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The Role of Visual Crowding in Eye Movements during Reading: Effects of Text Spacing

Tzu-Yao Chiu^{1,2} and Denis Drieghe¹

¹School of Psychology, University of Southampton, UK

²Department of Psychology, The Ohio State University, US

Author Note

Tzu-Yao Chiu <https://orcid.org/0000-0002-1820-2829>

Denis Drieghe <https://orcid.org/0000-0001-9630-8410>

Correspondence concerning this article should be addressed to Tzu-Yao Chiu, Department of Psychology, The Ohio State University, 225 Psychology Building, 1835 Neil Avenue, Columbus OH 43210.

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Abstract

Visual crowding, generally defined as the deleterious influence of clutter on visual discrimination, is a form of inhibitory interaction between nearby objects. While the role of crowding in reading has been established in psychophysics research using RSVP paradigms, how crowding affects additional processes involved in natural reading, including parafoveal processing and saccade targeting, remains unclear. The current study investigated crowding effects on reading via two eye-tracking experiments. Experiment 1 was a sentence-reading experiment incorporating an eye-contingent boundary change in which reader's parafoveal processing was quantified through comparing reading times after valid or invalid information was presented in the parafovea. Letter spacing was jointly manipulated to compare how crowding affects parafoveal processing. Experiment 2 was a passage-reading experiment with a line spacing manipulation. In addition to replicating previously observed letter spacing effects on global reading parameters (i.e. more but shorter fixations with wider spacing), Experiment 1 found an interaction between preview validity and letter spacing indicating that the efficiency of parafoveal processing was constrained by crowding and visual acuity. Experiment 2 found reliable but subtle influences of line spacing. Participants had shorter fixation durations, higher skipping probabilities, and less accurate return sweeps when line spacing was increased. In addition to extending the literature on the role of crowding to reading in ecologically valid scenarios, the current results inform future research on characterizing the influence of crowding in natural reading and comparing effects of crowding across reader populations.

Keywords: reading, eye movements, visual crowding, parafoveal processing

1 **The Role of Visual Crowding in Eye Movements during Reading: Effects of Text Spacing**

2 The human visual system is foveated, such that information presented at the center (i.e., the
3 fovea) is received with high-resolution whereas objects presented in the periphery (i.e., peripheral
4 vision) are perceived as more jumbled and indistinct. This feature, originally thought to be caused by the
5 rapid drop of visual acuity outside the fovea (Anstis, 1974), was later revealed to be largely attributable
6 to peripheral vision's susceptibility to visual crowding (Latham & Whitaker, 1996; Rosenholtz, 2016;
7 Strasburger, 2020). Visual crowding, generally defined as the deleterious influence of clutter on visual
8 discrimination, is a form of inhibitory interaction between nearby objects (Levi, 2008; Pelli & Tillman,
9 2008). As an example, it should be easy to recognize the letter "a" whilst looking at the fixation cross in
10 Figure 1a. However, when flankers are present, as in Figure 1b, it becomes more difficult to identify the
11 letter "a" despite it being at the same distance to the fixation cross. In psychophysical studies, crowding
12 was commonly quantified using *critical spacing*: The target-flanker distance at which the observer's task
13 performance (e.g., letter recognition accuracy) reaches a certain criterion (e.g., 0.75 letter recognition
14 accuracy). Critically, there has been an abundance of evidence showing that critical spacing is across
15 studies approximately 0.5 times target eccentricity, a phenomenon termed as Bouma's law (Bouma,
16 1970, 1973; but see Whitney & Levi, 2011 for a discussion).

17 As the visual environments humans live in are inherently cluttered, crowding is ubiquitous in
18 spatial vision and serves as a fundamental sensory limitation on visual cognition. Reading in particular,
19 may be prone to constraints of crowding since written text is a compact form of visual information, with
20 crowding present between different units of text (i.e., letters, words, and lines). Early evidence
21 demonstrating the role of crowding in reading can be found in a line of psychophysical research on visual
22 span arguing that the number of letters readers can recognize without making an eye movement (i.e.,
23 the visual span) serves as a low-level sensory limitation on reading (Legge et al., 2007). Consistent with
24 this visual span hypothesis, these studies revealed that manipulations of text properties, including

1 contrast, text size, text spacing, affected the size of reader's visual span, which in turn highly correlated
2 with their reading speed (Legge et al., 2007; Legge et al., 2001; Yu et al., 2007). For the purpose of
3 understanding the limiting factor of visual span size, two studies dissociated visual acuity and visual
4 crowding in separate psychophysical measurements and found that crowding, but not acuity, accounted
5 for the observed correlation with reading speed (Levi et al., 2007; Pelli et al., 2007). These findings in
6 turn led to the conclusion of reading speed being proportional to the reader's crowding susceptibility.

7 It is important to note that although psychophysical studies provided compelling evidence to
8 support the role of crowding in reading, these studies measured reading speed by means of rapid serial
9 visual presentation (RSVP; Forster, 1970; Potter, 1984), thus making their findings not readily
10 generalizable to reading in natural settings (Benedetto et al., 2015; Rayner et al., 2016). A key difference
11 between RSVP and natural reading is that, in the latter scenario, eye movements are involved and
12 therefore readers are required to select saccade targets at different levels of text. When reading a
13 passage, readers are required to decide where to fixate within a word (McConkie et al., 1988; Rayner,
14 1979), which word to fixate next (Brysbart & Vitu, 1998), and where to fixate on the following line
15 (Hofmeister et al., 1999; Rayner, 1998). Additionally, RSVP differs from natural reading in the number of
16 words processed at a given fixation. In reading research, it is well-established that reader's word
17 processing takes place both of the fixated word and of the word in the region slightly right to the fixation
18 point (i.e., parafoveal processing; see Schotter et al., 2012 for a review), as preventing information in
19 parafovea largely slows down reading speed (McConkie & Rayner, 1975; Rayner, 2014). Conversely, as
20 words are presented one-at-a-time in RSVP paradigms, only foveal word processing is permitted whereas
21 parafoveal processing is eliminated. Taken together, it is apparent that the current understanding of the
22 role of crowding in reading is far from complete and eye-tracking studies, during which reading
23 resembles natural reading to a higher extent, are needed to bridge this gap.

24 Cognitive processes associated with word recognition are often assumed to be the driving force

1 behind eye movements during reading (Engbert et al., 2005; Reichle et al., 2003), thus we first review
2 research on how crowding influences word recognition. To investigate crowding effects on word
3 recognition, previous studies induced differences in crowding by manipulating the distance between
4 letters (i.e., letter spacing; Eriksen & Eriksen, 1974) and recorded participant's performance in isolated
5 word recognition tasks (e.g., lexical decision task, naming task). For instance, Perea et al. (2011)
6 presented words with subtly varied letter spacing and found that the reader's response time decreased
7 linearly as letter spacing increased. Later studies revealed that the facilitative effect of reduced crowding
8 likely takes place during early perceptual encoding, as the facilitation was found to be independent of
9 lexical factors (e.g., word frequency; Perea et al., 2011; Slattery et al., 2016). However, reducing
10 crowding by means of increasing letter spacing does not yield unbounded benefits on word recognition
11 (see Slattery et al., 2016; van den Boer & Hakvoort, 2015 for discussions). Specifically, increasing the
12 amount of letter spacing over a certain criterion, likely around the width of a single character (Slattery et
13 al., 2016), was shown to damage the perceptual integrity of words and hinder the reader's parallel letter
14 recognition processing, which together outweighed benefits of reduced crowding and resulted in
15 prolonged word recognition time (Cohen et al., 2008; Risko et al., 2011; Vinckier et al., 2011).

16 Reading research using eye-tracking methodology measures the time readers spend fixating on a
17 word (i.e., fixation duration) as an indicator of the amount of cognitive effort associated with recognizing
18 that word (Rayner, 1998, 2009). Take word frequency, a factor known to be influential to lexical
19 processing difficulty, as an example whereby words of high frequency, such as "chair", often receive
20 shorter fixation durations than low-frequency words, such as "scone" (Inhoff & Rayner, 1986; Rayner &
21 Duffy, 1986). Although crowding effects on fixation duration were indirectly obtained in several word
22 spacing studies (Drieghe et al., 2005; Rayner et al., 1998), direct demonstrations were provided by later
23 studies in which letter spacing manipulations were implemented. For instance, Slattery and Rayner
24 (2013) induced subtle changes in letter spacing and found facilitative effects of reduced crowding

1 manifested by words with wide letter spacing receiving shorter fixation duration compared to words
2 with condensed letter spacing (see also Perea et al., 2016; Perea & Gomez, 2012). Further, the benefit of
3 reduced crowding was only observed in early eye-movement measures that are indicative of early visual
4 processing (Radach & Kennedy, 2013) and the effect was independent of lexical variables (e.g., word
5 frequency; Li et al., 2018; Slattery & Rayner, 2013), which together suggested that the influence of
6 crowding on word processing during reading was qualitatively similar to that when words were
7 presented in isolation. However, these studies also discovered that the total time readers spent reading
8 text materials (i.e., sentences, passages) was similar across letter spacing conditions despite early
9 fixation durations being shorter when letters were widely spaced. This in turn suggested that whilst how
10 crowding affects word recognition is well understood, research on the ways in which crowding influences
11 additional components of natural reading (i.e., parafoveal processing, saccade targeting) is required to
12 establish an understanding of the relationship between crowding and reading.

13 The extent to which crowding constrains parafoveal processing during reading is interesting for
14 two reasons. First of all, according to Bouma's law (Bouma, 1970, 1973), crowding is more damaging to
15 object recognition in the parafovea than in the fovea due to higher eccentricity. This in turn predicts
16 crowding as a stronger constraint on word recognition when words are presented away from the fovea, a
17 prediction often corroborated in psychophysical studies (Chung, 2002, 2004) but not yet directly tested
18 in eye-tracking experiments. Secondly, although crowding and visual acuity are often described by
19 reading researchers as limiting factors on parafoveal processing (Schotter et al., 2012), quantitative
20 models of eye-movement control during reading (i.e., E-Z Reader, SWIFT; Engbert et al., 2005; Reichle et
21 al., 2003) uniformly formulate eccentricity-dependent drop in processing efficiency as a function of
22 visual acuity alone, an assumption that lacks support from empirical evidence. Parafoveal processing in
23 reading can be investigated by measuring parafoveal preview benefit and/or word skipping (Schotter et
24 al., 2012). In a gaze-contingent display-change experiment (Rayner, 1975), an invisible boundary is

1 positioned to the left of a target word and the information at the target location before the reader's eyes
2 cross the boundary (i.e., preview) is manipulated. Preview benefit—the difference in the reader's
3 fixation duration on the target word when it was preceded by either a valid preview (i.e., target word) or
4 an invalid preview (e.g., visually dissimilar nonword)—can be calculated and compared across
5 experimental conditions. Word skipping, a phenomenon referring to words occasionally being skipped
6 (i.e., not fixated during first-pass) during reading, can also be used to measure parafoveal processing, as
7 skipped words can only be processed parafoveally and are known to be processed to some extent before
8 being skipped (Drieghe et al., 2005).

