Cognition 261 (2025) 106149

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Parafoveal preview benefits magnified

Bo Yao [a,*], Christopher J. Hand [b], Sébastien Miellet [c], Sara C. Sereno [d,**]

[a] Department of Psychology, Lancaster University, UK
[b] School of Education, University of Glasgow, UK
[c] School of Psychology, University of Wollongong, Australia
[d] School of Psychology and Neuroscience, University of Glasgow, UK

ARTICLE INFO

Keywords:
Word-initial letter constraint
Contextual predictability
Parafoveal processing
Parafoveal magnification
Eye tracking
Reading

ABSTRACT

This study investigated the impact of word-initial letters and contextual predictability on eye movements during reading. In two experiments, we manipulated the constraint of the target word's initial trigram (e.g., *dwarf* or *clown*) within contexts of varying predictability. Experiment 1 followed a normal-viewing reading paradigm, while Experiment 2 employed gaze-contingent magnification to enhance parafoveal text. We employed Bayesian ex-Gaussian mixed models to determine the effects of word-initial trigram, contextual predictability and parafoveal preview manipulations on the centre and skew of fixation durations specifically. We found that parafoveal magnification enhanced parafoveal identification of word-initial letters, but this effect was only observable for less predictable and challenging words. During target word fixations, word-initial trigrams were shown to contribute to lexical selection for all words, regardless of preview manipulation. Our results elucidate the dynamic impact of word-initial trigram information across parafoveal and foveal processing, whilst demonstrating the utility and potential of parafoveal magnification as a novel tool for studying the scope and limits of parafoveal processing during reading.

1. Introduction

During fluent reading, we typically move our eyes rapidly from word to word and efficiently extract meaning from text. One key finding in eye movement research on reading is that, in addition to obtaining information from the foveated (fixated) word, we acquire information from the parafoveal (to-be-fixated) word which serves to facilitate the upcoming processing of that word (e.g., Rayner, 1975, 1998, 2009). This facilitation is called the parafoveal preview benefit. The current study examines the consequences of an *enhanced* parafoveal preview on eye movements during reading.

Empirically, parafoveal processing has been predominantly studied using the "moving window" (McConkie & Rayner, 1975) and "boundary" (Rayner, 1975) paradigms. In both paradigms, changes are made in the text contingent on the position of the reader's eyes. In the moving window technique, the text is dynamically updated in accordance with readers' fixation position, with valid text presented around the fixation and invalid text (e.g., strings of Xs) presented beyond this window. In addition, the size and symmetry of the window can be manipulated to limit the amount of parafoveal information available. The boundary technique, in contrast, implements a single change in the text during reading. A specified target word is initially presented (i.e., parafoveally, before it is fixated) in an invalid form (e.g., a string of Xs or other letters). During the saccade into the target region, the invalid parafoveal preview changes into the valid target word. Additionally, the relationship between the (invalid) parafoveal preview and the (valid) foveal target are manipulated to determine the depth of orthographic, phonological, and semantic parafoveal processing (for reviews, see Balota & Rayner, 1990; Schotter et al., 2012).

Research using these paradigms compared the fixation time advantage on a target word (fixation *n*) when the parafoveal preview of that word (fixation *n-1*) was valid versus invalid. Considerable evidence suggests that valid previews activate low-level orthographic, phonological and lexical properties of the parafoveal word, facilitating its subsequent foveal processing (for reviews, see Andrews & Veldre, 2019; Balota & Rayner, 1990; Kliegl et al., 2006; Schotter et al., 2012). However, it remains less clear (1) to what extent orthographic information of the to-be-fixated word is processed parafoveally, and (2) how parafoveal preview of this information may be influenced by contextual factors.

* Correspondence to: Bo Yao, Department of Psychology Fylde College, Lancaster University, Lancaster LA1 4YF, UK.
** Correspondence to: Sara C. Sereno, School of Psychology and Neuroscience, University of Glasgow, 62 Hillhead Street, Glasgow G12 8QB, UK.
E-mail addresses: b.yao1@lancaster.ac.uk (B. Yao), Sara.Sereno@glasgow.ac.uk (S.C. Sereno).

https://doi.org/10.1016/j.cognition.2025.106149
Received 19 January 2024; Received in revised form 7 April 2025; Accepted 12 April 2025
Available online 24 April 2025

To address these questions, we simultaneously manipulated orthographic and contextual factors in two reading experiments with normal and enhanced parafoveal previews, respectively, and examined how these factors contribute to parafoveal processing when the preview is perceptually enhanced. In the following literature review, we first review parafoveal preview effects independently related to word-initial letters (orthographic) and word predictability (contextual), and then explore the interplay between these factors and the implications for parafoveal processing.

1.1. Word-initial letter constraint

It is established that the identification of a foveal word critically depends on the identification of word-initial letters and that parafoveal preview of these letters facilitates the recognition of the word upon its ensuing fixation (e.g., Inhoff, 1990; Johnson et al., 2007; Rayner et al., 1982). For example, Rayner et al. (1982) found that when the first three letters of the parafoveal preview (fixation *n-1*) were identical to those of the target word (fixation *n*), reading rate was virtually unaffected whether the remaining letters of the preview were identical to the target word. Johnson et al. (2007) extended this research by demonstrating that parafoveal letter identity information is still extracted when their positions were transposed, suggesting that word-initial letters may be identified not as a series of discrete letters, but instead as clusters.

Indeed, the first three letters of a word, or the word-initial trigram, are thought to form a critical cluster in lexical candidate selection in English (e.g., Hand et al., 2012; Lima & Inhoff, 1985). This is because word-initial trigrams effectively constrain lexical candidates in a cohort of words that share the same trigram. A word can either be high constraint (HC), having a relatively rare word-initial trigram (e.g., *dwa-*) that starts few words, or be low constraint (LC), having a more common word-initial trigram (e.g., *clo-*) that starts many words. Intuitively, lexical selection should be easier for an HC word, as there are very few competing candidates in its trigram neighbourhood (e.g., *dwarf*, *dwarves*, *dwam*); lexical selection should take longer for an LC word where a far greater number of candidates are activated (e.g., *clown, close, clock, cloud, cloth, cloak, clone, clout, clove, clog, cloy, clothes, clover, closet, cloister, clobber*, etc.).

However, empirical evidence on the parafoveal effects of *word-initial trigram constraint* remains limited and inconsistent. Lima and Inhoff (1985; Experiment 1) used a moving window paradigm to compare reading performance in a one-word moving window condition (invalid preview of Xs, with word-spacing otherwise preserved) to a two-word window (valid preview) and a normal reading condition (valid preview). They found counterintuitive evidence that HC words (e.g., *dwarf*) were fixated for longer than LC words (e.g., *clown*). While parafoveal preview benefits were present in general, they were not different between HC and LC targets, suggesting that word-initial trigrams did not contribute to lexical selection parafoveally, but may have influenced the efficiency of foveal orthographic processing. That is, the longer fixation times on HC words may reflect less efficient recognition of word-initial trigrams in the lexicon that are rarer (shared by few words) than those starting LC words (shared by many words).

Hand et al. (2012), in contrast, did show a parafoveal advantage for HC words. Under normal viewing conditions, the duration of the pre-target fixation (*n-1*) showed such an advantage. In addition, Hand et al. (2010) used launch site (i.e., the distance from the pre-target fixation to the target) to approximate 'valid' (near launch distance, 1–3 characters) versus 'invalid' (far launch distance, 7–9 characters) parafoveal preview conditions. Their *post hoc* analysis of target first fixation durations (FFDs; the initial fixation made on a target word regardless of whether additional fixations are made) on HC and LC words arising from near or far launch distances also showed a similar pattern (the constraint by launch distance interaction, however, was significant only by participants).

The discrepant findings between the two studies may reflect different distributions of word-initial trigram neighbours for target words: LC words in Hand et al. (2012) had much denser neighbourhoods (20–209 neighbours) than those in Lima and Inhoff (1985) (9–80 neighbours), hence the difference between HC and LC words was more pronounced in Hand et al. (2012). Moreover, the lack of word-initial constraint preview effects in Lima and Inhoff (1985) may be partially explained by the unnatural display of text; the cyan dot-matrix font on a black background used in their study was arguably more difficult to read parafoveally than the more natural black Sans Mono font on a white background used in Hand et al. (2012). As such, LC trigrams may be easier to identify when preview is difficult (Lima & Inhoff, 1985), whereas HC trigrams may have the upper hand in lexical selection under conditions more akin to real-world reading (Hand et al., 2012). As both interpretations are plausible, further research is needed to characterise the conditions in which word-initial trigram constraint may differentially contribute to parafoveal and foveal processing.

1.2. Contextual predictability

Contextual predictability has been extensively studied in reading (see, e.g., Staub, 2015, for a review). The general finding is that high predictable (HP) words are read faster than low predictable (LP) words, but on condition of valid parafoveal preview. For example, Balota et al. (1985) manipulated parafoveal preview and contextual predictability (based on Cloze probabilities; Taylor, 1953) in a boundary experiment. Sentence contexts (e.g., *Since the wedding was today, the baker rushed the wedding*…) were constructed for HP (e.g., *cake*) and LP (e.g., *pies*) targets. Parafoveal previews varied in terms of their visual and semantic similarity to the target. For example, the HP target *cake* had previews that were (1) visually similar (*cahc*), (2) semantically related but less predictable (*pies*), (3) visually different (*picz*), (4) and semantically anomalous (*bomb*); the LP target *pies* had similar preview conditions (i.e., *picz* was visually similar, *cake* was semantically related but more predictable, *cahc* was visually different, and *bomb* remained semantically anomalous). Balota et al. (1985) found greater skipping and shorter FFD and gaze duration (GD; the sum of all consecutive first-pass fixations on a word) for HP than LP targets, but only when parafoveal preview was visually similar to the target (e.g., *cake*, *cahc*). White et al. (2005) also used a boundary paradigm which manipulated preview word length and contextual predictability of the target. They found predictability influenced FFD (with faster HP fixations) when preview word length was correct, but not when it was incorrect. A similar predictability × preview-word-length interaction was found for skipping, but only when saccades were launched from near the target word, where preview was likely to be most informative. These early findings highlight that contextual predictability likely facilitates pre-lexical visual processing of the parafoveal word and only results in preview benefits when a visually similar preview is available.

To explore which distributional parameters are affected by contextual predictability, several studies have modelled the effects of contextual predictability on FFD and/or single fixation duration (SFD; when exactly one first-pass fixation is made on a target word, representing prototypical target fixations) via ex-Gaussian distributions. Ex-Gaussian distributions can model positively skewed data by combining exponential and Gaussian elements, characterised by three parameters: *mu* for central tendency, *sigma* for dispersion, and *tau* for skewness (Dawson, 1988). A shift in *mu* suggests that the experimental manipulation affects processing stages consistently across all trials, while a change in *tau* indicates that the manipulation primarily impacts the slower, more difficult trials at the tail of the distribution. Ex-Gaussian analyses of eye fixation durations have successfully highlighted distinct effects of word frequency (e.g., White et al., 2018) and predictability (Staub, 2011). For example, while word frequency influenced both the *mu* and *tau* (Staub et al., 2010), predictability only impacted the *mu* (Staub, 2011). Specifically, Staub (2011) recorded eye fixation times on 50 target words that were embedded in HP versus LP contexts. For both FFD and SFD, ex-Gaussian analysis revealed that the *mu* of the target fixation distribution was significantly shifted to the left (shorter durations) when a word was highly predictable; however, the *tau* was not affected by predictability. Similar findings were reported by Sheridan and Reingold (2012), whose survival analysis additionally reported that the effects of predictability appeared as early as 140 ms from fixation onset. Predictability effects on the *mu* of the fixation distribution highlights that predictability likely interacts with early visuo-orthographic processing that occurs on all fixations, similar to effects of parafoveal stimulus quality (White & Staub, 2012).

What remains less clear is to what extent predictability may influence parafoveal identification of letter clusters that are critical for lexical candidate selection. Hand et al. (2012) examined the relationships between word-initial letter constraint, word frequency, and contextual predictability in an eye movement study. They observed significant individual effects of constraint, frequency, and predictability across all fixation duration measures. Moreover, in FFD and SFD, they found an interaction between constraint and predictability; fixation durations were shorter for HC words than LC words in LP contexts, but this HC advantage was not observed in HP contexts. Although the constraint × predictability interaction indicates that letter identification can be influenced by predictability, the nature of this interaction was difficult to interpret for several reasons. First, as preview validity was not manipulated, it was unclear to what extent the interaction reflected parafoveal or foveal processing of the target. Second, the interaction was somewhat weak as it was not significant in both F_1 and F_2 ANOVAs. Third, the weak interactions may highlight the ANOVA's limitation in assuming a normal distribution when applied to inherently skewed fixation data, treating distribution tails as noise rather than modelling meaningful skewness effects.

1.3. The current study

Building on the findings of Hand et al. (2012), the current study aimed to examine (1) to what extent constraint and predictability interact during target fixations in reading, and (2) to what extent their interaction benefits from parafoveal preview. Specifically, we examined the effects of word-initial trigram constraint (LC, HC) and contextual predictability (LP, HP) on target fixations in reading.

To increase the robustness of our evidence, we nearly doubled the materials from Hand et al. (2012) from 88 to 160 target words. We also dropped word frequency from the current study design, as frequency did not interact with constraint or predictability in Hand et al. (2012). Nevertheless, during the experimental design phase, we carefully controlled word frequency to account for its known impact on eye movements during reading (e.g., Hand et al, 2010; Sereno et al., 2018).

To investigate parafoveal preview effects of constraint and predictability, we implemented a novel parafoveal magnification (PM) paradigm where the efficacy of parafoveal preview is enhanced rather than blocked (Miellet et al., 2009). Under PM, with each new fixation, text outside the fovea is enlarged progressively as a function of its eccentricity from fixation. Unlike the moving window or boundary paradigms, PM does not block or reduce parafoveal preview, so it will not disrupt the integration of information between pre-target and target fixations. Instead, PM enhances the perceptual impact of the upcoming text, analogous to creating a "supernormal" stimulus (Tinbergen & Perdeck, 1951). If constraint and predictability interact during parafoveal processing of the target, their interaction should be significantly enhanced by PM and be more easily detected than with a normal, valid preview using a uniform font.

