bars represent within-subjects SEMs

modulated by the lexical status of the string. That is, the reduction in spacing hindered short and long strings in the same way. The lack of interaction suggests that the locus of the spacing effect precedes the locus of the length effect (cf. Besner & Roberts, 2003). A widely accepted explanation of the length effect is that it arises from serial left-to-right parsing of letters in the sublexical route. In computational models of reading with a dual-route architecture (DRC: Coltheart, Rastle, Perry et al., 2001; CDP+: Perry et al., 2007, 2010), the time required for parsing the string during phonological decoding is proportional to the length of the string, whereas access to whole-word representations in the lexical route is unaffected by length because letter activation spreads in parallel to the orthographic lexicon. A significant interaction between spacing and length would have pointed to the sublexical route (and presumably to letter parsing) as locus of the spacing effect. Conversely, the lack of interaction suggests that spacing affects a processing stage that is shared by the two processing pathways, such as the letter detectors. This conclusion is consistent with Perea et al.'s (2012) finding (using diffusion modelling) that spacing affects the encoding process rather than the quality of lexical information during word recognition, as well as with the effect of spacing on gaze duration during rapid naming of individual letters (Moll & Jones, 2013).

Nevertheless, pseudoword identification was impaired more than word identification in the decreased spacing condition, suggesting that the processing of crowded letters is facilitated by top-down feedback from orthographic lexical representations (as assumed in the CDP+ and DRC models). Indeed, the identification of each letter is critical for successful pseudoword processing (phonological decoding; Perry et al., 2007), whereas visual word recognition is resilient to noisy or partial letter input (McClelland & Rumelhart, 1981; Zorzi, Testolin & Stoianov, 2013). Accordingly, pseudoword processing requires focused visuospatial attention, whereas processing of familiar words seems to benefit from a broader distribution of attention (see Montani, Facoetti, & Zorzi, 2014). The mediating effect of lexical status is also consistent with the neuro-computational model of visual processing and crowding of Jehee, Roelfsema, Deco, et al. (2007), which assumes that processing of visual stimuli requires several feedback-feedforward cycles to reach a stable state corresponding to stimulus recognition. Feedforward activity conveys the globally most salient information, while feedback activity from higher areas toward lower areas is necessary in order to obtain spatial details. Only familiar visual words have a learned neural representation, probably located in the left ventral occipito-temporal cortex ('visual word form area'; Dehane & Cohen, 2011), that can provide a strong feedback signal toward lower areas of the visual system allowing for fast identification of the string despite the crowded condition.

The results of the LDT in Experiment 2 depicted a slightly different scenario but substantially confirmed the detrimental effect of decreased letter spacing on visual word recognition. A symmetrical increase in letter spacing induced a trend towards faster responses, in line with the findings of Perea and colleagues (Perea et al., 2011; Perea & Gomez, 2012), though the effect failed to reach statistical significance. As in Perea et al. (2011), word responses in LDT were not affected by length and there was no interaction with spacing. Responses to pseudowords, regardless of stimulus length, were unaffected by spacing. Thus, the results of Experiment 2 suggest an interaction between spacing and lexical status for LDT with the opposite direction from that obtained for perceptual identification. Perea and Gomez (2012) obtained the same pattern of lexical decision results and pointed to the specific nature of word versus pseudoword decisions in the LDT as a potential explanation of this unexpected finding. In fact, we suggest that this interaction fits well with the theoretical framework that we used to explain the perceptual identification data. As previously discussed, spatial details in vision are extracted through several feedforward-feedback cycles (e.g., Jehee et al., 2007). Crowding affects early stages of visual processing but it emerges relatively late in time. For example, the effect of crowding in a classic flanker task emerged slowly and manifested as a suppression of the N1 component (after 180 ms) of the electrophysiological signal (Chicherov, Plomp, & Herzog, 2014). Pseudoword decisions in the LDT might rely on more global lexical information that is available before the extraction of fine details is completed (i.e., when there is still uncertainty about letter identities).

In conclusion, our findings support the notion that crowding poses critical constraints on visual word processing and that increased crowding might be a cause of reading difficulties. According to the modified receptive field hypothesis (Tydgat & Grainger, 2009), skilled readers are tuned to the standard spacing and have adapted to crowding in order to optimize parallel processing of letters. As a result, increased crowding due to smaller-than-normal spacing cannot be compensated without extensive training. The stronger effect of spacing on pseudoword identification suggests that increased crowding is particularly harmful for phonological decoding, which leads to the prediction that the benefit of wider spacing for dyslexic readers might be stronger when decoding unfamiliar words and pseudowords. It is worth noting that impaired phonological decoding (i) has a profound adverse effect on reading development and orthographic learning, as shown by Ziegler, Perry and Zorzi (2014) in their simulations of typical and atypical reading development, and (ii) is specifically linked with visual spatial attentional deficits in dyslexia (Facoetti et al., 2006, 2010).

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