9 The existing literature on how crowding affects parafoveal processing during reading is limited,
10 with two lines of research providing only inconclusive evidence. The first line of research adopted the
11 individual difference approach similar to psychophysical studies, with RSVP reading replaced by eye-
12 tracking experiments implementing parafoveal preview manipulations. For instance, Risse (2014)
13 measured a reader's visual span (Legge et al., 2007) and their eye movements in a display-change
14 reading experiment. In contrast to the robust correlations observed in psychophysical research
15 ($r^2 > 0.95$), this study found only weak correlations between crowding and reading speed and no reliable
16 relationship between a reader's crowding susceptibility and the magnitude of the reader's parafoveal
17 preview benefit effects, which suggested crowding played a negligible role in parafoveal processing (see
18 also Frömer et al., 2015). However, it is important to note that the observed null findings may be a result
19 of insufficient statistical power, as it requires substantially large samples to detect the predicted
20 correlations in eye-tracking and reading experiments. Findings related to the effect of crowding on
21 parafoveal processing can also be seen in letter spacing studies in which word skipping was reported
22 (Korinth et al., 2020; Li et al., 2018). Specifically, these studies found reduced word skipping when
23 reading widely spaced sentences and concluded that despite reduced crowding facilitating early
24 encoding of the foveal word, larger letter spacing pushed letters further away from the fixation point and

1 consequently hindered parafoveal processing. In other words, visual acuity rather than crowding served
2 as the critical determinant of parafoveal processing. Nevertheless, the lower word skipping probability
3 observed when letters were widely spaced does not necessarily negate the role of crowding in
4 parafoveal processing, as low-level visual factors, such as a word's physical length, were not equated
5 across the comparison between words with wide and normal letter spacing. Studies presenting readers
6 with words of identical number of letters yet different in physical length have consistently found
7 differences in word skipping probability (Hautala et al., 2011; Hermena et al., 2017), suggesting a low-
8 level influence on word skipping. As such, the reduced skipping of words with wide letter spacing may be
9 reflective of a reader's use of low spatial-frequency information rather than parafoveal word processing.

10 In addition to word recognition, reading involves deciding where to send the eyes, a process
11 termed saccade targeting (see Rayner, 1998; 2009 for reviews). Whether crowding affects saccade
12 targeting is of interest because whilst saccade targeting relies on spatial information located at different
13 levels of eccentricity (e.g., next word, beginning of next line), the extent to which spatial information is
14 preserved depends on the eccentricity of the intended saccade target. Saccade targeting at the sentence
15 level involves readers deciding where to fixate on the next word (i.e., initial landing position). Previous
16 studies consistently showed that the center of the distribution of the reader's initial landing positions is
17 at a location slightly left to the word center, a phenomenon called the preferred viewing location (PVL;
18 Rayner, 1979) and has been interpreted as readers aiming for the word center (optimal viewing position;
19 O'Regan & Jacobs, 1992; O'Regan et al., 1984) but falling short due to saccadic range errors (McConkie et
20 al., 1988). For readers to implement such a saccade targeting strategy, low spatial-frequency
21 information, such as word length and inter-word spaces, is crucial, as removing inter-word spaces was
22 shown to eliminate the PVL phenomenon (Rayner et al., 1998). When reading multiline text, saccade
23 targeting also includes return sweeps: saccades that bring the eyes from the end of one line to the
24 beginning of the next line (Hofmeister et al., 1999; Rayner, 1998). Return sweeps are substantially longer

1 than intra-line saccades and, as a result, more likely to undershoot the intended target due to stronger
2 saccadic errors (McConkie et al., 1988). To study return sweep, undersweeps—the eyes making a
3 leftward saccade immediately after return sweeps (Parker et al., 2017)—can be used as an indicator of
4 return sweep accuracy. More specifically, recent studies demonstrated that undersweeps reflect
5 oculomotor correction after undershooting the intended return sweep target (i.e., beginning of the next
6 line) and its prevalence can be reduced by increasing saliency of the line-initial words (Slattery & Parker,
7 2019; Slattery & Vasilev, 2019).

8 The effect of crowding on saccade targeting depends on the decision at hand. When selecting
9 targets for intra-line saccades (i.e., initial landing position), readers rely on spatial information located at
10 on average approximately 8 characters to the right of the fixation point. However, when making inter-line
11 saccades (i.e., return sweeps), targets are often more than 50 characters away from the fovea.
12 Consistent with the idea that these saccade targeting is different in these two situations, previous
13 studies in which letter spacing was manipulated showed little or no difference in initial landing position
14 when measured using percentage into the target word (Paterson & Jordan, 2010; Perea & Gomez, 2012;
15 Slattery & Rayner, 2013). Conversely, the role of crowding on targeting return sweeps was demonstrated
16 by earlier studies in which line spacing was manipulated (Kolers et al., 1981; Kubota, 1991; see Morrison
17 & Inhoff, 1981 for a review). For instance, Kubota (1991) manipulated line spacing and found that
18 undersweeps were less frequent when lines were more widely spaced. However, it is important to note
19 that these findings were based on either coarse eye-movement measures or visual inspection of eye-
20 movement patterns and therefore should be considered with caution.

21 In summary, it is clear from an examination of past research that despite a robust association
22 between crowding and reading established in psychophysical research, the ways in which crowding
23 constrains additional processes involved in natural reading, such as parafoveal processing and saccade
24 targeting, remain largely unknown. The current study, as a crucial step towards bridging this gap,

1 investigated crowding effects on reading via two eye-tracking experiments. Experiment 1 was a
2 sentence-reading experiment in which letter spacing and preview validity were jointly manipulated.
3 Critically, preview benefit effects are expected to be larger when crowding was reduced by means of
4 wider letter spacing. Experiment 2 was a passage reading experiment in which line spacing was
5 manipulated. This experiment allowed the test of crowding effects on word skipping whilst controlling
6 physical width of the words and sentences and the examination of how crowding influences return
7 sweeps. Increased word skipping and less undersweeps when crowding is reduced through wider line
8 spacing is expected.

9 **Experiment 1**

10 In Experiment 1, we conducted a sentence-reading experiment and manipulated the spacing
11 between letters (wide, standard, and condensed letter spacing) and the validity of reader's parafoveal
12 information (valid, invalid parafoveal information). If crowding plays a role in parafoveal processing, we
13 expect the difference in fixation duration between valid and invalid parafoveal information to be larger
14 when letter spacing was wide (i.e., less crowding). Conversely, if crowding plays a negligible role in
15 parafoveal processing, we expect the inversed pattern (i.e., smaller effect of preview validity as letter
16 spacing increases) as wider letter spacing increases retinal eccentricity.

17 **Method**

18 ***Participants***

19 A total of 36 undergraduate students from the University of Southampton were recruited as
20 participants. All participants were native English speakers, had no known reading difficulties, and had
21 normal or corrected-to-normal vision. Participants received course credits in psychology courses as
22 compensation for their participation. At this sample size, we were able to test an effect with 0.34
23 Cohen's d at 0.5 statistical power. The sample size was determined based on previous letter spacing
24 studies (Li et al., 2018; Slattery & Rayner, 2013) and the minimum number of participants required to

1 counterbalance the experimental manipulation and the order in which the two experiments were
2 completed (see *Procedure* section below).

3 ***Apparatus***

4 Participants were seated 65 cm away from a 20-inch ViewSonic G225f monitor with a 75Hz
5 refresh rate. At this viewing distance, 1° visual angle was occupied by 2.38, 2.85, 3.56 characters in the
6 wide, standard, and condensed letter spacing condition, respectively. Sentences were written in 19-point
7 Inconsolata font and displayed on a single line located at the middle of the screen. Participant's eye
8 movements were recorded using an EyeLink 1000 eye-tracker sampling at 1000Hz. In order to implement
9 the gaze-contingent boundary technique (Rayner, 1975), an invisible boundary was positioned between
10 the word prior to the target word and the space immediately preceding the target word. The display
11 changes were triggered by 3 samples crossing the invisible boundary. Though participants were
12 instructed to read binocularly, eye movements were only recorded from their right eye.

13 ***Materials and Design***

14 A total of 96 sentences were selected from 3 published studies (Drieghe et al., 2017;
15 Fitzsimmons & Drieghe, 2011; White et al., 2016). The sentences were 9 to 17 words in length (M =
16 12.94, SD = 1.54) with a target word positioned near the middle (Ordinal target word number: M = 6.2,
17 SD = 1.03). All target words were 5 letters in length and not predictable from the preceding sentence
18 context (see original studies for details of the material). According to the SUBTLEX-UK database (van
19 Heuven et al., 2014), target words included low to high frequency words (Zipf frequency: M = 4.04, SD =
20 0.61, Min = 3.0, Max = 5.031).

21 Example stimuli are shown in Figure 2. Letter spacing and preview validity were manipulated
22 within participants. Letter spacing included 3 levels: Wide (W), standard (S), and condensed (C) letter
23 spacing. Whilst default spacing of the Inconsolata font was used as the standard letter spacing
24 condition, the wide and condensed letter spacing conditions were created by adding and subtracting

1 10% letter spacing, respectively. Average center to center distance between letters were 0.42, 0.35, 0.28
2 degree visual angle for the wide, standard, and condensed letter spacing conditions, respectively.
3 Preview validity included 2 levels: Valid (V) and invalid (I) preview. Participants were presented with the
4 target word itself (i.e., valid preview) or a pronounceable nonword (i.e., invalid preview) before their
5 eyes crossing the invisible boundary. After crossing the boundary, participants saw the target word
6 regardless of preview validity condition. The pronounceable nonwords were generated by keeping the
7 first letter identical to the target and substituting the remaining four letters (*shico* as the preview of
8 *stone*). Note that the invalid parafoveal preview and target words were both 5-letter in length. Overall,
9 Experiment 1 had a 3 x 2 experimental design with 16 sentences assigned to each condition.

10 **Procedure**

11 Upon arriving for the experiment, participants were first given a consent form and instructions.
12 After giving informed consent, participants were asked to rest on a chin rest to minimize head
13 movements. A 3-point calibration procedure was then carried out. Before reading each sentence in the
14 experiment, a drift check was performed by asking participants to fixate on a fixation point shown at the
15 left-center of the screen. If successfully completed, the fixation point was then replaced by the first letter
16 of the sentence. Participants were instructed to silently read the sentences and were informed that a
17 yes/no question would appear after one-third of the sentences. Prior to the experiment, participants
18 read 6 practice sentences to familiarize themselves with the procedure. The experimental sentences
19 were presented according to a pseudorandom order selected from 6 lists to counterbalance the
20 experimental conditions across participants. Participants read a total of 102 sentences, which took
21 approximately 20 minutes to complete. Note that participants also took part in Experiment 2. The order
22 in which the two experiments were completed was counterbalanced across participants.

23 **Results**

24 Average comprehension question accuracy was 93%, which indicated that participants

1 understood the sentences correctly. Fixations shorter than 80 milliseconds and within 3-character
2 distance were merged together. Remaining fixations shorter than 80 milliseconds or longer than 1000
3 milliseconds were removed. Trials in which 1) eye blink or track loss occurred whilst participants were
4 fixating on the target word, 2) the target word received the first or last fixation in a given trial, 3) the
5 fixation duration on the target word was more than 3 standard deviations away from the grand mean,
6 and 4) when the display change occurred too early (i.e., triggered by fixations or saccades before the
7 boundary) or too late (i.e., occurring more than 9 milliseconds after boundary crossed) were removed.
8 Overall, 84.9% of the data remained in the analysis.

9 The dependent measures included *First Fixation Duration* (FFD; duration of the first first-pass
10 fixation on a word), *Single Fixation Duration* (SFD; duration of the fixation on a word when it was fixated
11 exactly once during first-pass reading), *Gaze Duration* (total duration of all first-pass fixations made on a
12 word), and *Total Viewing Time* (total duration of all fixations made on a word). *Skipping Probability* (Skip;
13 probability of a word being skipped during first-pass reading), *Refixation Probability* (Refix; probability of
14 a word receiving more than one first-pass fixations), and *Initial Landing Position* (ILP; position of the first
15 first-pass fixation on a word) were also computed.