Parafoveal preview was manipulated between two eye tracking experiments, with normal reading in Experiment 1 ($N = 40$) and reading with PM in Experiment 2 ($N = 40$), respectively. Importantly, we improved the analysis methods used by Hand et al. (2012) and Lima and Inhoff (1985) by employing ex-Gaussian Bayesian Mixed Models (BMMs) for fixation data, which model both the central tendency and skewness of the data (Staub, 2011), and by incorporating random effects for both participants and words. Following Dienes' (2021) recommendations, we used empirically informed normal priors based on typical effect sizes from the prior literature on constraint and predictability effects. Inferences were based on credible intervals of the posterior distributions, and the evidence for H_1 over H_0 was quantified by Bayes Factors.

In Experiment 1, we aimed to replicate Hand et al.'s (2012) results, which reported main effects of constraint (HC < LC) and predictability (HP < LP) across all fixation duration measures, and an interaction between constraint and predictability in early measures (FFD, SFD). The predictions for Experiment 2 were harder to make, given this was the first study investigating the effect of PM on orthographic and contextual factors in reading. Overall, we expected at least some of these main effects to be significantly greater, due to the parafoveal perceptual enhancement of the target word. Critically, we were interested in whether the constraint × predictability interaction could be significantly enhanced by PM.

2. Experiment 1

Experiment 1 investigated the independent and interactive effects of target word-initial letter constraint and target word contextual predictability on eye movement behaviour during normal reading.

2.1. Sample size justifications

As we adopted a Bayesian approach in data analysis, our study did not primarily rely on power calculations to determine sample size. This is because Bayesian inference is primarily concerned with the probability distribution of parameters given the data rather than the probability of observing the data under repeated sampling assuming the null hypothesis (Kruschke & Liddell, 2018). Practical limitations also prevented us from running simulations to estimate posterior precision. On the one hand, the minimal effect sizes and their variance for the novel effects we are testing are unknown for such simulations, due to the unavailability of original data from Hand et al. (2012) and Lima and Inhoff (1985). On the other hand, running simulations using Bayesian Mixed Models (BMMs) with maximal random effects is highly computationally intensive, and could require hundreds of hours per parameter per fixation measure.

Our desired sample size was therefore determined based on the sample sizes used in Hand et al. (2012) and Lima and Inhoff (1985), and the recommended number of observations from the literature for well-powered reaction time studies under the frequentist framework (Brysbaert & Stevens, 2018).

To accommodate time and resource constraints, we designed our experiment with 160 pairs of target words and 40 participants. We vastly increased the materials from Lima and Inhoff's (1985) 42 pairs and Hand et al.'s (2012) 88 pairs of words to 160 pairs of words. Word frequency was excluded from the current study design, as it did not interact with constraint or predictability in Hand et al. (2012). However, we ensured careful control of word frequency due to its well-established influence on eye movement behaviour during reading (e.g., Hand et al., 2010; Sereno et al., 2018). As for participant numbers, this was on par with Hand et al.'s (2012) 48 participants and much higher than Lima and Inhoff's (1985) 18 participants.

With the increased number of word items and a simplified design, our experiment is set to achieve up to 3200 observations per condition (80 trials per condition × 40 participants), which is well above the minimum of 1600 observations per condition needed to detect effect sizes of 10–20 ms as recommended by Brysbaert and Stevens (2018) under the frequentist framework.

2.2. Participants

Forty native English speakers took part (28 females, 12 males; M_{age} = 22.8 years, *SD* = 5.7; range: 18–32 years). Participants were compensated with £5 or course credits for their time. Participants had either normal or corrected-to-normal vision and had not been diagnosed with any reading disorder (e.g., dyslexia). All participants gave written informed consent, and the experimental procedure was approved by the University Research Ethics Committee at the University of Glasgow.

2.3. Materials, design and apparatus

One hundred and sixty 5-letter target words were selected for this experiment. Target words and the frequencies of their trigram neighbourhoods were obtained using the on-line resource for the British National Corpus (BNC) for written words (Davies, 2004). Half of the target words were relatively LC (e.g., *spade*, which shares its initial trigram *spa-* with a relatively large number of words) while the other half of the target words were relatively HC (e.g., *yolks*, the only 5-letter English word that has the initial trigram *yol-*). Word-initial trigram constraint was characterised by dividing each target word's frequency of occurrence (per million) by the summed frequency of all 5-letter words (including the target) that shared the target word's trigram. As compared to the number of word-initial trigram neighbours, this measure better captures the essence of 'constraint' in the context of lexical selection, as it estimates the relative 'dominance' (frequency ranking) of a given target in its word-initial trigram neighbourhood. Target word frequency was balanced and controlled overall within each Constraint condition, with half of the target words being relatively low-frequency (e.g., *spade*) and the other half being relatively high-frequency (e.g., *plant*).

Target words (LC, HC) were embedded in one-line sentences and were positioned near the middle of a line of text (e.g., *He had enjoyed being a clown but it was time to retire.*). In line with the paradigm of Hand et al. (2012), target sentences were either presented alone, such that the target words were difficult to predict (LP), or were preceded by a context sentence (e.g., *Pierre had entertained kids at the circus for 50 years. / He had enjoyed being a clown but it was time to retire.*), such that the target words were much easier to predict when reading the target sentence (HP).

The level of contextual predictability was quantified subjectively in a Cloze probability task ($N = 26$). The materials were divided into two sets, with equal number of LP and HP sentences, and were presented to two participant groups to avoid repetition of the target sentence across conditions (13 participants per group; none of whom participated in either Experiments 1 or 2). Participants were given each experimental item up to but not including the target word. Their task was to generate the next word in the passage. Items were scored as "1" for target-match responses and "0" for all other responses, resulting in a Cloze probability for each target. Target word specifications across conditions are summarised in Table 1. Example materials in each condition are presented in Table 2. The full list of materials is included in the **Appendix**.

As Predictability was manipulated within items (as in Hand et al., 2012), two stimulus lists with counterbalanced item-condition combinations (40 targets for each of the 4 conditions) were prepared for eye tracking stimulus presentation. Each stimulus list was presented in two blocks: the LP trials (1 sentence per trial) were always presented in the first block, with the HP trials (2 sentences per trial) presented in the second block. This setup, also employed by Hand et al. (2012), was utilised for several reasons. First, we wanted to directly replicate Hand et al. (2012) with the identical setup; an initial block of single-line sentences would also be comparable to Lima and Inhoff's (1985) original study. Second, we thought it would be less confusing for the participants if the LP 1-sentence trials and the HP 2-sentence trials were presented in separate blocks. Third, we suspected that possible strategies that participants developed in reading 2-sentence HP trials might change how they read subsequent 1-sentence LP trials. Finally, because stimuli could only be presented one sentence at a time in Experiment 2 with PM (i.e., context and target sentences appeared on separate screens instead of both sentences on a single screen), the blocked design served to reduce any confusion about what constituted a single experimental trial. Within each block, experimental items were presented in a different random order to each participant. Each of the two scripts was assigned to 20 participants.

Eye movements were monitored via an SR Research (Mississauga, Ontario, Canada) Desktop Mount EyeLink 1000 eye tracker, with a chin-forehead rest. The eye tracker has a spatial resolution of 0.01° and eye position was sampled at 1000 Hz using corneal reflection and pupil tracking. EyeTrack software, developed by the University of Massachusetts, Amherst, controlled stimulus presentation (https://blogs.umass.edu/eyelab/software/). Text (black letters on a white background using the non-proportional 14-point Bitstream Vera Sans Mono font) was presented on a Dell P1130 19-in. CRT monitor (1024 × 768 resolution, 100 Hz). Viewing was binocular, and eye movements were recorded from the right eye. At a viewing distance of approximately 72 cm, approximately four characters of text subtended 1° of visual angle.

Table 1
Means (with standard deviations in parentheses) of target word specifications across experimental conditions.

Measure	LC	HC
N	160	160
Length	5 (0)	5 (0)
Number of Trigram Neighbours	17.5 (7.3)	2.2 (2.6)
% Frequency of Trigram Neighbourhood	10.7 (7.8)	95.9 (4.6)
Target Word Frequency	44.3 (57.9)	48.2 (64.1)
LP (Cloze)	0.04 (0.10)	0.04 (0.07)
HP (Cloze)	0.57 (0.26)	0.54 (0.26)

Note: LC = low constraint; HC = high constraint; *N* = number of items; Length in number of characters; Number of Trigram Neighbours = number of 5-letter word-initial trigram neighbours; % Frequency of Trigram Neighbourhood = target word's frequency of occurrence (per million) divided by the summed frequency of all 5-letter words that share that trigram; Target Word Frequency = written frequency of occurrence (per million) for the target word; LP = low predictability (target sentence only); HP = high predictability (context sentence plus target sentence); Cloze = Cloze value of target, on a scale of 0 (target word not guessed) to 1 (target word correctly guessed).

Table 2
Example materials by condition.

Condition	Example
LP	
LC	*They were hoping to begin the trial as quickly as possible.*
HC	*Afterwards, they agreed that the fight was very exciting.*
HP	
LC	The lawyers were behind schedule in selecting the jurors. *They were hoping to begin the trial as quickly as possible.*
HC	Dave and Gordon were going to watch the boxing match. *Afterwards, they agreed that the fight was very exciting.*

Note: Target sentences are italicised. Target words are underlined. LP = low predictability; HP = high predictability; LC = low constraint; HC = high constraint.

2.4. Procedure

Participants were given instructions about the eye tracking task and were told to read for comprehension. The first block of the experiment started with an initial 9-point calibration of the eye-tracking system, extending over the maximal horizontal and vertical range of the display. The accuracy of participants' initial fixations was then checked by a subsequent validation in which participants fixated on the calibration points for a second time. The experiment proceeded only when the calibration was adequately accurate (average error < 0.30°; maximal error on any one calibration point < 0.50°).

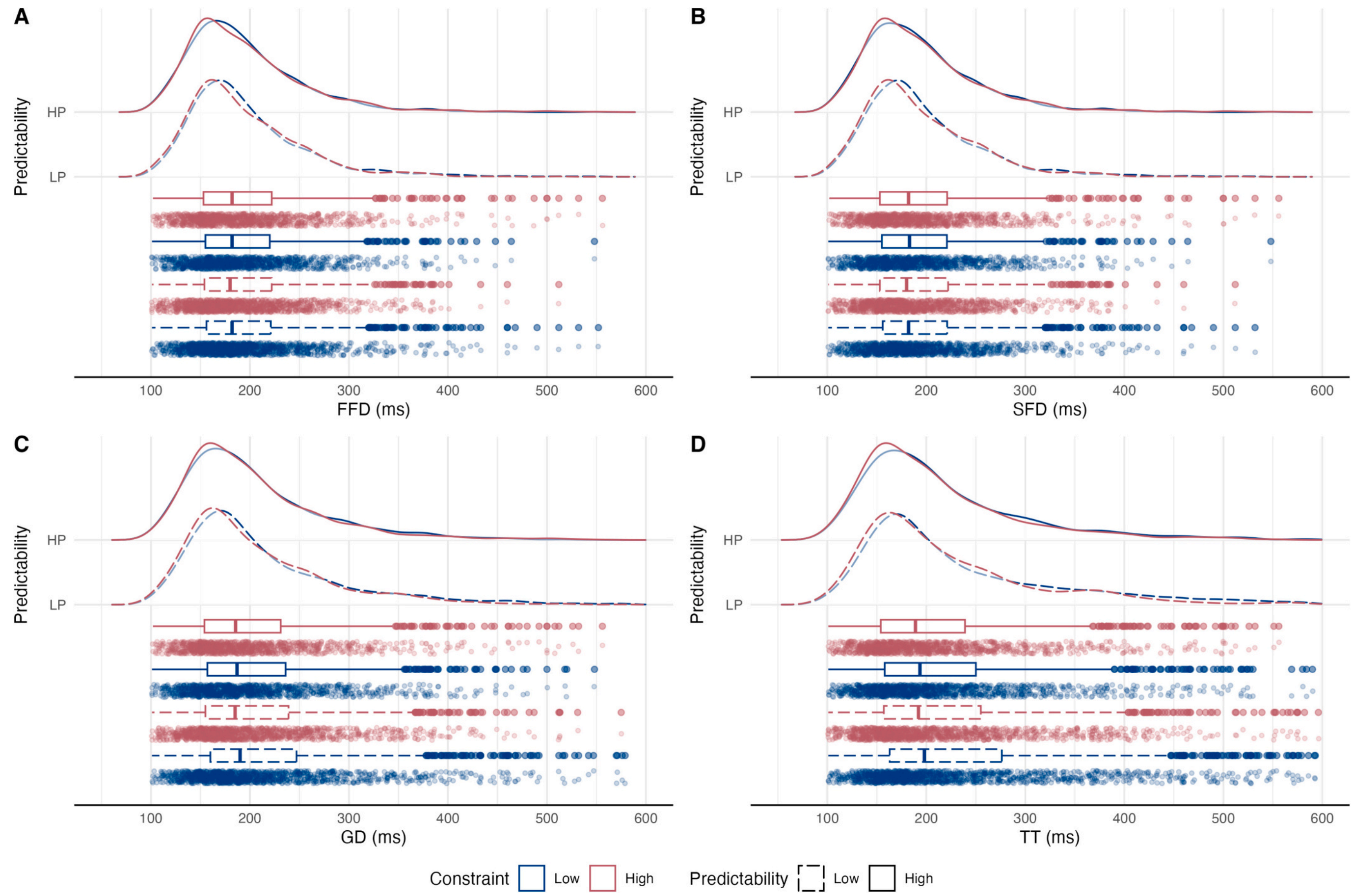


Fig. 1. Raw distributions of fixation durations by experimental design for Experiment 1.
Note: Top-left (A) shows FFD (first fixation duration); top-right (B) shows SFD (single fixation duration); bottom-left (C) shows GD (gaze duration); bottom-right (D) shows TT (total fixation time). Word-initial trigram constraint is categorised by line colour, with red = high constraint (HC), and blue = low constraint (LC). Contextual predictability is categorised by line type, with solid lines = high predictability (HP), and dashed lines = low predictability (LP).