16 We constructed linear mixed-effect models (LMMs) for all dependent measures to provide
17 inferential statistics. LMMs were constructed using the *lme4* (Version 1.1-29; Bates et al., 2014) and
18 *lmerTest* (Version 3.1-3; Kuznetsova et al., 2017) packages in R version 4.1.2 (R core team, 2021).
19 Generalized linear mixed-effect models were constructed with binomial distribution for binary measures
20 (i.e., Skip, Refix). Letter spacing and preview validity were entered using successive differences contrast
21 (Schad et al., 2020). Target word frequency was also entered as fixed effect in the word-level analysis to
22 account for its influence on the dependent variables. Following Barr et al. (2013)'s suggestion, we started
23 from models with the maximal random effect structure and trimmed the models until convergence was
24 achieved (see Appendix A for model trimming process). We also performed a sentence-level analysis,

1 through which we found similar total sentence reading time across letter spacing conditions (see
2 Appendix B), confirming that our letter spacing manipulation was subtle and not disruptive to the
3 physical integrity of words (Paterson & Jordan, 2010).

4 Descriptive statistics for the dependent measures are provided in Table 1. Statistics from
5 (G)LMMs are provided in Table 2. Word frequency had significant effects on all fixation duration
6 measures. Readers fixated longer on low frequency target words than on high frequency target words.
7 Parafoveal preview validity also had significant influences on all fixation duration measures. Readers
8 spent longer fixating on target words when they were preceded by invalid previews compared to when
9 the parafoveal preview was valid. Letter spacing effects on fixation duration measures were only reliable
10 when comparing between the standard and condensed letter spacing conditions. Target words received
11 longer fixation durations when letter spacing was condensed than when letters were of standard letter
12 spacing. Finally, there were (marginally) significant interactions between preview validity and letter
13 spacing on single fixation duration, indicating that the difference between valid and invalid preview was
14 largest in the standard letter spacing condition and decreased in magnitude when letter spacing was
15 increased or decreased (see Figure 3). Follow-up contrasts revealed that 1) the condensed letter spacing
16 condition had a longer single fixation duration than the standard letter spacing condition only when
17 participants had intact parafoveal preview of the target words ($t_{\text{valid}} = -4.33, p < .001$; $t_{\text{invalid}} = -1.11, p$
18 $= .267$) and 2) the wide letter spacing condition had slightly shorter single fixation duration when
19 parafoveal preview was invalid ($t_{\text{valid}} = 0.91, p = .364$; $t_{\text{invalid}} = -1.69, p = .092$). Other early fixation
20 duration measures (i.e., first fixation duration and gaze duration) showed qualitatively similar trends.

21 Word frequency had significant influences on refixation probability. Participants were more likely
22 to refixate low frequency target words than high frequency target words. Preview validity effects were
23 significant on skipping and refixation probability. Readers were more likely to skip and less likely to
24 refixate on target words when they received valid preview of the target word than when preview was

1 invalid. Letter spacing effects on skipping and refixation probability were only significant when
2 comparing between wide and standard letter spacing conditions. Target words with wide letter spacing
3 had lower skipping and higher refixation probability than target words with standard letter spacing. No
4 significant two-way interactions were found. Preview validity and letter spacing had no influence on
5 initial landing positions. Initial landing position curves (Figure 4) showed that reader's initial landing
6 positions centered around word center regardless of the letter spacing manipulations.

7 **Discussion**

8 Results of Experiment 1 revealed two interesting findings. First of all, increasing and decreasing
9 letter spacing relative to standard letter spacing yielded qualitatively distinct effects on reader's eye-
10 movement behaviors. Whilst decreasing letter spacing resulted in inflated fixation duration, effects of
11 increasing letter spacing were mainly observed on fixation probability measures (i.e., skipping and
12 refixation probability). Secondly, interactions between letter spacing and preview validity indicated that
13 crowding played a role in parafoveal processing. This was evidenced by elevated crowding between
14 letters with condensed spacing reducing reader's use of parafoveal information.

15 The effects of condensed letter spacing on fixation duration measures were consistent with
16 those reported in previous studies (Korinth et al., 2020; Li et al., 2018). As condensed letter spacing
17 improved visual acuity of letters within the fixated word, a prediction based solely on visual acuity would
18 expect shorter fixation durations in the condensed letter spacing condition, a pattern opposite to the
19 observed effects. The observed effect therefore supports the notion that visual acuity alone is
20 insufficient to account for the low-level constraints readers encounter in word recognition during
21 reading. Alternatively, as argued by earlier psychophysics research (Legge et al., 2007; Levi et al., 2007;
22 Pelli et al., 2007), crowding likely plays a crucial role and, when the degree of crowding becomes
23 stronger in the case of decreased letter spacing, imposes a limitation on visual processing and
24 consequently slows down word recognition. Additionally, it is worth noting that the condensed letter

1 spacing effects were present on the earliest fixation duration measure (i.e., first fixation duration) and
2 remained at an approximately similar magnitude in later measures, indicating an early temporal locus
3 that is in line with the sensory nature of crowding. Altogether, the observed condensed letter spacing
4 effects likely reflected crowding as a low-level constraint on foveal word processing during reading, in
5 turn extending previous findings in RSVP paradigms (Chung, 2002; Legge et al., 2007; Legge et al., 2001)
6 into reading in natural settings.

7 With regards to the influences of increased letter spacing, current results failed to replicate the
8 previously observed facilitation on early fixation duration measures (Perea & Gomez, 2012; Slattery &
9 Rayner, 2013). One possible explanation concerns the inevitable trade-off between visual acuity and
10 crowding when letter spacing was manipulated. More precisely, as increasing letter spacing results in
11 reduced crowding and visual acuity, an “optimal” letter spacing for word recognition may exist, possibly
12 somewhere in between the standard and wide letter spacing conditions. When letter spacing was
13 increased beyond this optimal point, the benefit of reduced crowding no longer outweighs the
14 aggravated acuity degradation for letters close to the end of the fixated word, consequently forcing
15 readers to program an additional inter-word saccade (i.e., refixation) to complete word recognition.
16 Nevertheless, based on the results at hand we cannot rule out an alternative hypothesis in which
17 perceptual constraints are assumed to play a minimal role in word recognition. Considering that saccade
18 target selection, including word skipping and refixation, are known to be affected by a word’s physical
19 length (Hautala et al., 2011; Hermena et al., 2017), effects of increased letter spacing on fixation
20 probability measures may be caused by differences in target word’s physical length across letter spacing
21 conditions: Target words with wide letter spacing were physically longer, which in turn reduced the
22 probability of being skipped and increased the probability of receiving more than one fixation.

23 Following the trade-off explanation, the current results can be interpreted as a weak version of
24 the increased letter spacing effects previously observed (Perea & Gomez, 2012; Slattery & Rayner, 2013).

1 The increased probability of refixation reflects the reader's response to the wide letter spacing
2 condition's deviation from the optimal letter spacing and, when the degree of deviation becomes
3 stronger, may lead to the previously observed letter spacing effects. Alternatively, based on the saccade
4 targeting explanation, effects of increased letter spacing on word skipping and refixation together reflect
5 reader's use of low spatial-frequency information in parafoveal vision. At this point, we remain agnostic
6 as to which of the explanations accounts for the observed results. It is also important to note that the
7 two explanations need not to be mutually exclusive. Future research crossing word length with letter
8 spacing manipulations (Korinth et al., 2020) and/or implementing computational models in which acuity
9 and crowding are simultaneously formulated will be required to ascertain the boundary conditions or
10 relative contributions of both possibilities to letter spacing effects on eye-movement behaviors.

11 The finding of crowding effects on single fixation duration qualified by validity of parafoveal
12 information confirmed the main hypothesis and supported the role of crowding in parafoveal processing
13 during reading. One way to interpret the observed interaction was that when words were presented in
14 the reader's parafoveal vision, where crowding was stronger due to higher eccentricity (Bouma, 1970,
15 1973), elevated crowding due to condensed letter spacing caused a disruption on word recognition.
16 However, when parafoveal information was prevented and words were only subsequently processed
17 with foveal vision, where crowding was found to be trivial (Liu & Arditi, 2000; Toet & Levi, 1992) or non-
18 existent (Strasburger et al., 1991), differences in levels of crowding no longer exerted influence on word
19 processing. On one hand, a strong version of this interpretation would contend that crowding only
20 affects parafoveal word processing during reading and argue that the letter spacing effects observed in
21 previous studies (Korinth et al., 2020; Li et al., 2018) were lag effects (Radach & Heller, 2000; Vitu et al.,
22 2001) in disguise. Specifically, as word processing in natural reading commences in the reader's
23 parafoveal vision, the previously observed crowding effects on fixation duration can be caused by
24 differences only in parafoveal processing of the target words but not subsequent foveal processing when

1 directly fixated. By contrast, one may maintain a role of crowding in foveal word processing by arguing
2 that the current results were caused by differences in foveal load affecting reader's parafoveal
3 processing (Henderson & Ferreira, 1990). More precisely, as letter spacing was manipulated at the
4 sentence level, it is possible for crowding to disrupt foveal recognition of the word prior to the target and
5 consequently reduce the amount of time available for processing the target word in parafoveal vision.
6 However, this interpretation is less likely to hold considering that models of reading (Reichle et al., 2003)
7 assumed only lexical variables but not low-level sensory factors, such as crowding, affect parafoveal
8 processing of the upcoming word (see Drieghe, 2008 for a discussion). Finally, it is important to
9 acknowledge the fact that the interaction only emerged on one fixation duration measure, suggesting
10 that this finding should be considered cautiously and future replications are needed.

11 Additionally, there was a marginal significant interaction between preview validity and the
12 contrast between wide and standard letter spacing conditions on single fixation duration indicating
13 reduced use of parafoveal information when letter spacing was increased. One way of understanding this
14 pattern was that words with wide letter spacing had a slight benefit over those with standard spacing
15 when parafoveal preview was invalid (i.e., a pronounceable nonword), which in turn raises the issue of
16 how preview masks used in the invalid preview condition were processed. Recent studies showed that
17 preview masks commonly used in display change experiments (e.g., Xs, random letter strings, nonwords)
18 were not representative of a neutral baseline but rather an interference (Hutzler et al., 2013; Kliegl et al.,
19 2013; Vasilev & Angele, 2017; Yan et al., 2012) that increases as preview duration increases (Pan et al.,
20 2020). As an alternative, parafoveal degradation, achieved via randomly omitting black pixels from the
21 parafoveal word, was proposed since such an approach reduced the interference caused by presenting
22 preview masks and therefore served as a cleaner baseline for the calculation of preview benefit effects
23 (Gagl et al., 2014; Marx et al., 2015; Vasilev et al., 2018). Provided that wide letter spacing pushing the
24 parafoveal word further away results in added perceptual constraint on parafoveal processing, the

1 observed interaction can be construed as wide letter spacing, resembling the influences of parafoveal
2 degradation, reducing the interference associated with the preview mask. Questions regarding why
3 increasing and decreasing letter spacing exerted influences on fixation duration differently according to
4 the availability of parafoveal information requires future investigation.

5 **Experiment 2**

6 In Experiment 2, we conducted a passage-reading experiment and varied the amount of spacing
7 between lines (wide, standard, condensed line spacing). If vertical crowding between lines affects foveal
8 and parafoveal processing, we expect shorter fixation duration and higher skipping probability when line
9 spacing was increased (i.e., reduced crowding). Additionally, if crowding influences inter-line saccade
10 targeting, we expect more accurate return sweeps and therefore less undersweeps when line spacing
11 was increased.

12 **Method**

13 ***Participants***

14 The 36 participants from Experiment 1 also participated in Experiment 2.

15 ***Apparatus***

16 The apparatus was identical to that in Experiment 1. 4-line passages were written in 19-point
17 Inconsolata font, left justified, and positioned at screen center. At 65 cm viewing distance, 2.85
18 characters occupied 1° visual angle.

19 ***Materials and Design***

20 A total of 60 passages were excerpted from UK national newspapers, sampled from a wide
21 variety of topics. Passages were 42 to 67 words in length (M = 52.4, SD = 4.92) and separated into 4 lines
22 (Number of words in line: M = 13.09, SD = 1.68). Excluding words 1) with upper case letters, 2) included
23 Arabic numbers, 3) included or located next to punctuation marks, 4) at the beginning or ending of lines,
24 and 5) function words, a total of 1,102 words were entered in the analysis. Word length ranged from 2 to

1 13 letters ($M = 5.62$, $SD = 1.9$), whereas Zipf word frequency (van Heuven et al., 2014) ranged from 1.3
2 to 7.18 ($M = 4.84$, $SD = 0.92$). Example stimuli are provided in Figure 5. Line spacing was manipulated
3 within participants and included 3 levels: Wide (W), standard (S), and condensed (C) line spacing. Line
4 spacing was 1.75, 0.45, 0.09 degree visual angle for the wide, standard, condensed line spacing
5 conditions, respectively. Overall, Experiment 2 had a 1 x 3 within participant design, with 20 passages
6 allocated to each line spacing condition.

7 ***Procedure***

8 Procedure was similar to Experiment 1 with the following exceptions. Participants underwent a
9 9-point calibration, read 3 practice passages followed by 60 experimental passages, which together took
10 approximately 30 minutes to complete. The passages were presented based on a pseudorandom order
11 selected from 3 lists to counterbalance the line spacing manipulation across participants.

12 **Results**

13 Responses to comprehension questions had an average of 83%, which suggested that readers
14 understood the passages correctly. Data cleaning was conducted according to the same standard as
15 Experiment 1 (but excluding criteria concerning display changes), resulting in 97.2% of data entering the
16 analysis. All dependent measures except for initial landing position were calculated for every word.
17 Additionally, Undersweep Probability (US; probability of readers making a leftward saccade immediately
18 after making a return sweep) was calculated. LMMs were constructed following the same procedure as
19 in Experiment 1 (see Appendix C for model trimming process). Line spacing was coded using successive
20 differences contrast. Line spacing, word length, and word frequency were entered as fixed effects,
21 whereas word and participant identifiers were treated as random effects.

22 Descriptive statistics for word-level measures are summarized in Table 3. Results from the
23 (G)LMMs are summarized in Table 4. Word length had significant effects on gaze duration, total viewing
24 time, skipping probability, and refixation probability. Participants spent longer fixating, were less likely to

1 skip and more likely to refixate long words when compared to short words. Word frequency effects were
2 significant on all measures. Low frequency words were fixated longer, were less likely to be skipped, and
3 more likely to be refixated compared to high frequency words. Increasing line spacing from standard to
4 wide had significant influences on fixation duration measures. Readers had shorter fixation durations
5 when fixating on words that had wider line spacing. Line spacing also had significant influences on
6 skipping probability. This effect was significant across all levels of line spacing and manifested by readers
7 more likely to skip words when line spacing was increased. The effect of line spacing on refixation
8 probability was only significant between standard and wide line spacing. Words that were further away
9 from adjacent line(s) were less likely to be refixated compared to those with standard line spacing.
10 Finally, a significant difference in undersweep probability was obtained. Readers were more likely to
11 make a leftward corrective saccade after return sweeps when line spacing was increased.

12 **Discussion**

13 In Experiment 2, results were expected to show that reducing vertical visual crowding by means
14 of increased line spacing facilitated passage reading behaviors. Consistent with the expectations, results
15 showed benefits of increased line spacing on fixation duration and probability measures: Readers spent
16 shorter time fixating on and were more likely to skip words when line spacing was increased. However, in
17 contrast to the expectation, results on undersweep probability failed to result in improvements on a
18 reader's return sweep accuracy. Readers were less accurate in making return sweeps, as more
19 undersweeps occurred when line spacing was made wider.

20 The finding of increased line spacing reducing a reader's fixation duration has two important
21 implications. First, the observed effect extended previous line spacing research utilizing global reading
22 time as dependent measure (Chan & Lee, 2005; Kruk & Muter, 1984; Van Overschelde & Healy, 2005) to
23 the fixation times on individual words. The observed effects also improve understanding of cross-line
24 interference during passage reading. In Pollatsek et al. (1993)'s gaze-contingent moving-window

1 experiment, they found that the presentation of visually dissimilar words at the line below the current
2 fixation interfered with the reading process and resulted in longer reading times. The results reported in
3 the current study demonstrated that, in addition to the content from the line below, the spatial distance
4 at which the neighboring lines are positioned affects the reading process. As vertical rather than
5 horizontal spacing was manipulated, visual acuity of words within a line was controlled across line
6 spacing conditions. Also, considering that word length and word frequency were included in the LMMs
7 as fixed effects and passages were assigned to each line spacing condition equally often across
8 participants, the observed effect could not be attributed to higher level factors. Taken together, it can be
9 inferred that increasing the amount of spacing between lines reduced levels of vertical crowding, which
10 in turn led to a facilitation on early visual processing of words. Further, although the differences between
11 line spacing conditions were subtle, with increased line spacing saving merely 2 to 3 milliseconds per
12 word, the effect were present whilst the task involved reading passages and may accumulate into larger
13 benefits when reading larger text bodies (e.g., books, novels).

14 Critical to the research aim was the observation of increased line spacing leading to increased
15 word skipping. The magnitude of such effect was approximately 3% when comparing between the
16 condensed and wide line spacing conditions, not that unsimilar to those of word frequency yet far
17 smaller than that of word length (Brysbaert & Vitu, 1998). Considering that the physical length of words
18 was controlled when making comparisons across line spacing conditions, influences of low spatial
19 frequency information on word skipping (Hautala et al., 2011; Hermena et al., 2017) could not account
20 for the observed effects. One interpretation concerns differences in the efficiency of parafoveal word
21 processing. More precisely, as words have been found to be processed to a certain extent prior to being
22 skipped (Drieghe et al., 2005), line spacing effect on word skipping may reflect wider spacing between
23 lines reducing levels of vertical crowding, which in turn facilitated reader's early visual processing in
24 parafoveal vision. Moreover, through comparing line spacing effects on fixation duration and word

1 skipping, there is a suggestion of the decision of whether to skip a word being more sensitive to
2 variations in line spacing, as differences in skipping probability were statistically significant between all
3 levels of line spacing. This feature, though merely based on qualitative comparison, suggested that line
4 spacing had stronger effects on parafoveal processing than on foveal processing, in turn aligning with the
5 known characteristic of crowding being influential in parafoveal vision (Bouma, 1970, 1973) and less
6 pronounced in foveal vision (Liu & Arditi, 2000; Strasburger et al., 1991; Toet & Levi, 1992).

7 Conversely, as line spacing was manipulated at the passage level, observed line spacing effects
8 on word skipping could also be interpreted in terms of global reading strategy (Brysbaert & Vitu, 1998;
9 Radach et al., 2008). When readers were presented with widely spaced passages in which interferences
10 from adjacent lines were reduced, they were more likely to adopt a “risky” reading strategy (O’Regan,
11 1990, 1992) and consequently make longer saccades and skip words more often. This possibility could be
12 further bolstered when aspects of the experimental methodology were taken into account. Since
13 passages across line spacing conditions differed in total height but were uniformly centered vertically on
14 the screen, the fixation point used during drift check, aligned to the first letter of the upcoming passage,
15 were positioned differently on the vertical axis which in turn can be used as a pre-cue for the upcoming
16 text configuration. For instance, if readers saw a fixation point further away from the vertical center
17 point of the screen during drift check (i.e., higher along the vertical axis), they could predict that the
18 upcoming passage has wide line spacing. Also, considering that the completion of the drift check was at
19 least partially controlled by readers (i.e., deliberately looking away from the fixation point prevents trial
20 onset), the drift check procedure could be used as a temporal buffer for readers to fine-tune their global
21 reading strategy. This interpretation, albeit plausible, should be considered with caution due to the lack
22 of evidence supporting global modulation on reading strategy in the literature.

23 Finally, contrary to previous findings, increasing line spacing diminished the reader’s return
24 sweep accuracy and increased their probability of making corrective saccades after return sweeps. As

1 the observed effect was based on statistical tests on an eye-movement measures more directly reflective
2 of return sweep accuracy (i.e., undersweep probability; Parker et al., 2017), the current results are
3 favored over those reported in previous line spacing studies (Kolars et al., 1981; Kubota, 1991) and
4 indicate that crowding had no influence on return sweep accuracy. Alternatively, saccadic range error
5 (McConkie et al., 1988), the phenomenon of readers being more likely to undershoot the intended
6 saccade target when it was further away, likely played a role in the saccade target selection of return
7 sweeps. Since increasing line spacing inevitably pushed line-initial words, the intended targets of return
8 sweeps, further away, such manipulation forced readers to plan a longer return sweep saccade and
9 therefore more likely undershoot due to oculomotor errors.

10 **General Discussion**

11 The current study was set out to investigate the role of visual crowding in parafoveal processing
12 and saccade targeting during reading. In two eye-tracking experiments, we found that crowding affected
13 measures of parafoveal processing, including parafoveal preview benefit and word skipping, but not
14 other indicators of saccade targeting, such as initial landing position and return sweep. Collectively,
15 these results suggest that whilst crowding constraints the efficiency of linguistic processing in parafoveal
16 vision, it exerts negligible influence on saccade targeting within words and across lines during reading.
17 We begin by discussing the theoretical implications of the role of crowding in foveal and parafoveal
18 processing during natural reading, specifically the ways in which the current results relate to previous
19 RSVP research (Chung, 2002, 2004; Legge et al., 2007) and models of eye-movement control during
20 reading (Engbert et al., 2005; Reichle et al., 2003). We then discuss the applied values of the current
21 findings in terms of designing reading aids targeting specific clinical populations.

22 The first issue concerns a comparison between the current findings and previous RSVP research
23 (Chung, 2002, 2004; Legge et al., 2007). In general, the current results supported the notion of crowding
24 as an early sensory limitation on reading (Legge et al., 2007; Levi et al., 2007; Pelli et al., 2007) and

1 further extends the idea into a reading task of higher ecological validity (i.e., natural reading). The role of
2 crowding in reading was not only preserved when eye movements were involved (see also Yu et al.,
3 2007), but also extended to the processing of words aside from the fixated word. Nonetheless, one must
4 acknowledge that albeit being statistically significant, the crowding effects obtained in natural reading
5 tasks (Korinth et al., 2020; Li et al., 2018) were less pronounced when comparing to those reported in
6 RSVP studies (Legge et al., 2007). One likely reason for the observed difference in magnitude lies in the
7 ways in which these reading tasks are implemented. On the one hand, RSVP paradigms implemented in
8 previous studies instructed readers to read words aloud as fast as possible, with no additional
9 constraints on whether the order of words within the sentences were reported correctly or if the
10 sentences were understood correctly. As such, the task emphasized the rate of early, sub-lexical
11 processing (i.e., phonological processing) and likely accentuated the contribution of early sensory
12 factors, such as crowding. Conversely, natural reading experiments instruct readers to read for
13 comprehension and occasionally test readers with comprehension questions during the experiments.
14 This in turn increases reader's emphasis on higher-level processing (i.e., semantic, syntactic, discourse)
15 and likely attenuates the influences of low-level, visual factors. Overall, the current results provide
16 supporting evidence for crowding as an essential yet subtle constraint on reading in natural settings.