After the initial calibration, participants were asked to read five practice 1-line sentences, and then were recalibrated a second time. Each trial began with a central fixation point for drift correction (validation check), followed by a black square which corresponded to the position of the first letter of the to-be-presented sentence (i.e., to the middle left of the screen). An accurately calibrated fixation at this location triggered the presentation of the sentence.[1] After reading each sentence, participants moved their eyes to the lower, right corner of the screen and pressed a button to clear the screen. Participants were then presented with 80 1-sentence (LP) trials. Following 50 % of the trials, a yes/no comprehension question regarding the content of preceding sentence. Participants were required to respond to the question by pressing either the right button (for a “yes” answer) or the left button (for a “no” answer) on a game controller. Answering the question triggered the presentation of the next trial.

The procedure for the second block, similar to the first block, involved a recalibration, reading 5 practice 2-line (HP) sentences, another recalibration, reading 80 2-sentence (HP) trials, again answering yes/no comprehension questions. Over all trials, participants had very little difficulty in answering these questions (average over 90 % correct).

[1] If participants struggled to trigger the text presentation, the trial was interrupted, and the 9-point calibration was performed until the tracking was accurate. The same trial was then repeated.

2.5. Results

2.5.1. Data preprocessing

Fixations were mapped onto each character of the text. Following Hand et al.’s (2012) protocol, individual fixations shorter than 100 ms or longer than 750 ms were discarded. The target region comprised the word itself (always five letters long) and the preceding space. Fixations on the target region were summarised in terms of the following: (1) first fixation duration (FFD), the duration of the first fixation on the target (whether a single fixation or the first of successive fixations); (2) single fixation duration (SFD), the duration of the first-pass fixation on the target when only one fixation is made; (3) gaze duration (GD), the duration of either single fixations or the sum of consecutive fixations on the target before exiting this region; and (4) total fixation time (TT), the sum of all first-pass fixations and re-fixations on the target. FFD and SFD represent the immediate stages of foveated target word processing as they comprise the initial and often only fixation on the target. GD includes cases when an additional consecutive fixation is made on the target, capturing overall first-pass processing of the target. TT represents relatively delayed, later stages of target word processing, as it comprises re-fixations after first-pass fixations. Trials in which target words were skipped initially or entirely were excluded from analyses of the corresponding fixation time measures (FFD, SFD, GD, or TT). In Experiment 1, target words were skipped initially in 28.5 % of trials, and entirely in 22.3 % of trials. Of the 71.5 % included first-pass trials, 89.0 % were single fixations and 11.0 % were fixated more than once consecutively. The raw distributions of fixation durations are illustrated by experimental design in Fig. 1.

2.5.2. Predictor coding and model choice

In both Hand et al. (2012) and Lima and Inhoff (1985), the Constraint and Predictability factors were treated as categorical variables in factorial ANOVAs. We identified this as problematic as the lexical constructs underlying trigram constraint and contextual predictability do not always exhibit a bimodal distribution. Specifically, we operationalised Constraint as ‘the word frequency percentage of a given target word within its length-matched word-initial trigram neighbourhood’. We operationalised Predictability by means of Cloze values of target words. While Constraint displayed a bimodal-like distribution, Cloze values were more uniformly distributed across all possible values in the HP condition (see Fig. 2). To more precisely model the inter-word variations, particularly with respect to predictability, we instead coded both Constraint and Predictability as continuous variables in our models.

Instead of employing factorial ANOVAs with F_1 and F_2 tests as in Lima and Inhoff (1985) and Hand et al. (2012), which is no longer the best practice in psycholinguistics (Baayen et al., 2008), we adopted a Bayesian Mixed-effects Modelling (BMM) approach for four reasons. First, a mixed-effect modelling approach allows the simultaneous incorporation of by-participants and by-item random effects within a single model, unlike the separate models required by AVOVA (Baayen et al., 2008). Second, the BMM approach enables us to choose the most appropriate distribution family to more effectively model the positively skewed fixation time data, offering superior model fits (see Yao et al., 2024 for a comparable example using Gamma models). Third, ex-Gaussian BMM explicitly separates the effects of experimental manipulations on the centre and skew of the distribution, allowing for finer grained insights into how these manipulations impact specific distributional parameters. This model choice appears ideal, as the boxplots in Fig. 1 reveal conditional differences not only in medians, but also in skewness, reflected in the asymmetry and differing proportions of box lengths and whiskers between conditions. Fourth, this approach focuses on the Bayes Factors to quantify the evidence strength for H_1 over H_0, based on empirically informed prior distributions.

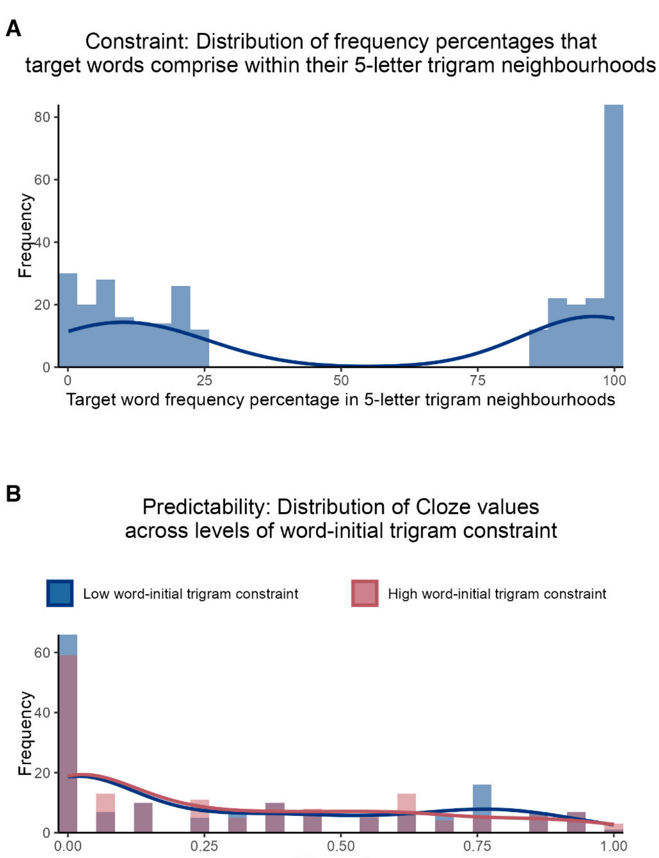


Fig. 2. Histograms of lexical variables underlying Constraint (A) and Predictability (B), overlaid with density curves.

2.5.3. Software packages

Data were analysed using the *brms* package (Bürkner, 2017) in R (https://www.r-project.org/). BMMs were fitted using the brm() function. The Bayes Factors (BF_{10}) for fixed effects were computed using the hypothesis() function. Marginal conditional means and effects were calculated using the brmsmargins() function from the *brmsmargins* package (Wiley & Hedeker, 2022). Figures were generated using the *ggplot2* package (Wickham, 2016).

2.6. Ex-gaussian BMMs

2.6.1. Specifying prior distributions

We specified empirically informed normal priors for fixed effects. The prior for the intercept of *mu* was centred at 225 ms ($SD = 50$ ms), based on average eye fixation times observed in the literature (Rayner, 1998). Based on parameters reported in Staub (2011), the prior for the intercept of *sigma* was centred at 25 ms ($SD = 5$ ms), and the prior for the intercept of *beta* (log scale) was centred at 4.09 (log of 60 ms) with an *SD* of 0.22 (log of approximately 12–15 ms around 60 ms).

Following Dienes’ (2021) recommendations, we used empirically observed, representative effect sizes as scale factors for the priors of all fixed effects. Priors for all fixed effects on *mu* were normal distributions centred at 0 with an *SD* of 10 ms for FFD and SFD, and 15 ms for GD and TT, based on reported effect sizes of Constraint and Predictability (Hand et al., 2012; Lima & Inhoff, 1985; Staub, 2015). For *beta* (log scale), priors were normal distributions centred at 0 with an *SD* of 0.24 for FFD and SFD, and 0.35 for GD and TT, based on effects of word frequency on skew (~10–15 ms difference on the raw scale) as reported by Staub et al. (2010). Although there is a lack of empirical data on skew effects for Constraint or its interactions with Predictability, we argue that their effect sizes are unlikely to significantly deviate from those for word frequency, thus justifying their use as reasonable scale factors for our priors.[2] The variance priors for both random effects distributions (subject and item) were specified using Student’s *t*-distributions centred on 0, with a degree of freedom of 3 and *SD*s equal to those set for the corresponding fixed effects.

The prior specifications reflect our expectations about the possible values of the fixed effects in the models, including both main effects and interactions. Specifically, the priors assume that the most likely effect is zero but allows for the possibility of non-zero effects, in both positive and negative directions, given the mixed findings in the literature regarding the direction of constraint effects (e.g., Hand et al., 2012; Lima & Inhoff, 1985). These non-zero values are more likely to be smaller than the effect sizes typically reported in the literature, but remain possible to be larger.

This approach of using empirically informed scale factors for priors, as recommended by Dienes (2021), offers several advantages. First, it eliminates the need to specify a minimum effect size of interest, instead using previous research to inform the range of plausible effects. Second, by including zero as the most likely value in the alternative hypothesis while still allowing for non-zero effects, this approach is inherently conservative.

To test our hypotheses, we calculated Bayes Factors (BF_{10}) using the Savage-Dickey density ratio (Wagenmakers et al., 2010). This method compares a model (H_1) where the parameter of interest allows non-zero values based on the empirically-informed priors described above, against an alternative model (H_0) where the parameter of interest equals zero. The resulting BF_{10} indicates the relative evidence for H_1 over H_0.

[2] *Beta* in brms is equivalent to *tau* as referenced in previous literature.

This approach requires data to clearly distinguish between the models to provide strong evidence for either hypothesis, effectively balancing sensitivity to detect genuine effects while guarding against false positives.

2.6.2. Prior predictive checks

We examined the distributional properties of prior samples extracted from our BMMs to assess the plausibility of prior predictions for fixation durations. Using consistent priors (with minor width adjustments between early and late fixation measures), we found that simulated fixation durations followed positively skewed quasi-Gaussian distributions with medians around 225 ms (range: ~100–400 ms) and scaled median absolute deviations between 30 and 125 ms, with appropriate rightward shifts and increased skew for late measures (**Fig. S1** in **Supplemental Materials**). The prior parameter estimates for fixed effects reflected our prior specifications (**Tables S1–S2**). These checks demonstrate that our prior specifications generate realistic fixation duration patterns and appropriate parameter ranges, providing strong validation for our modelling approach.

2.6.3. Model fitting

Fixation durations were modelled in ex-Gaussian BMMs with identity links for *mu* (central tendency) and *sigma* (dispersion), and a log link for *beta* (skewness). Continuous predictors of Constraint and Predictability were used to model variation between individual words. To reiterate, we used the relative frequency percentage of a given target word in its word-initial trigram 5-letter neighbourhood as Constraint, and Cloze values as Predictability, respectively. All predictors were centred and rescaled, with a mean of 0 and *SD* of 0.5. Fixed effects included all main effects and interaction combinations of Constraint and Predictability. All BMMs employed maximal random effect structures with a *subject* random intercept and *by-subject* random slopes for all fixed effects and their interactions, and with a *by-item (word)* random slope for Predictability (manipulated within words). The by-item (word) intercept was excluded because by-item variation is modelled in the continuous fixed factors of Constraint and is not treated as random. All BMMs were fitted with four chains, each consisting of a minimum of 5000 iterations (half for warmup and half for sampling). All BMMs converged.

The coefficients and its posterior credible intervals, and BF_{10} values are reported in Table 3. Fixed effects are estimated from the BMMs' posterior distributions, with the probabilities of the estimated parameters directly quantified in 95 % Credible Intervals (CrIs). If the CrIs do not include zero, this suggests that the observed data strongly support the existence of a non-zero effect. The confidence (or strength of evidence) for a detected effect is quantified by the Bayes Factor (BF_{10}), which measures the likelihood of evidence for the alternative hypothesis (H_1) over the null hypothesis (H_0). A $BF_{10} > 3$ is considered to indicate moderate evidence for H_1 over H_0 for a given effect (Jeffreys, 1998).

2.6.4. Posterior predictive checks

To validate our models' ability to capture empirical patterns in the data, we extracted posterior samples (using *posterior_predict()*) and compared their distributions against observed fixation durations. Posterior predictions showed excellent correspondence with the observed data distributions across all measures (see **Fig. S2–S4** in **Supplemental Materials**), with highly overlapping density plots demonstrating that our models successfully capture both the central tendencies and the distributional characteristics of the empirical data. This close alignment between model predictions and observed patterns provides strong evidence for the adequacy of our BMMs in capturing empirical characteristics of the observed data.

2.6.5. Model results

All marginal means and effects (contrasts) are computed between the high (*Mean* + *SD*) and low (*Mean* – *SD*) levels of relevant factors, with their 95 % CrIs reported in square brackets. Means and effects on *beta* are transformed back from the log scale to the raw fixation time scale for more intuitive interpretations. All numbers are reported in milliseconds.

For Constraint, there was strong evidence that it negatively modulated the *mu* of GD and TT (BF_{10}s > 13). The marginal means for *mu* were substantially shorter for HC targets (e.g., *dwarf*; $Mu_{HC\_GD,TT}$ = **202** [193, 211], **215** [205, 225]) than LC targets (e.g., *clown*; $Mu_{LC\_GD,TT}$ = **207**

Table 3
BMM results by fixed effects and fixation measures for Experiment 1.

Factors Measure	b(mu)	$CrI_{2.5}$	$CrI_{97.5}$	BF_{10}	b(beta)	$CrI_{2.5}$	$CrI_{97.5}$	BF_{10}
Intercept								
FFD	192.25	185.58	198.91		3.83	3.73	3.93	
SFD	192.84	186.05	200.00		3.84	3.74	3.94	
GD	204.35	195.87	213.18		4.10	3.99	4.21	
TT	221.13	211.17	230.71		4.40	4.31	4.48	
Constraint								
FFD	−2.31	−5.29	0.67	0.46	0.02	−0.06	0.09	0.18
SFD	−2.65	−5.76	0.45	0.68	−0.00	−0.08	0.07	0.17
GD	**−5.45**	**−9.03**	**−1.88**	**13.11**	−0.05	−0.12	0.01	0.34
TT	**−11.50**	**−16.09**	**−7.02**	**>1000**	**−0.11**	**−0.17**	**−0.05**	**41.42**
Predictability								
FFD	*−3.88*	*−7.47*	*−0.36*	*1.79*	−0.04	−0.12	0.04	0.31
SFD	*−4.17*	*−7.88*	*−0.43*	*2.05*	−0.06	−0.14	0.02	0.45
GD	**−10.33**	**−14.52**	**−6.19**	**>1000**	**−0.16**	**−0.23**	**−0.09**	**>1000**
TT	**−16.86**	**−21.68**	**−12.23**	**>1000**	**−0.21**	**−0.27**	**−0.14**	**>1000**
Constraint × Predictability								
FFD	2.27	−3.69	8.32	0.40	0.08	−0.06	0.23	0.58
SFD	2.25	−3.82	8.52	0.41	0.09	−0.06	0.25	0.69
GD	3.11	−3.77	9.87	0.33	0.07	−0.07	0.20	0.31
TT	3.52	−4.80	11.56	0.38	0.07	−0.05	0.19	0.34

Note: FFD = first fixation duration; SFD = single fixation duration; GD = gaze duration; TT = total fixation time. Effects with Credible Intervals (CrIs) not including zero and a BF_{10} of more than 3 are highlighted in **bold**. Effects with CrIs not including zero or a BF_{10} of more than 3, but not both, are *italicised*.