17 For the second issue, the ways in which the current findings shape models of eye-movement
18 control during reading were discussed. First, it is important to note that in two experiments, crowding
19 was found to exert influences on parafoveal preview benefit as well as word skipping. Although preview
20 benefit and skipping can be categorized as indicators of parafoveal processing efficiency at face value, a
21 closer examination of the literature indicated that the two measures differ in the extent of parafoveal
22 processing involved (Drieghe et al., 2005). More precisely, whilst preview benefit reflects the difference
23 in parafoveal processing prior to reader's eyes making the saccade onto the parafoveal word, the
24 decision of word skipping must be made relatively early in time and can be made based on partial lexical

1 recognition (Drieghe et al., 2005; Rayner et al., 2011). As such, results of crowding influencing both
2 preview benefit and skipping suggested a temporal locus of crowding effect on parafoveal processing
3 commencing early in time. Taken together with the lack of interaction between crowding and lexical
4 variables (i.e., word frequency; Li et al., 2018; Perea & Gomez, 2012; Slattery & Rayner, 2013) previously
5 reported, the current findings place a temporal constraint on the influence of crowding on early visual
6 processing in the parafovea. Furthermore, the demonstration of crowding as a sensory limitation on
7 word identification in addition to retinal acuity sheds light on the formulation of visual constraints in
8 models of eye-movement control during reading. At present, prominent models of reading (i.e., E-Z
9 Reader, SWIFT; Engbert et al., 2005; Reichle et al., 2003) uniformly assume acuity degradation as the sole
10 visual constraint on word identification and modelled word processing to decrease as a function of
11 eccentricity (i.e., letters further away from fovea were processed less efficiently). The current results of
12 crowding affecting word processing in fovea and parafovea in turn challenge these assumptions and
13 argue that distance to nearby objects, the crucial determinant of crowding, should be taken into account
14 whilst modelling word processing in reading (see also Veldre et al., 2022).

15 Finally, the applied value of the current findings are discussed. Although the magnitude of
16 crowding effects obtained in the current study was subtle when tested on skilled adult reader's eye-
17 movement behaviors during reading, these effects may be stronger for readers from other populations,
18 particularly those who were found to be more susceptible to visual constraints. For instance, in a
19 sentence reading experiment, Li et al. (2018) found that elder readers were more disrupted when letter
20 spacing was condensed when compared to young readers. Readers suffering from amblyopic vision (Levi
21 et al., 2007) and a sub-population of dyslexic readers (Joo et al., 2018) were also found to be more
22 strongly constrained by crowding during reading. With these population-specific findings in mind, the
23 current results can in turn serve as a powerful tool for designing a battery of quantitative measurements
24 that can be used to assess readers with visual impairments. The derived measures can be useful in

1 assessing the specific components of natural reading that are limited by declined visual ability (e.g.,
2 reduced foveal/parafoveal processing, less accurate saccade targeting), potentially informing clinicians'
3 selection of the corresponding intervention plans and aiding graphic designers in designing text
4 interfaces that are optimal for different reader populations. Future research contrasting the role of
5 crowding in natural reading across populations will be fruitful for understanding the reading difficulties
6 encountered by specific reader populations and guiding text designs aiming to ameliorate such
7 difficulties.

8 In summary, the two experiments reported here provided compelling evidence for the role of
9 crowding in eye movements during reading. Crowding, when manipulated via text spacing, influenced
10 not only the recognition of the fixated word but also constrained parafoveal word processing. These
11 findings not only extend the notion of crowding as a sensory limitation on reading (Legge et al., 2007;
12 Pelli et al., 2007) into the online linguistic processing spanned across fovea and parafovea, but also shed
13 light on the description of early visual processing in models of eye-movement control during reading
14 (Engbert et al., 2005; Reichle et al., 2003). Future research will need to concentrate on developing a
15 method of characterizing crowding effect during natural reading and on examining crowding effects
16 across reader populations.

17 **Conflict of Interests**

18 The authors have no known conflict of interest to disclose.

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20 This article was part of TC's master's dissertation. Proportion of the findings were presented as a
21 talk at the 21st European Conference on Eye Movements, University of Leicester.

22 **Open Practices Statement**

23 Data, experimental materials, and analytic scripts are publicly available on the study's Open
24 Science Framework webpage: <https://osf.io/8hzqc/>. The two experiments reported in this study were

1 not pre-registered.

2

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- 21

1 **Table 1**2 *Descriptive statistics for dependent measures in Experiment 1*

Letter spacing	Preview validity	FFD	SFD	GD	TVT	Skip	Refix	ILP
Condensed	Valid	248.21 (6.84)	253.68 (7.43)	274.86 (9.16)	322.31 (10.51)	16.17 (2.34)	10.31 (1.87)	0.47 (0.02)
	Invalid	285.02 (7.98)	300.42 (9.37)	335.05 (9.78)	396.71 (13.49)	9.65 (2.03)	19.68 (2.43)	0.42 (0.02)
Standard	Valid	228.23 (4.91)	228.44 (5.55)	252.9 (6.73)	295.2 (10.01)	12.36 (1.91)	12.2 (1.94)	0.45 (0.02)
	Invalid	278.57 (8.39)	293.58 (9.65)	327.64 (10.92)	382.58 (14.01)	8.13 (1.62)	19.43 (3.34)	0.44 (0.01)
Wide	Valid	227.12 (5.29)	230.52 (5.95)	262.3 (7.52)	301.71 (10.91)	6.96 (0.93)	17.33 (2.91)	0.45 (0.02)
	Invalid	268.59 (8.28)	282.74 (9.22)	323.16 (10.4)	382.62 (13.13)	3.25 (0.9)	25.4 (2.95)	0.46 (0.02)

3

4 *Note.* Standard errors are provided in parentheses. Fixation duration measures were measured in

5 milliseconds. ILP was measured as proportion into words.

6

1 **Table 2**2 *(G)LMM results for dependent measures in Experiment 1*

Fixed effect	Statistics	FFD	SFD	GD	TVT	Skip	Refix	ILP
Intercept	Estimate	5.49	5.52	5.61	5.75	-2.63	-1.87	0.45
	Std. Error	0.02	0.02	0.03	0.03	0.15	0.17	0.01
	t/z-value	238.43	229.02	222.61	202.2	-18.03	-11.27	37.04
Word frequency	Estimate	-0.05	-0.06	-0.08	-0.09	0.23	-0.33	— ^a
	Std. Error	0.01	0.01	0.01	0.02	0.13	0.1	—
	t/z-value	-4.25	-4.87	-5.46	-4.97	1.73	-3.47	—
	p-value	<.001	<.001	<.001	<.001	.084	<.001	—
Preview (V – I)	Estimate	-0.16	-0.2	-0.24	-0.26	0.7	-0.7	0.02
	Std. Error	0.02	0.02	0.02	0.02	0.15	0.11	0.01
	t/z-value	-7.95	-9.06	-13.73	-12.89	4.79	-6.45	1.73
	p-value	<.001	<.001	<.001	<.001	<.001	<.001	.084
Space (S – C)	Estimate	-0.05	-0.06	-0.06	-0.06	-0.29	0.12	-0.01
	Std. Error	0.01	0.02	0.02	0.02	0.15	0.14	0.01
	t/z-value	-3.44	-3.77	-3.47	-3.44	-1.89	0.85	-0.53
	p-value	<.001	<.001	<.001	<.001	.059	.398	.599
Space (W – S)	Estimate	-0.02	-0.01	0.01	0.02	-0.81	0.38	0.01
	Std. Error	0.01	0.02	0.02	0.02	0.19	0.13	0.01
	t/z-value	-1.35	-0.6	0.9	1.02	-4.24	2.98	1.14
	p-value	.176	.549	.368	.307	<.001	.003	.255
Preview x Space (S – C)	Estimate	-0.05	-0.06	-0.04	-0.03	-0.18	0.27	-0.03
	Std. Error	0.03	0.03	0.03	0.04	0.30	0.27	0.02
	t/z-value	-1.58	-2.09	-1.22	-0.68	-0.61	0.99	-1.25
	p-value	.114	.037	.222	.498	.541	.32	.213
Preview x Space (W – S)	Estimate	0.03	0.06	0.04	0.02	0.35	0.01	-0.02
	Std. Error	0.03	0.03	0.03	0.04	0.38	0.25	0.02
	t/z-value	1.08	1.84	1.39	0.55	0.92	0.05	-1.01

p-value	.281	.065	.165	.584	.359	.963	.314
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1

2 *Note.* Fixation duration measures were log-transformed. Significant effects are indicated in **bold**.3 Marginally significant effects are indicated in *italics*.4 ^aWord frequency was not included as fixed effect for the ILP analysis as it has been shown to have little
5 influence on ILP (Rayner et al., 1996).

6

1 **Table 3**2 *Descriptive statistics for dependent measures in Experiment 2*

Line spacing	FFD	SFD	GD	TVT	Skip	Refix	US
Condensed	232.31 (5.67)	232.83 (5.89)	260.31 (6.65)	311.44 (8.72)	22.31 (1.34)	11.11 (0.89)	36.48 (3.1)
Standard	230.11 (5.38)	230.69 (5.66)	260.12 (6.71)	309.17 (8.65)	23.49 (1.49)	11.78 (1.03)	39.78 (3.31)
Wide	227.74 (5.51)	228.15 (5.64)	256.27 (7.01)	305.55 (8.6)	25.33 (1.49)	10.79 (0.94)	41.24 (3.62)

3

4 *Note.* Standard errors are provided in parentheses. Units for fixation duration measures are milliseconds.

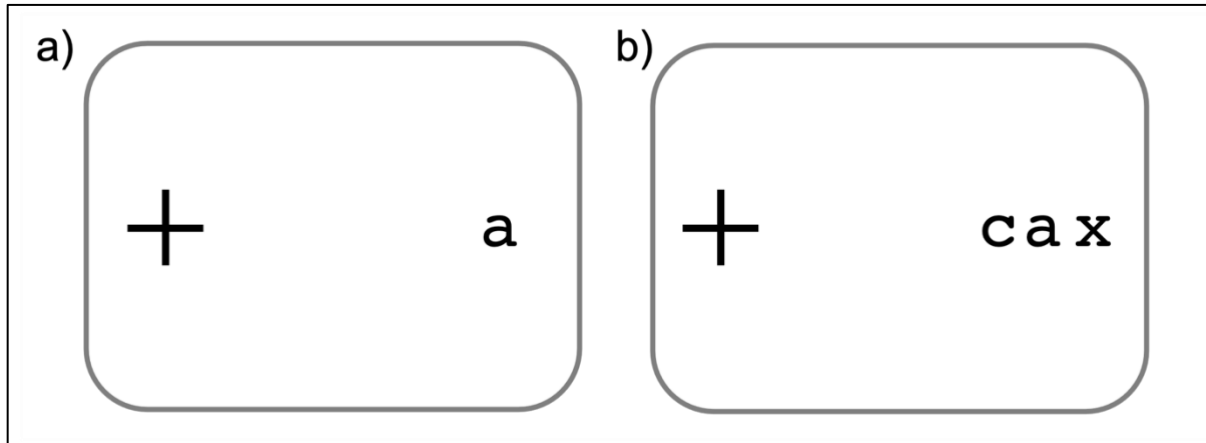
1 **Table 4**2 *(G)LMMs results for dependent measures in Experiment 2*

Fixed effect	Statistics	FFD	SFD	GD	TVT	Skip	Refix	US
Intercept	Estimate	5.38	5.38	5.47	5.6	-1.46	-2.46	-0.57
	Std. Error	0.02	0.02	0.02	0.03	0.09	0.13	0.18
	t/z-value	245.47	237.79	227.34	219.36	-15.68	-18.7	-3.12
Word length	Estimate	0	0	0.02	0.03	-0.44	0.26	–
	Std. Error	0	0	0	0	0.01	0.01	–
	t/z-value	-0.15	-0.11	6.99	10.74	-30.92	17.77	–
	p-value	.879	.9	<.001	<.001	<.001	<.001	–
Word frequency	Estimate	-0.02	-0.02	-0.02	-0.02	0.14	-0.14	–
	Std. Error	0	0.01	0.01	0.01	0.03	0.03	–
	t/z-value	-3.62	-3.1	-4.16	-2.89	5.27	-4.21	–
	p-value	<.001	.002	<.001	.004	<.001	<.001	–
Space (S – C)	Estimate	-0.01	-0.01	0	0	0.08	0.07	0.17
	Std. Error	0	0	0.01	0.01	0.03	0.04	0.07
	t/z-value	-2	<i>-1.89</i>	-0.74	-0.49	2.47	1.59	2.57
	p-value	.046	<i>.059</i>	.461	.627	.014	.111	.01
Space (W – S)	Estimate	-0.01	-0.01	-0.01	-0.01	0.1	-0.11	0.07
	Std. Error	0	0	0.01	0.01	0.03	0.04	0.07
	t/z-value	-2.15	-2.03	-2.39	-1.34	3.28	-2.55	1.08
	p-value	.032	.043	.017	.187	.001	.011	.279

3 *Note.* Fixation duration measures were log-transformed. Significant effects are indicated in **bold**.4 Marginally significant effects are indicated in *italics*.

1 **Figure 1**

2 *Demonstration of visual crowding*



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1 **Figure 2**2 *Example stimuli for Experiment 1**Condensed letter spacing (C)*

She removed the white paper/puxic from the photocopier...

Standard letter spacing (S)

She removed the white paper/puxic from the photocopier...

Wide letter spacing (W)

She removed the white paper/puxic from the photocopier...

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4 *Note.* Invisible boundaries used for boundary display change were marked with dotted lines.

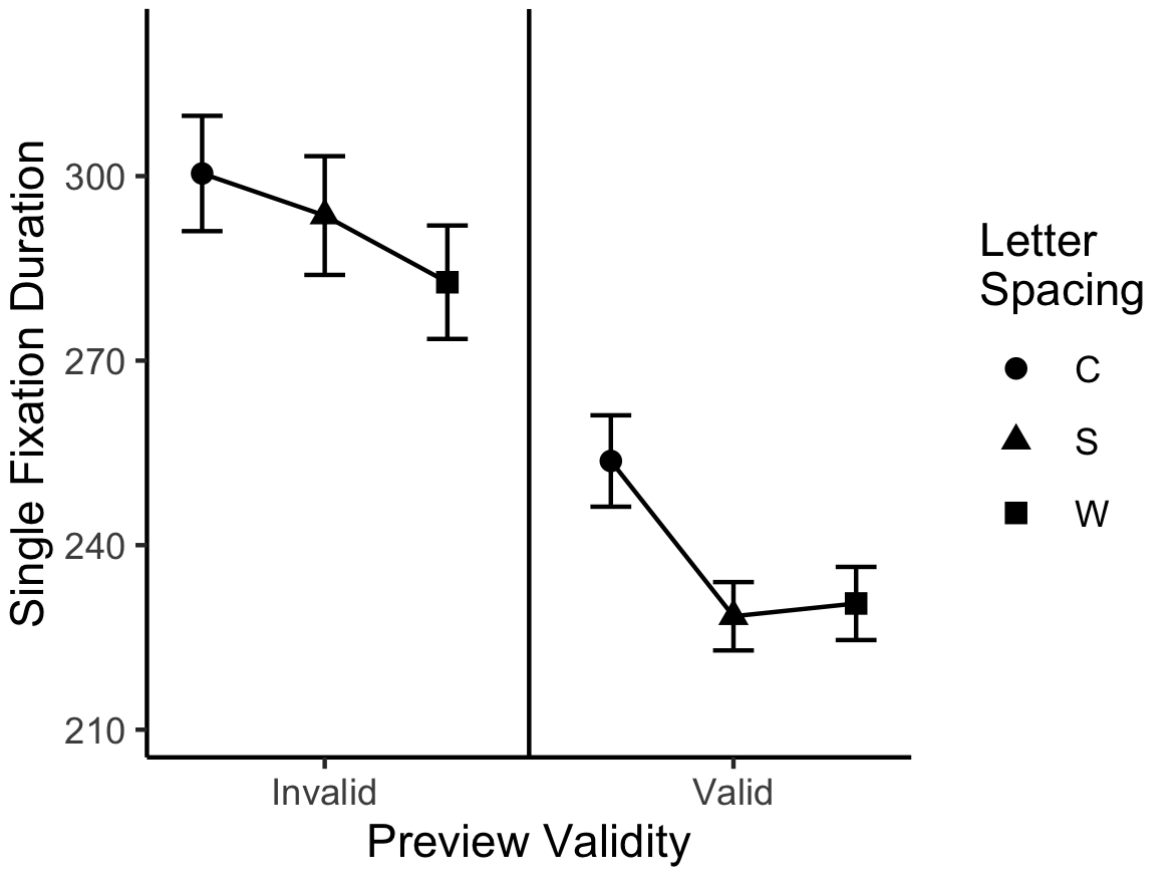
5 Valid previews are written before the slash, whereas invalid previews were written after the

6 slash.

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1 **Figure 3**

2 *Mean single fixation duration in Experiment 1*



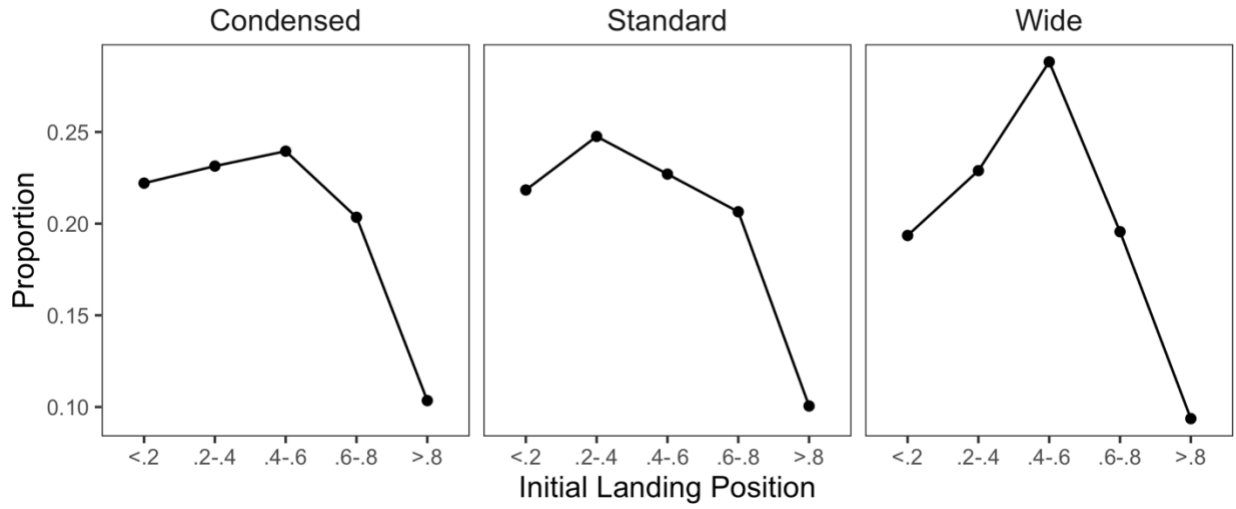
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4 *Note.* Error bars represent standard error of measure (SEM).

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1 **Figure 4**

2 *Initial Landing Position Curves across Letter Spacing Conditions in Experiment 1.*



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1 **Figure 5**2 *Example stimuli for Experiment 2***Condensed line spacing (C)**

Research into the effects of blue light has found adverse influences on health, eyesight, the quality of sleep and mental health condition. Fortunately, a recently published paper by Yale University stated that regularly taking a 10-minute pause can easily mitigate these effects.

Standard line spacing (S)

Research into the effects of blue light has found adverse influences on health, eyesight, the quality of sleep and mental health condition. Fortunately, a recently published paper by Yale University stated that regularly taking a 10-minute pause can easily mitigate these effects.

Wide line spacing (W)

Research into the effects of blue light has found adverse influences on health, eyesight, the quality of sleep and mental health condition. Fortunately, a recently published paper by Yale University stated that regularly taking a 10-minute pause can easily mitigate these effects.

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Appendix A

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Modeling trimming process for Experiment 1

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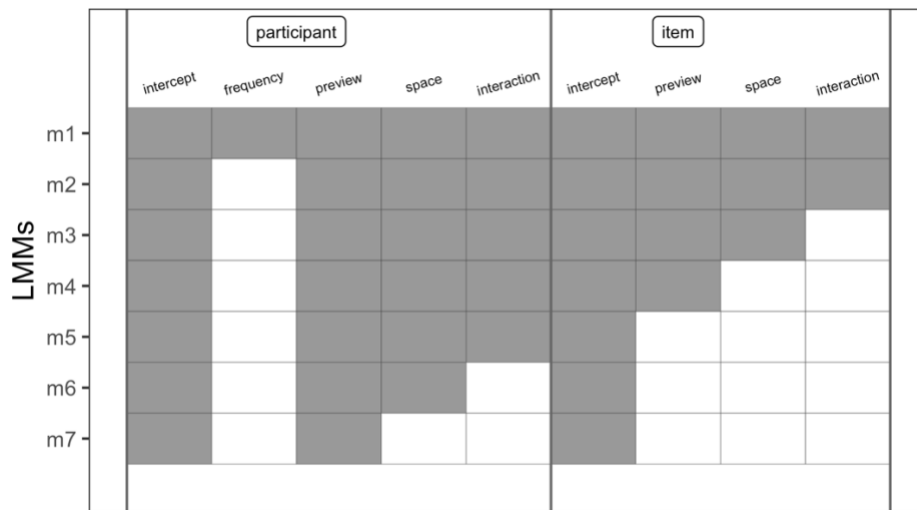
This appendix contains tile plots documenting the model trimming procedure used for each dependent measure in Experiment 1. The first model was the model with maximum random effect structure. Random structure was iteratively trimmed until model convergence was achieved.

6

Figure A1

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Model trimming for first fixation duration.



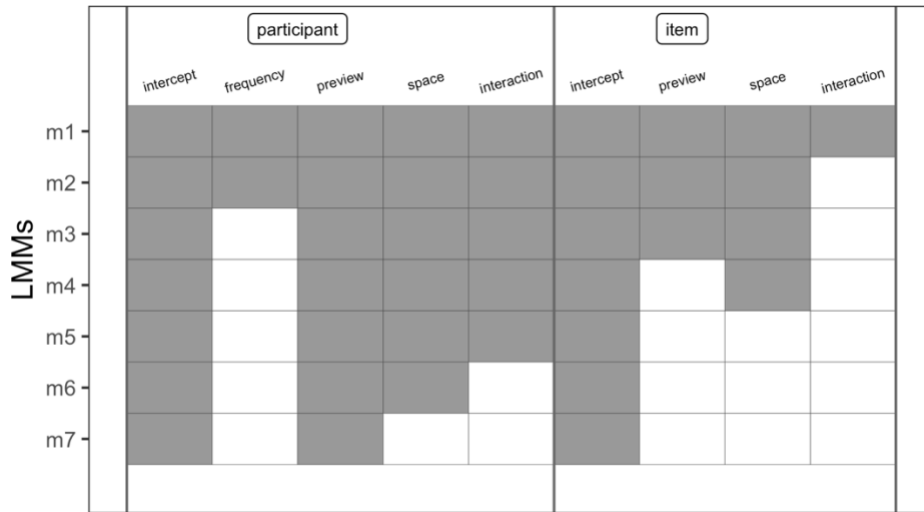
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1 **Figure A2**