[198, 216], **227** [217, 237]). There was also strong evidence that Constraint negatively modulated the *beta* of TT (BF_{10} = 41), with less skewness for HC targets ($Beta_{HC\_TT}$ = **78** [70, 85]) than LC targets ($Beta_{LC\_TT}$ = **87** [79, 95]). There was no sufficient evidence that Constraint affected FFD or SFD, BF_{10}s < 0.69.

For Predictability, there was extremely strong evidence that it negatively modulated both the *mu* and *beta* of GD and TT (BF_{10}s > 1000), with shorter and less skewed fixation times for HP targets ($Mu_{HP\_GD,TT}$ = **199** [191,208], **213** [202,223]; $BetaHP\_GD,TT$ = **56** [49, 62], **74** [67, 80]) than LP targets ($Mu_{LP\_GD,TT}$ = **210** [201, 219], **230** [219, 239]; $Beta_{LP\_GD,TT}$ = **66** [58, 73], **91** [83, 99]). There was weak evidence that Predictability negatively modulated FFD or SFD. Although their 95 % CrIs did not include zero, their BF_{10} were 1.79 and 2.05, respectively, indicating that the evidence for H_1 is not yet sufficient.

There was no sufficient evidence for any interactions between Constraint and Predictability, BF_{10}s < 0.70.

2.7. Discussion

Our results partly replicated Hand et al.'s (2012) results, showing independent effects of Constraint and Predictability on target word processing in normal reading. In addition to an HP advantage, we replicated an HC advantage on target word processing, lending more support to the role of word-initial trigram constraint in lexical selection.

However, the main effects of Constraint and Predictability were not observed on FFD or SFD as in Hand et al. (2012) and the Constraint × Predictability interactions were not observed on any fixation measures. This may be due in part to the following: (1) the use of a different, but larger set of stimuli (N = 80 vs. 22 per cell); (2) a different participant sample; (3) Bayesian mixed modelling with an ex-Gaussian (vs. Gaussian) distribution family for positively skewed fixation durations; (4) modelling by-subject and by-word random effects simultaneously rather in separate F_1 and F_2 ANOVAs; and/or (5) the use of continuous predictors to model word-level variations (vs. coarse categorical groupings). Because Constraint and Predictability were found to affect late fixation measures of GD and TT, it seems they contribute to lexical selection during foveal (but not parafoveal) processing.

Given that Constraint and Predictability did not interact on any of the fixation measures, this implies that they affect target word processing at non-overlapping, discrete time points in normal reading. To understand which of these effects are driven by parafoveal preview and which are restricted to foveal processing, Experiment 2 sought to examine the same effects but under parafoveal magnification.

3. Experiment 2

In Experiment 2, we combined the approaches of Experiment 1 with the PM paradigm of Miellet et al. (2009). This paradigm enhances the perception of parafoveal text and is expected to enhance parafoveal processing.

3.1. Sample size justifications

The same sample size justifications from Experiment 1 applied to Experiment 2.

3.2. Participants

Forty native English speakers – none of whom had taken part in either stimulus norming or Experiment 1 – took part (21 females, 19 males; M_{age} = 23.7 years, SD = 6.2; range: 18–43). As in Experiment 1, all had either normal or corrected-to-normal vision, and no diagnostic history of a reading disorder (e.g., dyslexia). All participants gave written informed consent, and the experimental procedure was approved by the University Research Ethics Committee at the University of Glasgow.

3.3. Materials, design, and apparatus

The target stimuli were identical to those used in Experiment 1. However, due to the implementation of gaze-contingent PM, context and target sentences in the HP condition were presented sequentially in Experiment 2. PM was used to perceptually equate parafoveal and foveal information (see Miellet et al., 2009). Parafoveal text was progressively magnified, with increasing font size for each successive letter outside the foveated letters. Each sentence display was calculated and updated online to assign a different size and position for each character depending on its fixation location in the sentence. The size-increase function was taken from Anstis (1974), who showed that as distance from the fovea increases, the stimulus needs to be enlarged to be perceived equally well. Anstis's original equation is as follows: $y = (0.046) * x$, where y is the letter size and x represents the visual eccentricity in degrees. As in Miellet et al. (2009), we chose a factor of 0.069 (1.5 times the original) to ensure a clear advantage in parafoveal identification. Similarly, we maintained the "centre of gravity" of text across all letters, aligning the middles of all letter bodies, so that eye movements programmed to the centre of an enlarged parafoveal letter would land on the centre of that letter when it became foveal (and smaller). The effects of PM are depicted in Fig. 3.

The software was written in MatLab (R2006a), using the Psychophysics (PTB-3) and EyeLink Toolbox extensions (Brainard, 1997; Cornelissen et al., 2002). The apparatus was identical to that used in Experiment 1. The same CRT which displayed stimuli to participants in Experiment 1 was run instead at a refresh rate of 170 Hz (800 × 600 resolution), and updating the display, contingent on gaze position, took 5.9 ms on average. Viewing was binocular, and eye movements were recorded from the right eye. At a viewing distance of approximately 72 cm, approximately four characters of non-magnified text subtended 1° of visual angle.

3.4. Procedure

The experimental procedure of Experiment 2 was highly similar to that in Experiment 1, with the addition of gaze-contingent PM. The same calibration and practice procedures were used as in Experiment 1. During the first block of LP trials and the second block of HP trials, any comprehension questions were presented in standard non-magnified text. As in Experiment 1, participants typically had no problems in answering these (each participant >90 % correct). Due to the nature of

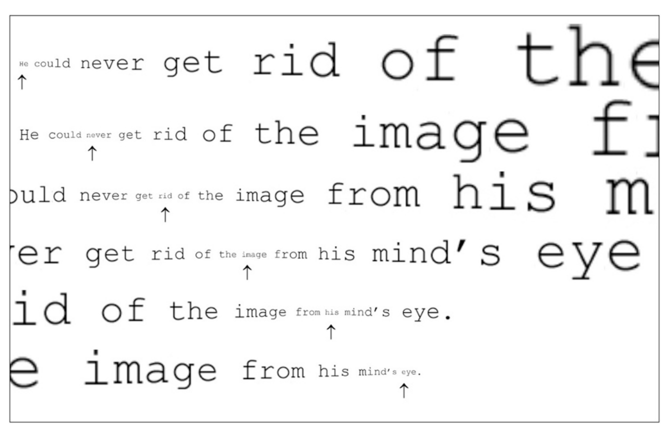


Fig. 3. Depiction of the parafoveal magnification paradigm (from Miellet et al., 2009).
Note: The location of each fixation is indicated with an arrow, and the corresponding display for that fixation is shown (with the chronological order of fixations represented across consecutive lines). In HP contexts, PM was applied to the second, target sentence only. The first, context sentence was presented in standard non-magnified text.

the PM manipulation, it was necessary to display HP stimuli sentence-by-sentence; the first, context sentence was presented in standard non-magnified text as in Experiment 1, while only the second, target sentence was presented in dynamic parafoveally magnified text. The font size of the fixated word in PM was equivalent to the font size for the context sentence and to font size used in Experiment 1.

3.5. Results and discussion

3.5.1. Eye movements under PM

In Experiment 2, as character size and position changed dynamically due to PM, fixation coordinates were mapped onto the character positions in accordance with the corresponding time point. Data preparation methods used in Experiment 1 were revisited in Experiment 2. Target words were skipped initially in 29.5 % of the trials, and entirely in 25.8 % of the trials. Of the 70.5 % valid trials, 84.1 % were single fixations and 15.9 % were fixated more than once consecutively. The trial distributions are on par with Experiment 1, with a slight increase (~5 %) in gaze duration fixations among included trials. The same suite of measures and BMM analyses as in Experiment 1 were carried out. The raw distributions of fixation durations are illustrated by experimental design in Fig. 4. The BMM results are reported in Table 4.

There was no sufficient evidence for Constraint effects on GD and TT, although there was weak evidence for a non-zero Constraint effect on the *mu* of TT, $b = -5.76$, $BF_{10} = 2.83$.

Contextual Predictability under PM, however, showed greater effects on all fixation measures, not just GD and TT as in Experiment 1. Fixation times for HP target words ($Mu_{\text{HP\_FFD,SFD,GD,TT}}$ = **234** [224, 244], **234** [224, 245], **238** [227, 250], **249** [235, 262]; $Beta_{\text{HP\_FFD,SFD,GD,TT}}$ = **53** [45, 60], **53** [45, 61], **56** [47, 65], **70** [60, 80]) were both shorter and less skewed than those for LP target words ($Mu_{\text{LP\_FFD,SFD,GD,TT}}$ = **250** [239, 259], **250** [240, 261], **258** [246, 270], **276** [263, 290]; $Beta_{\text{LP\_FFD,SFD,GD,TT}}$ = **66** [57, 75], **66** [56, 76], **73** [62, 84], **95** [82, 108]).

There was moderate evidence for Constraint × Predictability interactions on the *beta* of FFD and SFD, $BF_{10}s > 6.38$. For both measures, we found credible LC advantages (LC < HC) when target words were embedded in LP contexts ($Beta_{\text{LP\_LC\_FFD,SFD}}$ = **61** [53, 71], **61** [52, 71] vs. $Beta_{\text{LP\_HC\_FFD,SFD}}$ = **70** [60, 81], **71** [60, 81], $\Delta Beta_{\text{LP\_LC-HC\_FFD,SFD}}$ = **−9** [−15, −2], **−10** [−17, −3]), but no credible Constraint effects in HP contexts ($Beta_{\text{HP\_LC\_FFD,SFD}}$ = **54** [46, 62], **54** [46, 63] vs. $Beta_{\text{HP\_HC\_FFD,SFD}}$ = **51** [43, 59], **52** [44, 60], $\Delta Beta_{\text{HP\_HC-LC\_FFD,SFD}}$ = **3** [−3, 9], **3** [−3, 9]).

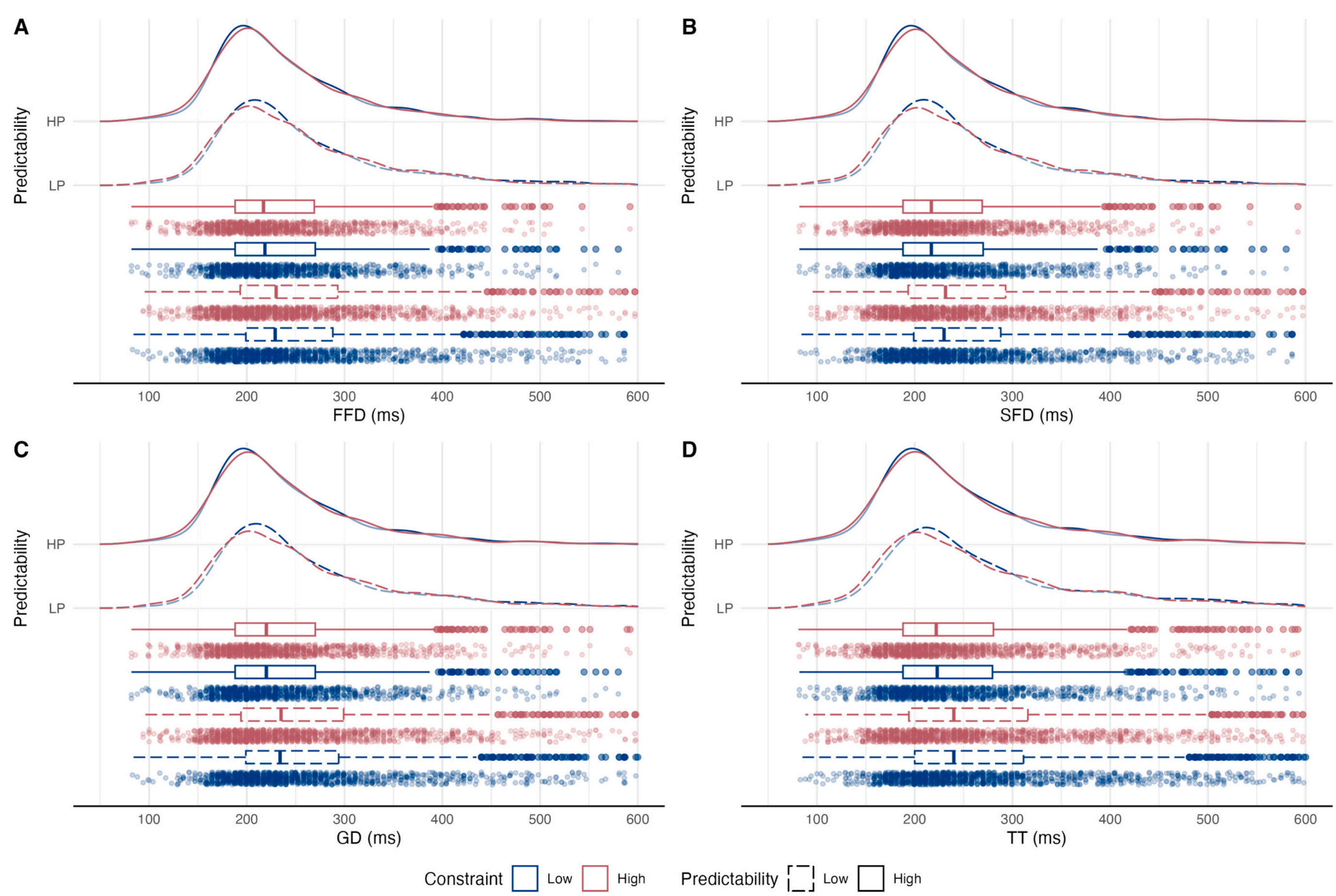


Fig. 4. Raw distributions of fixation durations by experimental design for Experiment 2.
Note: Top-left (A) shows FFD (first fixation duration); top-right (B) shows SFD (single fixation duration); bottom-left (C) shows GD (gaze duration); bottom-right (D) shows TT (total fixation time). Word-initial trigram constraint is categorised by line colour, with red = high constraint (HC), and blue = low constraint (LC). Contextual predictability is categorised by line type, with solid lines = high predictability (HP), and dashed lines = low predictability (LP).