2 *Model trimming for single fixation duration.*

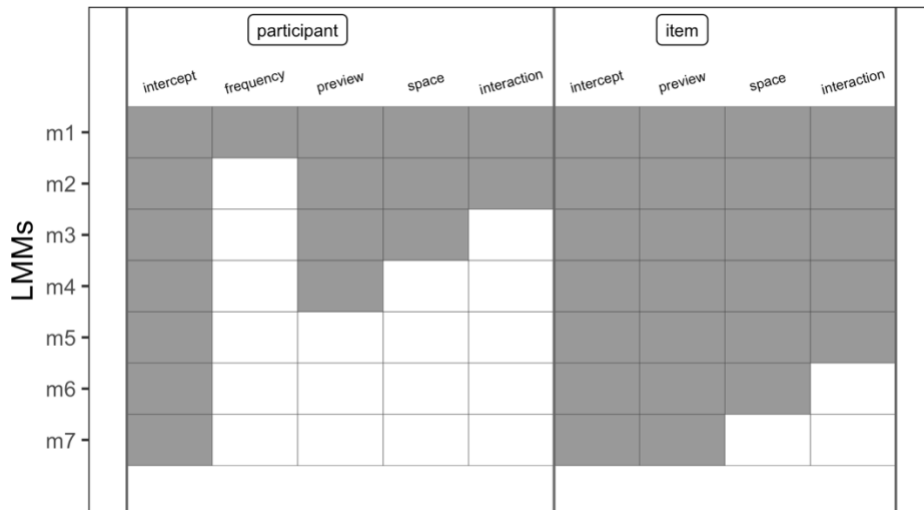


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5 **Figure A3**

6 *Model trimming for gaze duration.*



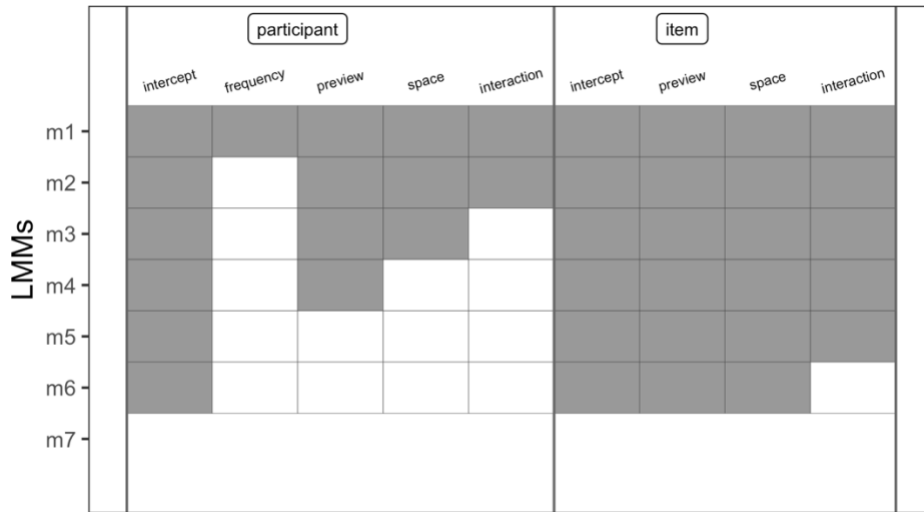
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1 **Figure A4**

2 *Model trimming for total viewing time.*

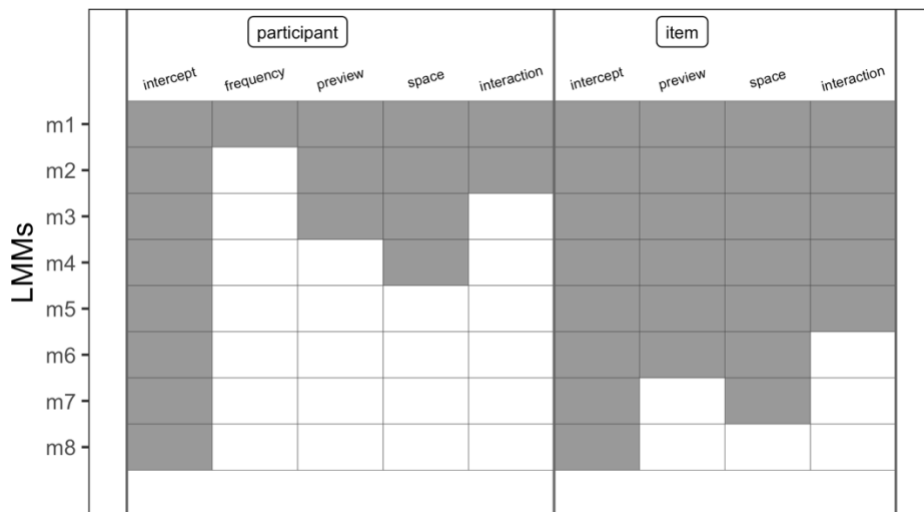


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5 **Figure A5**

6 *Model trimming for skipping probability.*



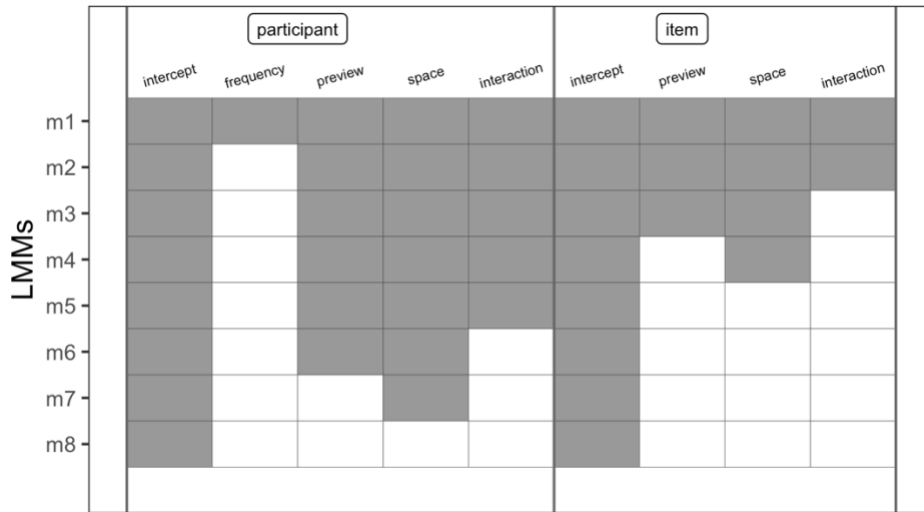
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1 **Figure A6**

2 *Model trimming for refixation probability.*

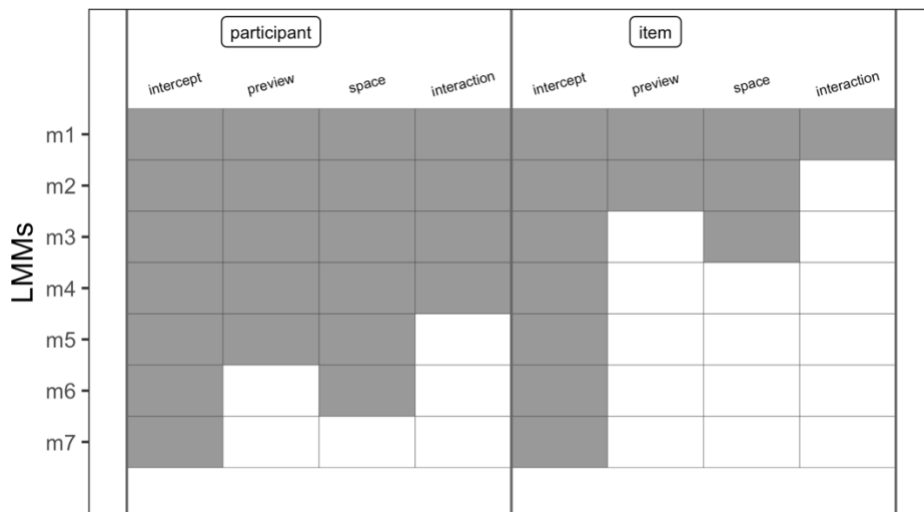


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5 **Figure A7**

6 *Model trimming for initial landing position.*



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Appendix B

Sentence-level analysis for Experiment 1

Analysis

This appendix includes the sentence-level analysis for Experiment 1 using data from the valid preview condition alone. For the sentence-level analysis, we calculated Number of Fixations (total number of fixations made whilst reading a sentence), Average Fixation Duration (average duration of all fixations made whilst reading a sentence), Average Saccade Amplitude (average amplitude of all saccades made whilst reading a sentence), and Total Time (total time spent reading a sentence). We constructed linear mixed-effect models (LMMs) for all dependent measures to provide inferential statistics. LMMs were constructed using the *lme4* (Version 1.1-29; Bates et al., 2014) and *lmerTest* (Version 3.1-3; Kuznetsova et al., 2017) packages in R version 4.1.2 (R core team, 2021). Generalized linear mixed-effect models were constructed with Poisson distribution for count measures (i.e., Number of Fixations). Letter spacing was entered using successive differences contrast (Schad et al., 2020). Following Barr et al. (2013)'s suggestion, we started from models with the maximal random effect structure and trimmed the models until convergence was achieved.

Results

Descriptive statistics for the dependent measures are summarized in Table B1, whereas statistics from (G)LMMs are summarized in Table B2. Letter spacing had significant effects on number of fixations, average fixation duration, and average saccade amplitude. These effects were significant across all three levels of letter spacing and were manifested by readers making more fixations, having shorter fixation durations, and making longer saccades when letter spacing was increased. Moreover, despite variations in number of fixations, average fixation duration, and average saccade amplitude, readers spent similar total time reading sentences across letter spacing conditions.

Results of Experiment 1 provided valuable insights into how crowding, when manipulated by

1 means of letter spacing, affects reader's eye movements during natural reading. The sentence-level
 2 results showed a trade-off between fixation duration and number of fixations: As letter spacing
 3 increased, readers made shorter yet more fixations whilst reading the sentences. These results
 4 replicated the previously observed letter spacing effects on global reading parameters (Perea et al.,
 5 2016; Perea & Gomez, 2012; Slattery & Rayner, 2013) and also demonstrate a reader's flexibility in
 6 adapting to variations in text configuration.

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8 **Table B1**

9 *Descriptive Statistics for dependent measures in Experiment 1*
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Letter spacing	Num. of Fixations	Avg. Fixation Duration	Avg. Saccade Amplitude	Total Time
Condensed	13.1 (0.43)	231.41 (4.87)	2.1 (0.08)	3407.99 (141.27)
Standard	13.54 (0.47)	226.54 (4.76)	2.43 (0.08)	3465.19 (140.34)
Wide	14.01 (0.49)	218.39 (4.26)	2.77 (0.09)	3503.03 (141.59)

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12 *Note.* Standard errors are provided in parentheses. Temporal measures were measured in milliseconds.

13 Saccade amplitude was measured in visual angle.

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1 **Table B2**2 *(G)LMM results for dependent measures in Experiment 1*

Fixed Effect	Statistics	Num. of Fixations	Avg. Fixation Duration	Avg. Saccade Amplitude	Total Time
Intercept	Estimate	2.58	5.4	0.84	8.16
	Std. Error	0.03	0.02	0.03	0.04
	t/z-value	75.84	269.53	26.32	202.79
Wide – Standard	Estimate	0.03	-0.03	0.13	0.01
	Std. Error	0.02	0.01	0.01	0.01
	t/z-value	2.18	-5.15	10.65	1.13
	p-value	.029	<.001	<.001	.32
Standard – Condensed	Estimate	0.03	-0.02	0.15	0.02
	Std. Error	0.02	0.01	0.01	0.01
	t/z-value	2.08	-3.34	12.03	1.52
	p-value	.037	.001	<.001	.128

22 *Note.* All dependent measures were log-transformed. Significant effects are indicated in **bold**.