Table 4
BMM results by fixed effects and fixation measures for Experiment 2.

Factors / Measure	*b(mu)*	$CrI_{2.5}$	$CrI_{97.5}$	BF_{10}	*b(beta)*	$CrI_{2.5}$	$CrI_{97.5}$	BF_{10}
Intercept								
FFD	241.77	232.05	251.60		4.07	3.93	4.20	
SFD	242.30	232.17	252.24		4.07	3.93	4.21	
GD	247.93	236.72	259.43		4.16	4.01	4.30	
TT	262.28	249.44	275.09		4.40	4.26	4.52	
Constraint								
FFD	−2.57	−6.24	1.16	0.48	0.04	−0.04	0.11	0.24
SFD	−2.41	−6.28	1.40	0.42	0.05	−0.03	0.12	0.35
GD	−2.81	−6.83	1.22	0.35	0.04	−0.03	0.11	0.15
TT	*−5.76*	*−10.39*	*−1.07*	*2.83*	−0.01	−0.07	0.05	0.10
Predictability								
FFD	**−15.80**	**−20.39**	**−11.27**	**>1000**	**−0.22**	**−0.31**	**−0.13**	**>1000**
SFD	**−16.01**	**−20.72**	**−11.34**	**>1000**	**−0.22**	**−0.31**	**−0.12**	**>1000**
GD	**−19.25**	**−24.48**	**−14.32**	**>1000**	**−0.25**	**−0.35**	**−0.16**	**>1000**
TT	**−27.45**	**−33.59**	**−21.50**	**>1000**	**−0.31**	**−0.39**	**−0.22**	**>1000**
Constraint × Predictability								
FFD	−6.39	−13.29	0.68	1.82	**−0.19**	**−0.33**	**−0.04**	**6.69**
SFD	−6.22	−13.14	0.69	1.69	**−0.20**	**−0.35**	**−0.04**	**6.38**
GD	−5.74	−13.23	1.67	0.81	*−0.16*	*−0.31*	*−0.01*	*1.73*
TT	−4.18	−12.72	4.37	0.45	−0.09	−0.23	0.05	0.46

Note: FFD = first fixation duration; SFD = single fixation duration; GD = gaze duration; TT = total fixation time. Effects with credible intervals not including zero and a BF_{10} of more than 3 are highlighted in **bold**. Effects with Credible Intervals (CrIs) not including zero or a BF_{10} of more than 3, but not both, are *italicised.*

3.5.2. The effect of reading condition

To identify which of these effects were substantially modulated by PM versus normal presentation, we combined the data from both experiments. The raw distributions of fixation durations are illustrated by experimental design and by reading condition in Fig. 5.

We refitted BMMs with Reading Condition (normal vs. PM) as an additional *between-subject* predictor (deviation-coded; normal = −0.5, PM = 0.5). BMMs for all measures were refitted, with their fixed effects including all main effects and interaction combinations of Constraint, Predictability, and Reading Condition. All BMMs employed maximal random effect structures with a *by-subject* random intercept and *by-subject* random slopes for all within-subject effects and interactions (Constraint * Predictability), and with *by-item (word)* random slopes for within-item effects and interaction (Predictability * Reading Condition). The full results are reported in Table 5**.**

3.5.3. Effects without reading condition

There was strong evidence that Constraint modulated the *mu* of GD and TT, BF_{10}s > 12.9. Fixation times were shorter for HC targets ($Mu_{\text{HC\_GD,TT}}$ = **223** [216, 230], **236** [229, 245]) than LC targets ($Mu_{\text{LC\_GD,TT}}$ = **228** [220, 235], **245** [237, 253]).

There was decisive evidence that Predictability modulated both the *mu* and *beta* across all fixation measures, BF_{10}s > 1000. Fixations times were shorter for HP targets ($Mu_{\text{HP\_FFD,SFD,GD,TT}}$ = **211** [205, 218], **212** [206, 219], **218** [211, 226], **230** [222, 238]) than LP targets ($Mu_{\text{LP\_FFD,SFD,GD,TT}}$ = **221** [215, 228], **222** [216, 229], **233** [225, 240], **252** [243, 260]). They were also less skewed for HP targets ($Beta_{\text{HP\_FFD,SFD,GD,TT}}$ = **48** [43, 52], **48** [44, 53], **56** [51, 61], **72** [67, 78]) than LP targets ($Beta_{\text{LP\_FFD,SFD,GD,TT}}$ = **56** [51, 62], **57** [51, 62], **70** [64, 77], **94** [87, 101]).

There was no evidence for the Constraint × Predictability interactions across all measures, BF_{10}s < 0.32.

3.5.4. Effects involving reading condition

There was decisive evidence that Reading Condition, or PM, substantially increased the *mu* of all fixation time measures (BF_{10}s > 1000; PM: $Mu_{\text{PM\_FFD,SFD,GD,TT}}$ = **234** [226, 243], **235** [226, 243], **243** [233, 252], **256** [246, 266] ms; noPM: $Mu_{\text{noPM\_FFD,SFD,GD,TT}}$ = **199** [191, 207], **200** [192, 209], **208** [199, 218], **225** [215, 236] ms), as well as the *beta* of FFD and SFD (BF_{10}s > 684; PM: $Beta_{\text{PM\_FFD,SFD}}$ = **62** [55, 69], **62** [55, 70] ms; noPM: $Beta_{\text{noPM\_FFD,SFD}}$ = **42** [37, 48], **43** [38, 48] ms).

There was moderate evidence for a Constraint × Reading Condition interaction on the *beta* of TT only, BF_{10} = 4.79. HC target fixations were less skewed that LC target fixations in the normal reading condition ($Beta_{\text{noPM\_HC}}$ = **74** [66, 82] ms, $Beta_{\text{noPM\_LC}}$ = **83** [74, 92] ms, $\Delta Beta_{\text{noPM\_HC-LC}}$ = **−9** [−14, −4] ms). This was statistically difference from the Constraint effect in PM, which had no impact on the skew ($Beta_{\text{PM\_HC}}$ = **88** [78, 97] ms, $Beta_{\text{PM\_LC}}$ = **87** [78, 97] ms, $\Delta Beta_{\text{PM\_HC-LC}}$ = **1** [−5, 6] ms).

There was very strong evidence for a Predictability × Reading Condition interaction on the *mu* of FFD, SFD (BF_{10}s = 81, 306) and moderate evidence for this interaction influencing the *mu* of GD (BF_{10} = 5). HP contexts had a statistically larger facilitation effects on fixation times under PM ($Mu_{\text{PM\_HP\_FFD,SFD,GD}}$ = **226** [218, 235], **227** [218, 235], **234** [223, 243] vs. $Mu_{\text{PM\_LP\_FFD,SFD,GD}}$ = **241** [233, 250], **242** [233, 251], **252** [242, 262]; $\Delta Mu_{\text{PM\_HP-LP\_FFD,SFD,GD}}$ = **−15** [−19, −10], **−15** [−20,−11], **−18** [−23, −14]) than in the normal reading condition ($Mu_{\text{noPM\_HP\_FFD,SFD,GD}}$ = **196** [188, 204], **198** [190, 207], **203** [193, 213] ms vs. $Mu_{\text{noPM\_LP\_FFD,SFD,GD}}$ = **201** [193, 210], **203** [194, 211], **213** [204, 223]; $\Delta Mu_{\text{noPM\_HP-LP\_FFD,SFD,GD}}$ = **−5** [−9, −1], **−5** [−8, −1], **−10** [−15, −6]). There was no sufficient evidence for this interaction on the *beta* of fixation measures BF_{10}s < 2.80.

Finally, there was moderate evidence for a three-way interaction between Constraint, Predictability, and Reading Condition on the *beta* of FFD and SFD, BF_{10}*s* = 5.81 and 4.70. For HP targets, Reading Condition had negligible impact on how Constraint influenced the skew of fixation times. *Beta* was virtually identical between HC and LC targets under PM ($Beta_{\text{HP\_PM\_HC\_FFD,SFD}}$ = **55** [47, 62], **55** [48, 63] vs. $Beta_{\text{HP\_PM\_LC\_FFD,SFD}}$ = **56** [48, 64], **56** [48, 64]; $\Delta Beta_{\text{HP\_PM\_HC-LC\_FFD,SFD}}$ = **−1** [−7, 5], **0** [−6, 6]) and under normal reading ($Beta_{\text{HP\_noPM\_HC\_FFD,SFD}}$ = **41** [35, 47], **41**

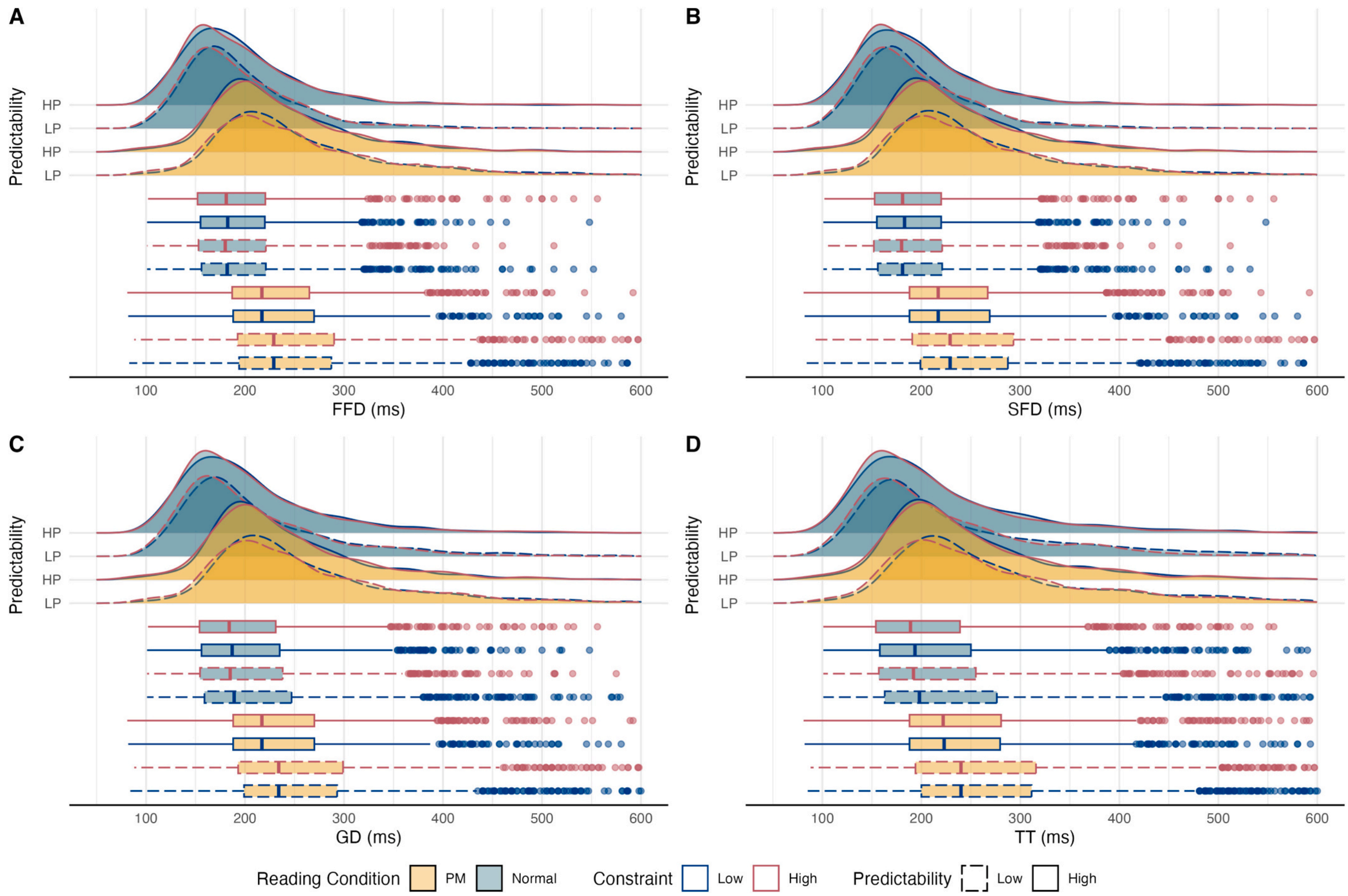


Fig. 5. Raw distributions of fixation durations by experimental design and reading condition.
Note: Top-left (A) shows FFD (first fixation duration); top-right (B) shows SFD (single fixation duration); bottom-left (C) shows GD (gaze duration); bottom-right (D) shows TT (total fixation time). Word-initial trigram constraint is categorised by line colour, with soft rose = high constraint (HC), and dark blue = low constraint (LC). Contextual predictability is categorised by line type, with solid lines = high predictability (HP), and dashed lines = low predictability (LP). Reading condition is denoted by fill colour, with teal = normal reading, and goldenrod = parafoveal magnification (PM).

Table 5
BMM results by fixed effects and fixation measures for the combined dataset of normal and PM reading conditions.

Factor / Measure	*b(mu)*	*CrI$_{2.5}$*	*CrI$_{97.5}$*	*BF$_{10}$*	*b(beta)*	*CrI$_{2.5}$*	*CrI$_{97.5}$*	*BF$_{10}$*
Intercept								
FFD	216.40	210.29	222.61		3.93	3.84	4.02	
SFD	217.45	211.23	223.62		3.94	3.85	4.02	
GD	225.37	218.36	232.67		4.13	4.04	4.22	
TT	240.68	232.91	248.64		4.41	4.33	4.48	
Constraint								
FFD	*−2.90*	*−5.35*	*−0.51*	*1.98*	0.03	−0.03	0.08	0.17
SFD	*−2.81*	*−5.23*	*−0.38*	*1.47*	0.02	−0.03	0.08	0.17
GD	**−4.37**	**−6.99**	**−1.81**	**12.97**	−0.01	−0.05	0.04	0.07
TT	**−8.55**	**−11.77**	**−5.36**	**>1000**	*−0.06*	*−0.10*	*−0.01*	*1.24*
Predictability								
FFD	**−9.82**	**−12.76**	**−6.89**	**>1000**	**−0.15**	**−0.22**	**−0.09**	**>1000**
SFD	**−9.92**	**−12.99**	**−6.92**	**>1000**	**−0.15**	**−0.21**	**−0.09**	**>1000**
GD	**−14.40**	**−17.87**	**−11.02**	**>1000**	**−0.22**	**−0.27**	**−0.16**	**>1000**
TT	**−21.73**	**−25.66**	**−18.02**	**>1000**	**−0.26**	**−0.31**	**−0.21**	**>1000**
Reading Condition								
FFD	**34.91**	**23.79**	**45.56**	**>1000**	**0.37**	**0.21**	**0.54**	**>1000**
SFD	**34.31**	**23.09**	**45.31**	**>1000**	**0.37**	**0.20**	**0.53**	**684.58**
GD	**34.68**	**21.73**	**47.35**	**>1000**	*0.20*	*0.02*	*0.37*	*2.44*
TT	**30.46**	**16.27**	**44.51**	**>1000**	0.11	−0.04	0.26	0.58

(continued on next page)

Table 5 (*continued*)

Factor Measure	*b(mu)*	*$CrI_{2.5}$*	*$CrI_{97.5}$*	*BF_{10}*	*b(beta)*	*$CrI_{2.5}$*	*$CrI_{97.5}$*	*BF_{10}*
Constraint × Predictability								
FFD	−1.82	−6.66	2.99	0.32	−0.03	−0.15	0.08	0.30
SFD	−1.59	−6.53	3.37	0.31	−0.02	−0.14	0.09	0.27
GD	−0.63	−5.88	4.60	0.19	−0.02	−0.12	0.08	0.16
TT	0.29	−5.75	6.33	0.21	0.01	−0.09	0.10	0.14
Constraint × Reading Condition								
FFD	0.37	−4.29	5.10	0.25	0.06	−0.04	0.17	0.48
SFD	0.52	−4.39	5.35	0.26	0.09	−0.02	0.20	0.87
GD	2.79	−2.48	8.09	0.31	*0.12*	*0.02*	*0.22*	*2.76*
TT	5.23	−1.11	11.53	0.76	**0.12**	**0.03**	**0.21**	**4.79**
Predictability × Reading Condition								
FFD	**−9.81**	**−15.25**	**−4.50**	**81.11**	*−0.13*	*−0.25*	*−0.01*	*2.79*
SFD	**−10.56**	**−15.97**	**−5.08**	**306.49**	−0.11	−0.24	0.01	1.30
GD	**−7.93**	**−14.12**	**−1.79**	**4.87**	−0.04	−0.15	0.07	0.20
TT	*−7.29*	*−14.44*	*−0.28*	*1.83*	−0.03	−0.13	0.07	0.18
Constraint × Predictability × Reading Condition								
FFD	−5.54	−13.61	2.66	0.99	**−0.24**	**−0.44**	**−0.03**	**5.81**
SFD	−5.51	−14.05	3.03	0.99	**−0.24**	**−0.46**	**−0.02**	**4.70**
GD	−6.80	−16.44	2.86	0.88	−0.20	−0.40	0.01	1.87
TT	−5.31	−16.06	5.83	0.57	−0.12	−0.30	0.06	0.63

Note: FFD = first fixation duration; SFD = single fixation duration; GD = gaze duration; TT = total fixation time. Effects with Credible Intervals (CrIs) not including zero and a BF_{10} of more than 3 are highlighted in **bold**. Effects with credible intervals not including zero or a BF_{10} of more than 3, but not both, are *italicised*.

[36, 47] ms vs. $Beta_{\text{HP\_noPM\_LC\_FFD,SFD}}$ = **40** [34, 46], **40** [35, 46] ms; $\Delta Beta_{\text{HP\_noPM\_HC-LC\_FFD,SFD}}$ = **1** [−3, 6], **1** [−4, 6]). However, for LP targets, PM substantially altered the skew of the Constraint effects. Fixation times were less skewed for LC targets over HC targets under PM ($Beta_{\text{LP\_PM\_LC\_FFD,SFD}}$ = **64** [56, 73], **64** [55, 72] vs. $Beta_{\text{LP\_PM\_HC\_FFD,SFD}}$ = **73** [64, 83], **73** [64, 83]; $\Delta Beta_{\text{LP\_PM\_LC-HC\_FFD,SFD}}$ = **−9** [−16, −2], **−10** [−17, −3]). In contrast, under normal reading, Constraint did not influence the skew of fixation times, ($Beta_{\text{LP\_noPM\_LC\_FFD,SFD}}$ = **45** [39, 51], **46** [40, 53] vs. $Beta_{\text{LP\_noPM\_HC\_FFD,SFD}}$ = **43** [37, 49], **43** [37, 50]; $\Delta Beta_{\text{LP\_noPM\_LC-HC\_FFD,SFD}}$ = **2** [−3, 7], **3** [−2, 9]). There was no evidence of this three-way interaction on the *mu* of fixation measures, BF_{10}s < 1.

To give a complete picture of the interactive effects of Constraint, Predictability and Reading Condition on fixation times, the marginal means and their 95 % CrIs at different levels of these factors are visualised in Fig. 6.

3.5.5. Prior width check

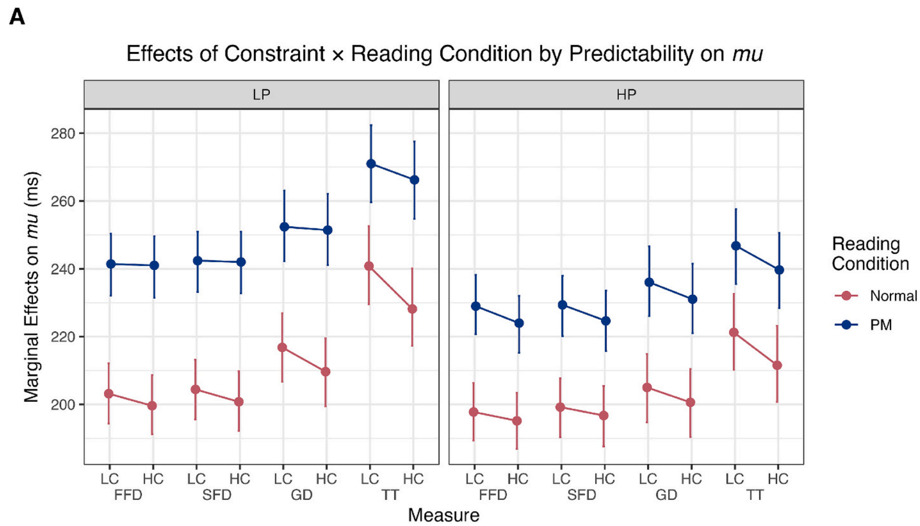
To illustrate how prior width affects BF_{10} values, we conducted a prior width check for the most critical three-way interactions (Constraint × Predictability × Reading Condition) on FFD and SFD *beta* parameters. We varied the prior's scaling factor (SD) on the log scale from 0.09 to 0.39, with our original analysis using 0.24. We refitted the BMMs using the new prior widths and calculated the BFs for the three-way interactions corresponding to each prior width. The results are reported in Table 6.

These results demonstrate the robustness of our findings across different prior widths. The most realistic prior widths likely fall between 0.19 and 0.29, corresponding to effect sizes of approximately 10–17 ms, which align well with typical effects in eye tracking research (Staub et al., 2010). While we also tested more extreme widths of 0.09 and 0.39, the BFs consistently remained above 3, except for the 0.09 width in SFD (BF_{10} = 2.80). Notably, the BF values are higher around the empirically plausible prior widths and decrease as the widths deviate towards either extreme, suggesting stronger evidence when prior specifications better align with established empirical effects. This pattern reinforces our original choice of prior width as appropriate for this type of effect, while demonstrating that our conclusions remain stable across a broad range of prior specifications.

3.6. Discussion

Overall, fixation times were substantially longer in PM than in the normal reading condition across all measures and more skewed under PM in early fixation measures. This difference can be partly attributed to different strategies employed under PM. Using a simple linear mixed model, we found that target sentences resulted in significantly fewer fixations during PM ($M = 6.3$, $CI_{95\%} = [5.8, 6.9]$) compared to normal reading conditions ($M = 8.1$, $CI_{95\%} = [7.5, 8.7]$), $b_{\text{PM-normal}} = -1.8$, $t = -4.5$, $p < .001$). It is possible that longer fixation times in PM are a result of spending more time on each fixation due to the increased availability of parafoveal information. Moreover, PM may enhance the influence of information from both sides of the foveal fixation. While it aids in processing upcoming text on the right, it also introduces unnecessary distractions from the left parafovea, resulting in longer and more skewed fixation times, particularly in early fixation measures capturing parafoveal processing. Lastly, the spatial location of letters in PM is in constant flux, as their sizes are adjusted with each new fixation. This ever-changing positioning relative to the current fixation point complicates saccadic remapping and may contribute to the overall increase in fixation times.

There was strong evidence for a main effect of word-initial trigram Constraint (HC advantage) in the 'late' measures of GD and TT, affecting only the *mu* but not *beta* of the fixation distributions. The observed HC advantage is compatible with findings in Hand et al. (2012), suggesting that highly constraining trigram information facilitates lexical selection. However, the current results did not replicate the Constraint effects in the 'early' measures of FFD and SFD. Because the observed Constraint effects on the *mu* of GD and TT did not interact with Reading Condition, this suggests that this HC advantage primarily reflects lexical selection during the later stages of foveal target processing. Moreover, the Constraint effects on the *beta* parameter of TT were moderately modulated by Reading Condition, with suggestive trends for similar effects in



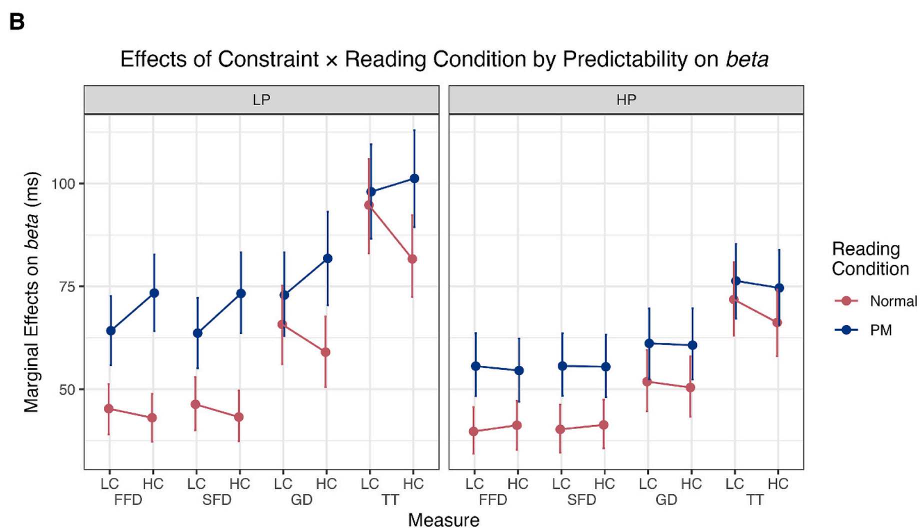


Fig. 6. Marginal means of (A) *mu* and (B) *beta* of fixation measures at high (Mean + *SD*) and low (Mean – *SD*) levels of Constraint, Predictability, and Reading Condition.
Note: LC = low constraint; HC = high constraint; LP = low predictability; HP = high predictability; FFD = first fixation duration; SFD = single fixation duration; GD = gaze duration; TT = total fixation time; Normal = normal reading condition; PM = parafoveal magnification reading condition. Error bars indicate the 95 % Credible Intervals (CrIs).

Table 6
Bayes Factors for the Constraint × Predictability × Reading Condition interactions on the *beta* of FFD and SFD across various prior widths.

Beta prior width (SD)	Decreasing Effect Size (ms)	Increasing Effect Size (ms)	BF_{10} (FFD)	BF_{10} (SFD)
0.09	−5.0	+5.4	3.29	2.80
0.19	−9.6	+11.4	6.19	4.16
0.24 (original)	−11.6	+14.4	5.81	4.70
0.29	−13.5	+17.4	5.23	4.84
0.39	−16.8	+23.4	4.65	3.67

Note: Decreasing and Increasing Effect Size (ms) measures indicate the decreases and increases in ms from a baseline skew of 60 ms (Staub, 2011), respectively, corresponding to the prior widths on the log scale. FFD = first fixation duration; SFD = single fixation duration.

GD. HC targets showed reduced distributional skewness compared to LC targets under the normal reading condition but this HC advantage appears masked under PM, likely due to the competing LC advantages enhanced by magnified preview from early stages of word recognition.

The main effect of Predictability (HP < LP) was observed only in the 'late' measures of GD and TT in normal reading (Experiment 1), but was evident across all fixation measures in PM reading (Experiment 2) as well as in the combined dataset (Experiments 1 and 2), affecting both *mu* and *beta*. However, the Predictability × Reading Condition interaction was strongly evident only in early fixation measures, indicating that enhanced parafoveal preview facilitates HP target processing more effectively compared to normal preview. Importantly, this PM-induced facilitation was consistent across all fixation trials, influencing the *mu* but not the *beta* of the fixation distributions. This aligns with previous research showing that predictability primarily affected the *mu* of early fixations (Staub, 2011), and further underscores its relevance for parafoveal processing across all fixations. The effects of predictability not accounted for by the Predictability × Reading Condition interactions likely reflect influences on foveal processing. These effects could also be partially attributed to differences in text presentation between the two reading conditions: in normal reading, context and target sentences were presented together, whereas in PM reading, they were presented sequentially due to the manipulation of PM selectively on target sentences.