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Appendix C

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Model trimming process for Experiment 2

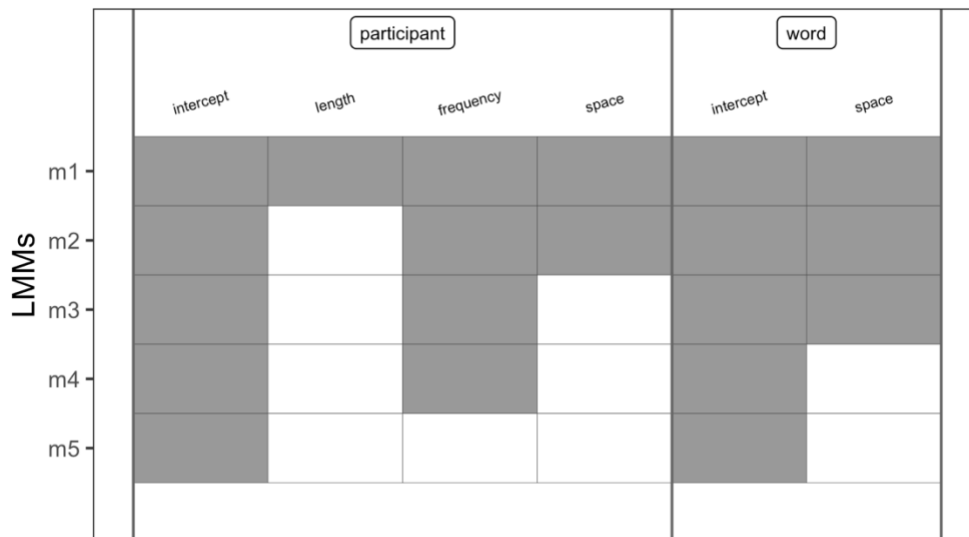
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This appendix contain tile plots documenting the model trimming procedure used for each dependent measure in Experiment 2. The first model was the model with maximum random effect structure. Random structure was iteratively trimmed until model convergence was achieved.

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Figure C1

8 *Model trimming for first fixation duration.*



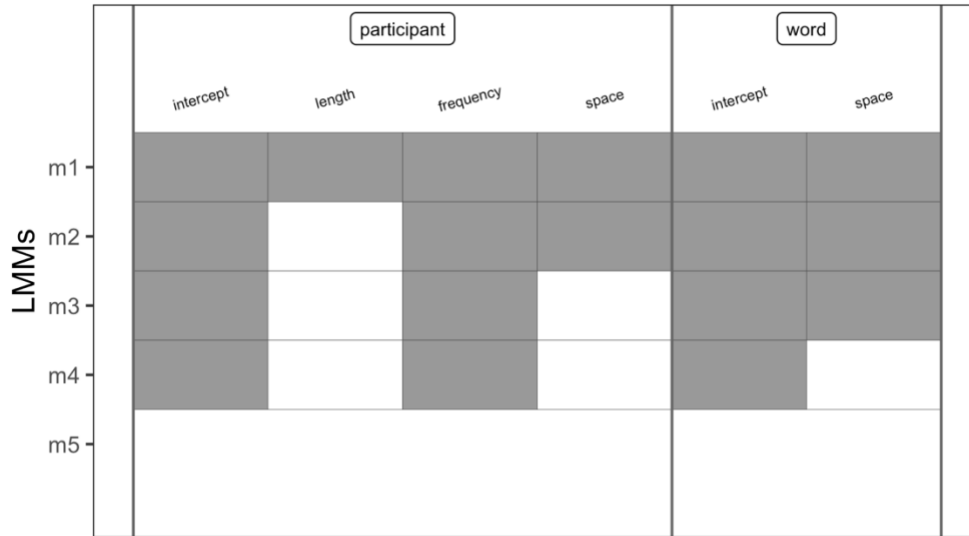
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1 **Figure C2**

2 *Model trimming for single fixation duration.*

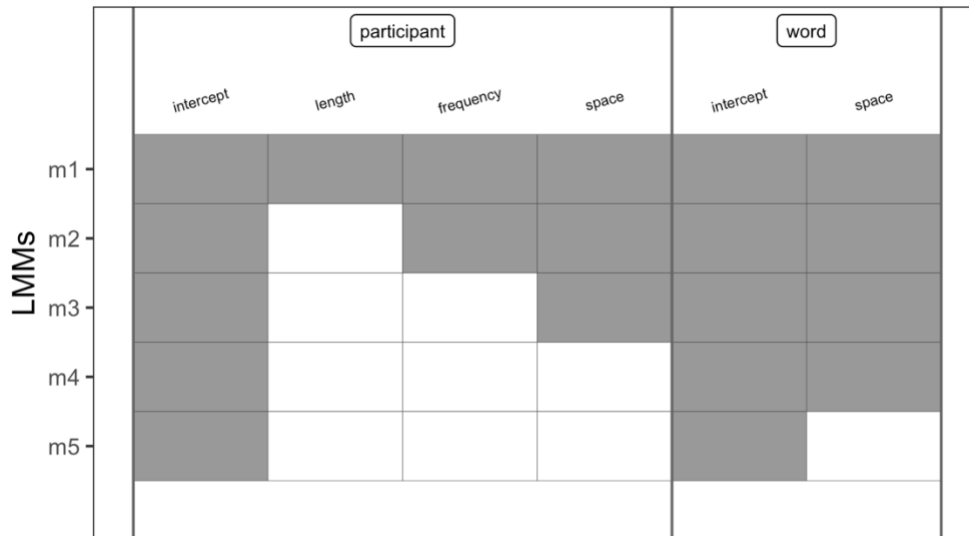


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5 **Figure C3**

6 *Model trimming for gaze duration.*

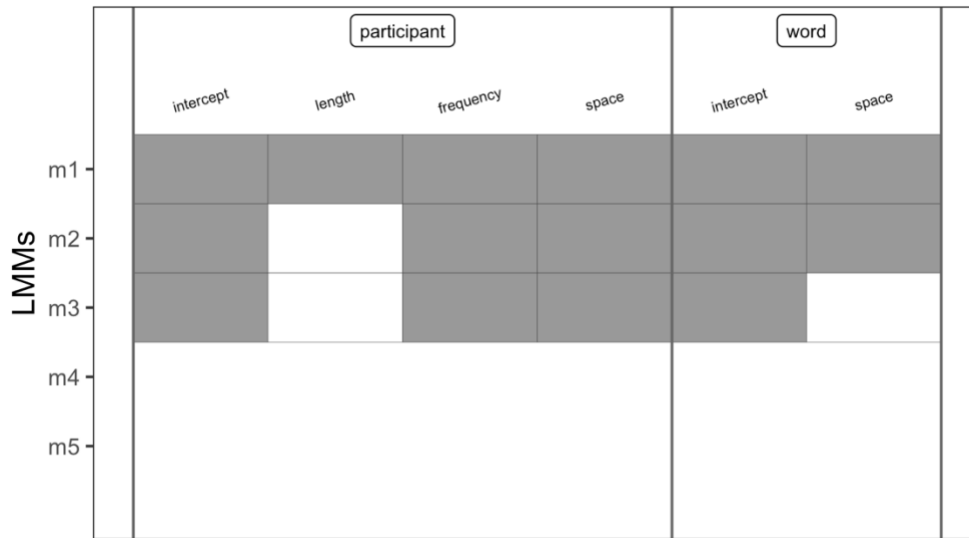


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1 **Figure C4**

2 *Model trimming for total viewing time.*

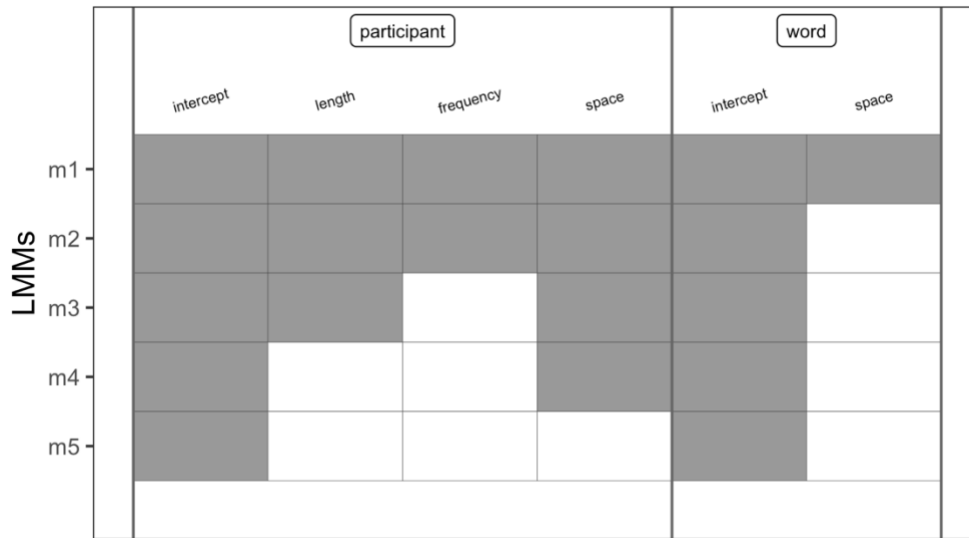


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5 **Figure C5**

6 *Model trimming for skipping probability.*



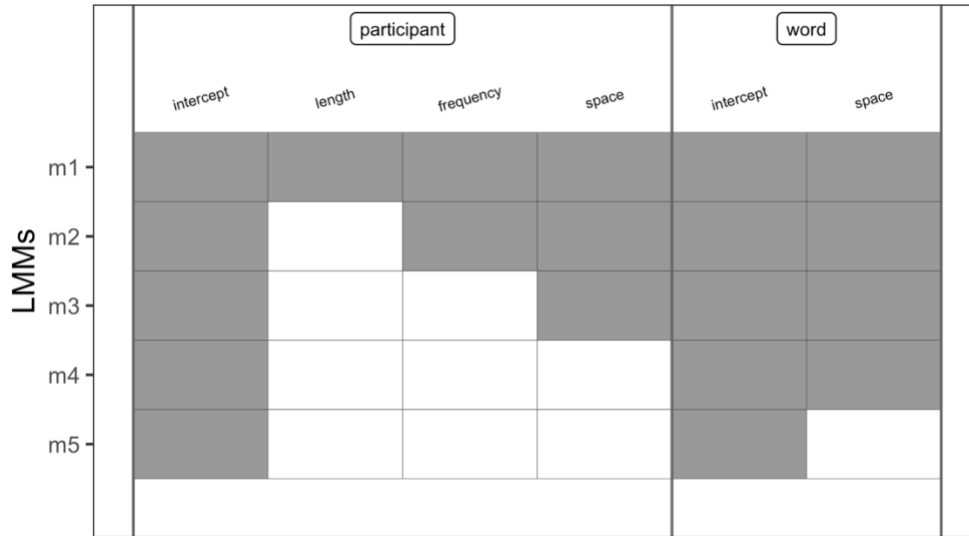
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1 **Figure C6**

2 *Model trimming for refixation probability.*

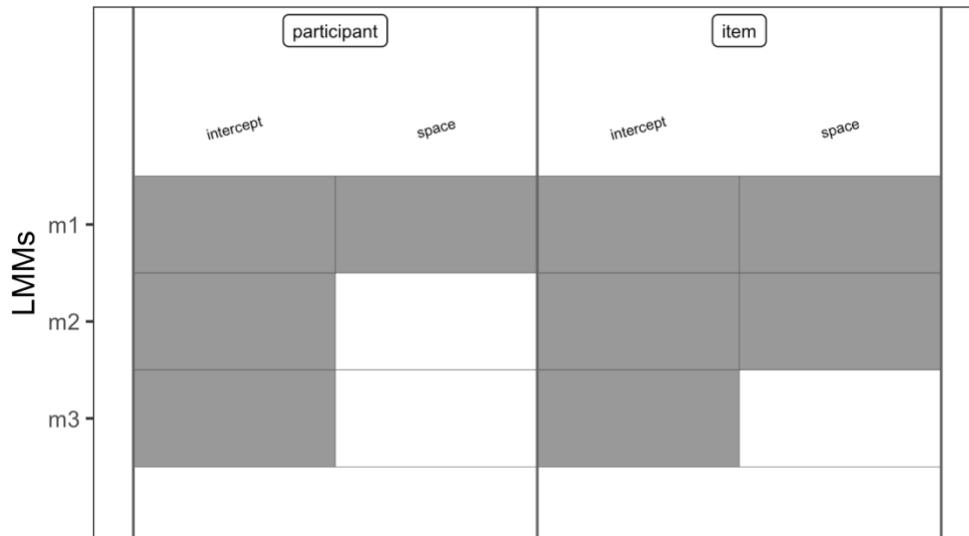


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5 **Figure C7**

6 *Model trimming for undersweep probability.*



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