There was moderate evidence for Constraint × Predictability interactions on the *beta* of early fixation measures in Experiment 2, which were modulated by Reading Condition in the combined dataset. This three-way interaction was robust across a broad range of prior widths (see **Supplemental Materials**). While Constraint had no impact on HP words, its impact on LP words differed substantially depending on the preview condition – PM shortened the distribution tail more substantially for LC words over HC words, whereas normal preview did not influence the skew of fixation times. This three-way interaction supports the LC advantage reported by Lima and Inhoff (1985), and further clarifies that Constraint does indeed influence parafoveal processing, especially when trigram information is enlarged in preview by PM. However, this effect is context-dependent and adaptive, selectively compensating for the absence of other informational cues in LP words that are more challenging to process, resulting in slower fixation times. A closer inspection of these LP words at the tail 15 % of the distributions (against the head 15 %) revealed that these challenging words are characterised by lower frequency and familiarity, lower arousal and dominance, smaller semantic size, later age of acquisition, and also relatively lower Cloze values; imageability and valence were the only two properties with less noticeable differences between the two ends of the distribution (Fig. 7).

This LC advantage on these more difficult LP words (characterised by slower processing times) primarily reflects perceptual processes during preview; in instances where words are harder to identify, LC trigrams – commonly shared among large trigram neighbourhoods – are identified more easily during preview than HC trigrams, thereby facilitating subsequent processing of target words.

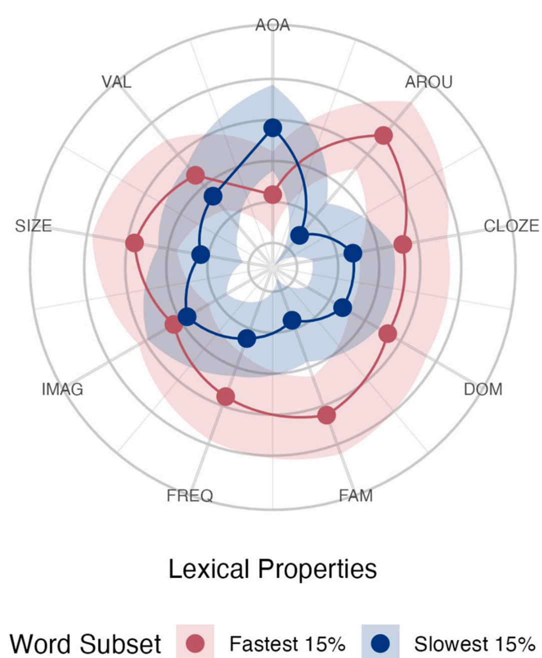


Fig. 7. Comparison of Lexical Characteristics between 'Easy' and 'Challenging' LP Words across the FFD Distribution under PM.
Note: Normalised values are shown to illustrate the relative differences between the 'easy' and 'challenging' words. Moving towards the centre, from the outermost ring labelled with lexical properties, each consecutive ring represents z-scored normalised levels as follows: 0.2, 0.1, 0, −0.1, and −0.2. Dots represent the mean values for each property, and the shading indicates the 95 % confidence intervals. AOA = age of acquisition. AROU = arousal. CLOZE = Cloze value. DOM = dominance. FAM = familiarity. FREQ = frequency per million. IMAG = imageability. SIZE = semantic size. VAL = valence. All word-level attributes (except for frequency and Cloze values) are taken from Scott et al. (2019).

4. General discussion

The present experiments explored the interplay between word-initial trigram constraint and contextual predictability in fluent reading, employing both a normal reading paradigm and a parafoveal magnification (PM) paradigm (Miellet et al., 2009). Our findings reveal that higher predictability facilitates target word processing across both reading conditions, with these effects be more pronounced under PM. Furthermore, we found that high constraint facilitates all target words in late fixation measures. In contrast, low constraint selectively facilitates the processing of challenging words in lower predictable contexts with PM preview in early fixation measures.

Our results reconcile the divergent effects of trigram constraint reported by Lima and Inhoff (1985) and Hand et al. (2012), elucidating how trigram constraint influences both parafoveal and foveal processing, contingent on the temporal loci of the effect, preview conditions, and contextual factors. Specifically, our findings indicate that low trigram constraint enhances *perceptual* identification during parafoveal preview, while high trigram constraint facilitates lexical candidate selection during foveal processing. This differential impact is underscored by the observation that the LC advantage was evident in early fixation measures and modulated by PM. Conversely, the HC advantage was prominent in late fixation measures and unaffected by PM. Furthermore, the effects of Constraint differ substantially across the distributions of fixations. The LC advantage is context-dependent and adaptive, selectively benefiting the processing of unpredicted and challenging words with lower pre-lexical activation. In contrast, the HC advantage is consistent across all words.

However, it is important to note that our interpretations of the three-way interactions, although consistent with previous literature, are *post hoc* in nature. Based on the mixed findings of Lima and Inhoff (1985) and Hand et al. (2012), we could not have anticipated that Constraint would have differential impacts on the perceptual identification of parafoveal trigrams and the lexical selection of foveal words, affecting different distributional parameters. Initially, we aimed to determine which of the previous studies was correct and whether PM could clarify the parafoveal nature of trigram constraint effects. Adopting a Bayesian analysis approach with priors that accommodate possible effects in either direction allowed us to test hypotheses flexibly and use Bayes Factors to quantify our confidence in the inferences. Given the strong and moderate evidence assigned to the main effects of Constraint and its interactions with Predictability and PM, respectively, our current observations provide a robust foundation for further confirmatory tests of the proposed mechanisms of word-initial constraint.

The differential effects of trigram constraint observed in this dataset reveal three key insights. First, the contribution of trigram information to parafoveal processing depends on the quality of the preview, and that enhanced preview boosts pre-lexical visual processing but does not extend to the orthographic processing of trigrams until foveal fixation. This is evident from the absence of constraint effects in early measures in Experiment 1 under normal preview conditions. When the preview is enhanced in Experiment 2, perceptual identification of trigrams improves, leading to a LC advantage. This LC advantage is underpinned by the commonality of trigrams in the language rather than their distinctiveness to constrain lexical selection within their trigram neighbourhoods. We can thus infer that PM can only improve pre-lexical visual processing of trigrams, and it is only upon foveal fixation, where trigrams are orthographically processed, that an HC advantage emerges, facilitating lexical selection.

The second key insight reveals how different aspects of trigram information dynamically contribute to word recognition. Under PM, there was moderate evidence for an LC advantage affecting the skew of LP words in early measures (FFD, SFD) but not in later measures (GD, TT). Similarly, the HC advantage affecting the skew was reduced in late measures (GD, TT) under PM, while showing no effects in early measures (FFD, SFD). These temporal patterns reflect the distinct roles of trigram constraint at different processing stages. During early prelexical processing, LC trigrams provide a perceptual advantage due to their familiarity, particularly when enhanced by PM. However, during later lexical processing, HC trigrams facilitate word recognition by constraining lexical candidates. The interaction of these effects manifests differently across reading conditions. Under PM, strong early LC advantages are subsequently counteracted by emerging HC advantages, resulting in attenuated constraint effects in later measures. In contrast, under normal reading, weak early LC advantages allow HC advantages to dominate more strongly in later measures. This temporal pattern has important theoretical implications for models of reading, demonstrating that word recognition involves distinct processing stages with different informational demands - perceptual familiarity dominates early processing while lexical constraint becomes crucial later. The evidence that different information types can compete and counteract each other indicates that reading models must consider the temporal dynamics of information processing, especially how various information sources interact *across* different processing stages.

The third, broader insight situates these findings within a theoretical framework of reading as an active inference process (Parr et al., 2019; Parr & Friston, 2018), where the brain dynamically integrates a multitude of available information to reduce uncertainty and make sense of what it perceives. Within this framework, different factors that influence the reading process are likely to exert their effects adaptively, rather than uniformly. Their impact depends on the timing of their occurrence, the current level of uncertainty about the target, and the additional benefits they provide at that moment. As demonstrated in our study, the effects of trigram constraint are variable, manifesting in different directions as they serve to minimise overall uncertainty, aligning with the dynamic interplay of perceptual and lexical information over time.

The current dataset also demonstrates the utility and potential of the PM paradigm (Miellet et al., 2009) in studying parafoveal processing in reading. Traditional paradigms, such as the “moving window” and “boundary” paradigms, often manipulate preview in an ‘right-or-wrong’ fashion (McConkie & Rayner, 1975; Rayner, 1975). Although there is considerable evidence for parafoveal preview benefits from valid (vs. invalid) preview conditions (Balota & Rayner, 1990; Schotter et al., 2012), it remains debatable whether the observed ‘benefits’ reflect genuine benefits of valid previews or could instead be attributed to disrupted reading following invalid previews. Moreover, reading static, conventionally presented text restricts how much visual information can be physically processed in the parafovea; as such, the upper limits of parafoveal processing remain unexplored, which may reveal the extent to which parafoveal processing is driven by perceptual information or attention. In comparison, PM does not block or reduce parafoveal preview and does not disrupt the integration of information between pretarget and target fixations. Instead, it alters the degree of perceptual information in the parafovea (cf. Gagl et al., 2014), which enables researchers to not only examine how parafoveal processing changes as a function of the degree of parafoveal information, but to also test the consequences of increasing parafoveal processing beyond the ‘normal’ level.

However, it is important to consider that PM increases the salience of text changes in the parafovea, potentially affecting the reader’s awareness and processing strategies. There is some evidence that increased awareness of parafoveal display changes may modulate the degree and patterns of the preview effects. For example, using the boundary paradigm, Slattery et al. (2011) showed that increased awareness of (delayed) display changes was associated with increased degree of preview. The effects of increased awareness were restricted to an early, orthography-based, preattentional stage as it did not modulate preview benefits on the target and was not influenced by pre-boundary word frequency (Angele et al., 2016). This early locus of awareness effects was reinforced by Vasilev et al. (2018), who demonstrated that perceptual degradation of parafoveal previews (cf. Gagl et al., 2014) renders participants unable to detect changes to orthographic information, as reflected by a lack of parafoveal-on-foveal effects and greater display change awareness independent of preview validity.

The present results, however, cannot be solely explained by increased awareness in display changes. First, the Constraint effects were not directly modulated by Reading Condition, indicating that PM did not significantly alter the *degree* of orthographic processing, at least not in terms of a word’s dominance within its trigram neighbourhood. Second, the interactions between Constraint, Predictability and Reading Condition were observed only in challenging words, not universally across all words. These selective benefits of low trigram constraint are more convincingly explained by enhanced pre-lexical visual processing of the trigram to reduce uncertainty, rather than a general increase in awareness that would affect all fixations equally.

While our results significantly contribute to the discourse on parafoveal processing, they also raise new questions regarding the precise impacts of PM in parafoveal processing. Our findings contribute to the ongoing debate about how attention is distributed across the parafovea under different reading conditions. PM could alter the way attention is allocated across the fovea and parafovea compared to normal reading conditions, where attention is drawn more to perceptually salient orthographic cues. It could also change the timing of how visuo-orthographic cues are previewed, without necessarily altering attention allocation strategies. These distinctions open new avenues for investigation, which may provide more insights into the dynamic mechanisms of the reading process.

In conclusion, our findings shed new light on the depth of parafoveal processing in sentence reading. We demonstrate that the degree of parafoveal preview can significantly alter the perceptual identification of word-initial trigrams, interacting with contextual factors to shape a graded pre-lexical activation. We also confirmed that word-initial trigrams inform the lexical selection process only during foveal fixations, regardless of preview condition. These findings highlight the potential of the PM paradigm in advancing our understanding of the scope and limits of parafoveal processing, opening new possibilities for exploring how PM influences the complex interplay of orthographic, lexical, and semantic processes in reading.

CRediT authorship contribution statement

Bo Yao: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Formal analysis, Data curation. **Christopher J. Hand:** Writing – review & editing, Resources, Methodology, Data curation, Conceptualization. **Sébastien Miellet:** Writing – review & editing, Software. **Sara C. Sereno:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Acknowledgements

This research was supported in part by Economic and Social Research Council Grant RES-000-22-1907 to S.C. Sereno, S. Miellet, and P.J. O’Donnell, and by Economic and Social Research Council Grant ES/N002784/1 and Bial Foundation grant (068/2022) to B. Yao. We thank the two anonymous reviewers’ constructive feedback and guidance, which has significantly improved this paper.

Appendix A. Appendix

A.1. Experimental materials

Materials in the high predictability (HP) condition are shown below (sentences were presented on separate lines in the experiments). Each item has two sentences: the first provides a predictable context, and the second contains the target word (underlined). In the low predictability (LP) condition, the second sentence is presented alone. Materials with low constraint (LC) word-initial trigram targets are presented first, followed by materials with frequency-matched high constraint (HC) targets. While organised categorically, our statistical analyses used continuous predictors of Constraint (frequency percentage of a given target within its 5-letter word-initial trigram neighbourhood) and Predictability (a target's Cloze value).

LC materials

1. Flo couldn't eat the sticky toffee because of her dentures.
   It was far too chewy and often got stuck to his false teeth.
2. The child couldn't sleep after watching the monster movie.
   It had been really scary and she was afraid to be alone.
3. Sandy suffered from the symptoms of Parkinson's Disease.
   His hands were very shaky and his family was worried.
4. Dee wanted to make a curry that was spicy and exciting.
   Sadly, her guests felt it was too bland and ate little.
5. Gavin placed the expensive necklace around his wife's neck.
   It was a string of pearl beads and she adored him for it.
6. There were fingerprints all over the handrail at the bar.
   They took away the shine from the brass and looked grubby.
7. The adventurous couple signed up for Latin dance lessons.
   They thought that the salsa class would be the most fun.
8. Rory was going to dig all day in the potato fields.
   He picked up his spade and headed off to work.
9. Pierre had entertained kids at the circus for fifty years.
   He had enjoyed being a clown but it was time to retire.
10. The Big Ranch restaurant's specialty was high quality beef.
    Bill ordered their biggest steak and a pitcher of beer.
11. In music class, Ricky discovered that he had natural rhythm.
    His teacher sat him at the drums and told him to play away.
12. Emily had never seen such an enormous bowl of ice cream.
    She excitedly grabbed a spoon and began to stuff herself.
13. The shopkeeper suspiciously eyed the girl in the hooded top.
    He knew she was a thief and hoped to catch her red-handed.
14. The teacher scrawled sentences onto the blackboard.
    The noise of the chalk sent shivers up everyone's spine.
15. Tania first prepared the tomatoes, cucumber and lettuce.
    She finished making the salad with oil and vinegar dressing.
16. The letter Lucas had posted was returned to him.
    He had forgotten to put a stamp on it before posting it.
17. Lisa really wanted a fish supper on her way home.
    She asked for the chips to be covered with salt and vinegar.
18. The vicious girl slapped Maria hard on the side of her face.
    Maria felt her cheek redden and started to cry.
19. At the cemetery, the mourners lifted the heavy coffin.
    They carefully lowered it into the grave and said a prayer.
20. Zoe had a bad habit of forgetting to check food in the oven.
    Most of the time, she burnt her meal and had to start over.
21. Brad and Phoebe bought a large box of popcorn at the movies.
    However, it tasted too salty so they didn't each much of it.
22. Leon was unhappy with the tough bread he got with his soup.
    He complained that it was stale and the waitress apologised.
23. Jill's friends were drinking red wine all night in her flat.
    In the morning, she noticed an enormous stain on the carpet.
24. Robert was polishing his shoes before his big job interview.
    He wanted them to be shiny enough to see his face in them.
25. The sun's heat can be used as a renewable source of energy.
    People can attach solar panels to their homes for power.
26. The amateur cyclists were struggling to ascend the hill.
    They found it too steep so they dismounted and walked up it.
27. Maude added two brown sugars to her cappuccino.
    She put her spoon through the froth and stirred them in.
28. The window cleaner always carried a supply of hot tea.
    He kept it in a flask that he filled up every morning.
29. Sidney had tried a new shampoo for his terrible dandruff.
    He massaged it into his scalp before rinsing it out well.
30. Eve's cat had begun to scratch her new furniture.
    She would need to get his claws cut to prevent more damage.
31. Gale force winds had ripped the slates from the tenements.
    They needed their roofs repaired and it would be costly.
32. Ray lived for six months with groups of pygmies in Africa.
    He studied each tribe and learned about their customs.
33. Albert thought he looked good with his new facial hair.
    His friends disagreed and thought his beard looked awful.
34. The beautiful girl saw beyond the monster's appearance.
    She knew that the beast had a good heart and fell in love.
35. The pregnant girl's family had a history of multiple births.
    The nurse told her she had twins when she went for her scan.
36. Lorna had gone on a five-mile run in the midday sun.
    You could see the sweat running down her face by the end.
37. There had been a plentiful harvest for barley growers.
    They had record levels of crops to sell this year.
38. It was a lovely summer's day until the sun went away.
    It disappeared behind a cloud and it became colder.
39. Luke's first job was working at the supermarket.
    His responsibility was to stack the shelves.
40. When Geoffrey got a nosebleed, Dawn nearly keeled over.
    We thought she was going to faint at the sight of his blood.
41. Melanie and Danielle shared the eighty jelly beans evenly.
    Each girl received forty sweets and ate them greedily.
42. The joiner hadn't smoothed the edges of the cabinets yet.
    They were still quite rough and not ready to be varnished.
43. Nigel was struggling to cut the turkey with a blunt knife.
    He asked his wife for a sharp one and he continued to carve.
44. The burglar wore soft shoes to avoid being heard.
    He was always very quiet and had never been caught.
45. The army designed new camouflage to be used in forests.
    It was mostly dark green but had patches of brown and black.
46. Frank had narrowly missed out on last year's bronze medal.
    This year, he hoped to come in at least third in the race.
47. The weather forecast predicted torrential rain and thunder.
    The streets were empty until the storm had cleared.
48. The gang leader had been gunned down as he left his house.
    It was done by members of a rival gang in a revenge attack.
49. During the War, German submarines targeted supply convoys.
    They would attack the ships that carried weapons and food.
50. The shepherd had spotted a wolf prowling around his fields.
    He kept a close eye on his sheep to protect the flock.
51. Every morning, Jeff would walk past the baker's shop.
    He enjoyed the smell of bread and frequently bought a loaf.
52. Everyone knew that "EastEnders" was just beginning.
    We recognised the familiar theme tune and sat down to watch.
53. The park-keepers took good care of the lawns.
    They made sure that the grass was cut every day.
54. There had been a terrible crash at the weekend's Grand Prix.
    Oil had leaked onto the track and caused a massive pile-up.
55. The yacht crew were pleased with the favourable strong wind.
    They used it to gain speed and were sure to win the race.
56. I could feel something in my shoe which dug into my heel.
    It was a small stone which had come from the gravel path.
57. George found a marquee to host his son's wedding reception.
    It was ideal for such an event so he hired it immediately.
58. Johnny liked his father to read to him before bedtime.
    There was one particular story he liked about a tiger.
59. David increased his vocabulary by reading lots of books.
    His knowledge of difficult words was far better than others.
60. Marvin had to go to the shops to buy a new ink cartridge.
    At present, he was unable to print any of his colour photos.
61. Maria's only son was graduating today from Oxford.
    As she watched, she felt so proud of his achievements.
62. At the end of season sale, prices were much reduced.
    The clothes were cheap but still of very high quality.

63. Jean was in a hurry when she went to see her father.
She was only paying him a quick visit to see if he was OK.
64. Marcus almost hurt himself badly lifting weights at the gym.
He had picked ones that were too heavy for him to lift.
65. There was a height restriction to get on the rollercoaster.
Some of the kids were too short to go on the ride.
66. During apartheid in South Africa, most races could not vote.
Only people who were white could take part in the elections.
67. Analysts detected a steady upward growth in the market.
It was forecast that this trend would continue for a while.
68. The assistant at the bank spilled ink all down his front.
This left a stain on his shirt and he was angry at himself.
69. Susan was bored in the lecture and time passed slowly.
She kept glancing at the clock and counted down the minutes.
70. Tony wanted to win in this year's maths competition.
He wanted the prize money more than anything else.
71. The pirates located the spot where the treasure was buried.
They opened up the chest and marvelled at the booty inside.
72. Mary's young son gave her a kick as she washed the dishes.
She was so surprised, she dropped a plate and it smashed.
73. Tiger Woods was angry when he was distracted playing a shot.
Apparently, someone in the crowd cheered as he hit the ball.
74. The lawyers were behind schedule in selecting the jurors.
They were hoping to begin the trial as quickly as possible.
75. Stuart did not want to travel to London by bus or plane.
He bought tickets for the train to Waterloo on the internet.
76. Terry went to the new gardening centre.
He bought a rare plant for his garden.
77. The plumber couldn't mend the boiler until next week.
He had to order the parts he needed from a specialist shop.
78. Harry was slightly late for the play in the theatre.
He missed the start but caught up with the plot quickly.
79. Ms. Hart had the flu and needed to have her classes covered.
She would be unable to teach for at least a week.
80. The toddler held onto the furniture to keep himself upright.
On his own, he was unable to stand without falling down.

HC materials

1. Andrea constantly suffered from severe eczema.
Her skin was always itchy and she constantly scratched it.
2. The forecast warned drivers of poor visibility on the roads.
As Will drove home, it became foggy and he could barely see.
3. At the ceilidh, Steven vigorously spun Emma round and round.
This made her very dizzy but she still had a good time.
4. The old professor dressed as a stereotypical academic.
His jacket was tweed and had patches on the elbows.
5. Waste from the nuclear plant had contaminated the land.
The soil was highly toxic and could not be used for decades.
6. The witness did not get a good look at the mugger.
Her description was vague and wasn't very helpful.
7. The Eskimo family prepared their home for a long winter.
They stocked their igloo with enough food to last months.
8. The grey squirrel was foraging at the foot of the oak tree.
He recovered the acorn that he had buried last winter.
9. Peter liked extra cheese and mushrooms as toppings.
He ordered a large pizza with a side of potato wedges.
10. Sebastian's holiday in Cuba had been the trip of a lifetime.
He often enjoyed a cigar in the evening after dinner.
11. Jamie loved basketball but he was very short for his age.
In gym class, he felt like a dwarf next to his classmates.
12. Ryan's friends influenced him to drink at the school disco.
It was because of pressure from his peers that he did it.
13. Poachers still illegally hunt elephants for their tusks.
It is possible to buy ivory items on the black market.
14. Karen had jumped and landed awkwardly while ice skating.
She badly hurt her ankle and would need to have an x-ray.
15. Leanne was thirsty so she ordered a diet coke from the bar.
It came with a slice of lemon and lots of ice and a straw.
16. The new store carried the latest range of denim clothing.
Kate treated herself to expensive jeans for her big date.
17. Maintaining a healthy digestive system requires roughage.
Foods that are high in fibre are recommended by experts.
18. The music teacher hired removal men when he moved house.
He couldn't move his piano on his own as it was too heavy.
19. Tara had taken heaps of photos of her Egyptian holiday.
She would have to begin a new album to keep them together.
20. After breakfast, the toddler had porridge all over his face.
His mother used a cloth and wiped him clean before nursery.
21. The bottle of coke had been opened a few days ago.
Liam drank some, but it was not fizzy and tasted bad.
22. Ali's Gran bought him a jumper that was three sizes too big.
It looked ridiculously baggy when he tried it on.
23. The heavy rain had washed the dirt and soil into the stream.
This made the water muddy and unsafe to drink.
24. I couldn't stop sneezing as I cleaned out the storage room.
Everything was dusty and it got up my nose as I worked.
25. After many washes, Karl's shirt had lost most of its colour.
It was so badly faded that he would need to buy a new one.
26. Fiona always had two cups of strong coffee to wake her up.
This made her feel more alert and ready to take on the day.
27. Betty only needed the egg whites to make her meringue nests.
Later, she used the yolks to make a separate dish.
28. Hounds used for hunting are trained in special kennels.
They are taught to chase foxes out of their burrows.
29. Before the new school year, all the furniture was replaced.
Pupils would have new desks that were free from graffiti.
30. Alison's eyes were watering as she chopped the vegetables.
She added the onion and peppers into the oil in the pan.
31. Heroin addicts often tie a belt tightly around their arms.
This makes it easier to find veins that they inject into.
32. Tina's mother was baking in the kitchen.
She made lots of cakes for the whole family to enjoy.
33. Everyone was excited about going to see big cats at the zoo.
The children wanted to see the lions and tigers most of all.
34. Nadia had been practising her tennis stroke for six hours.
She now had a pain in her elbow and went to get an ice pack.
35. The cause of death was a hammer blow to the head.
The damage to the victim's skull was quite sickening.
36. Maria carried a donor card in case she was in an accident.
Doctors could use any organ in the event of her death.
37. Valerie's neighbour's Alsatian kept coming into her garden.
She got her son to build a fence to keep the dog out.
38. The luxury cruise ship sailed across the Pacific to Hawaii.
The breeze from the ocean kept the passengers cool on deck.
39. Dr. Adams was still drunk when he was due to start work.
He would need to sober up quickly or he would be sacked.
40. The boys got into a fist fight in the playground.
They began to furiously punch each other in the face.
41. It had rained all night and the footpath was very muddy.
Hannah's shoes were dirty and she trailed mud in the house.
42. The farmer worked hard all day in his fields.
He was extremely tired when he came home.
43. Liz and her friends polished off all the food in her flat.
The refrigerator was empty after they left.
44. Matthew's younger sister was born several years after him.
Because he is much older than her, he is very protective.
45. The Queen has never voted in a General Election.
Members of the royal family are not allowed to.
46. Seth could easily carry six plastic chairs at a time.
They were incredibly light and could be stacked together.

47. Craig knew the law about carrying illegal weapons in public. He still carried a knife despite the risk of being caught.
48. New lines were painted on the grass for the football match. On the day of the game, the pitch looked better than ever.
49. The patient had been cared for in the hospital for weeks. He had a favourite nurse who looked after him.
50. Jack's aunt was supposed to pick him up after school. Instead, it was his uncle who was waiting for him.
51. Daphne's computer wasn't letting her open the application. She kept getting error messages and called the support line.
52. The Ministry of Defence discovered a spy in their operation. It was a Russian agent who was relaying details to Moscow.
53. Sarah had saved money to have veneers fitted at the dentist. When they were finished, her teeth looked fabulous.
54. The DVD is now the most common form of movie entertainment. It seems that the video will soon be a thing of the past.
55. Claire's knee was causing her a lot of pain after exercise. The specialist said the joint was inflamed and needed rest.
56. The thugs were arrested and brought to the police station. They put them in the cells overnight as punishment.
57. At the cafe, Rob ordered a cold drink to quench his thirst. He noticed that the glass was cracked and told the waitress.
58. It was a cold day and Barbara had forgotten her gloves. She decided to keep her hands in her pockets for warmth.
59. The cannibals had captured the missionaries in the jungle. They preferred the taste of human flesh over animals.
60. Jennifer tried a cigarette for the first time and loved it. She started to regularly smoke when she went out.
61. Meg was driving and spotted a badly injured hedgehog. She tried to prevent it from dying but it was too late.
62. Special police units rushed to the bank robbery in progress. The men inside were armed and had taken customers hostage.
63. Many people are opting to leave cities for a quieter life. They move to more rural areas and commute to work instead.
64. The couple finally got pregnant after trying for months. They were extremely happy when they eventually succeeded.
65. The secretary sliced the tip of her finger on the letter. She hated getting these paper cuts and swore loudly.
66. Derek asked for a bacon double cheeseburger at Burger King. He also ordered an extra large drink to wash it all down.
67. Sheena had to shop for many things in many different stores. She made up several lists so that she remembered everything.
68. In cities, there are often special bus and taxi lanes. Sometimes there are also cycle lanes to ease traffic.
69. Henry had been injured in a scrum at school. He was unable to play rugby for several weeks.
70. Ted was diabetic and had to monitor what he ate. If he ate too much sugar he could become unwell.
71. The paperback writer had completed his latest and best work. He hurriedly sent a copy of his new novel to the publishers.
72. Mark's car was damaged by the side-on crash at the junction. He would need two new doors before his car was roadworthy.
73. There had been much controversy surrounding the new movie. A warning was issued because of the adult content involved.
74. Dave and Gordon were going to watch the boxing match. Afterwards, they agreed that the fight was very exciting.
75. Dan was traumatised by seeing the mutilated body as a child. He could never get rid of the image from his mind's eye.
76. At school, Miss Jones told only the boys to leave early. She wanted to talk to the girls about the incident.
77. Keith liked to listen to Mozart, the Beatles, and techno. He liked all kinds of music with no particular preference.
78. The young couple were shopping for new kitchen furniture. They selected a table that was exactly what they wanted.
79. The Sultan kept his gold bullion hidden in his palace. There was always someone there to guard it around the clock.
80. The painters were told not to damage any of the furniture. Before they began, they had to cover everything with sheets.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2025.106149.

Data availability

The data and analysis codes are freely available at: https://osf.io/dw5nz/.

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