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Hand, C.J., O'Donnell, P.J., and Sereno, S.C. (2012) *Word-initial letters influence fixation durations during fluent reading*. *Frontiers in Psychology*, 3 (85). pp. 1-19. ISSN 1664-1078

<http://eprints.gla.ac.uk/69853/>

Deposited on: 4th October 2012



# Word-initial letters influence fixation durations during fluent reading

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The present study examined how word-initial letters influence lexical access during reading. Eye movements were monitored as participants read sentences containing target words. Three factors were independently manipulated. First, target words had either high or low constraining word-initial letter sequences (e.g., *dwarf* or *clown*, respectively). Second, targets were either high or low in frequency of occurrence (e.g., *train* or *stain*, respectively). Third, targets were embedded in either biasing or neutral contexts (i.e., targets were high or low in their predictability). This 2 (constraint) × 2 (frequency) × 2 (context) design allowed us to examine the conditions under which a word's initial letter sequence could facilitate processing. Analyses of fixation duration data revealed significant main effects of constraint, frequency, and context. Moreover, in measures taken to reflect "early" lexical processing (i.e., first and single fixation duration), there was a significant interaction between constraint and context. The overall pattern of findings suggests lexical access is facilitated by highly constraining word-initial letters. Results are discussed in comparison to recent studies of lexical features involved in word recognition during reading.

**Keywords:** reading, eye movements, word-initial letter constraint, word frequency, contextual predictability

## INTRODUCTION

The greatest advancements in understanding fluent reading over the past few decades have come from investigations that measure eye movement behavior (for reviews, see Rayner, 1998, 2009). Such studies have identified several oculomotor, perceptual, and cognitive factors that modulate the reader's decisions of where and when to move the eyes while processing text. For example, words in text which are shorter in length, higher in frequency of occurrence, or more predictable from a prior context are fixated for less time and are skipped more often than words that are longer, lower in frequency, or less predictable. The present study investigates the role of word-initial letters in reading.

One of the key findings of eye movement reading research is that the information available on a single fixation is not limited to the currently fixated (foveal) word. Readers are able to acquire information from the upcoming parafoveal word before its subsequent fixation. The importance of parafoveal vision in reading was substantiated in classic eye movement reading studies using the "moving window" (McConkie and Rayner, 1975) and "boundary" (Rayner, 1975) paradigms. In these paradigms, changes are made in the text contingent on the reader's eye position.

In "moving window" studies, text *outside* a window defined around the fixated letter is altered in some way (e.g., valid text is replaced by strings of Xs). Under such conditions, when parafoveal preview is invalid, reading time is slowed, demonstrating the use of both foveal and parafoveal information during normal reading. The *perceptual span* – the region of text from which useful information can be extracted – has been functionally approximated from "moving window" studies. For English, it is estimated to

extend from three characters to the left of fixation (approximately the beginning of the fixated word) to around 14 characters to the right of fixation (McConkie and Rayner, 1975; Mielliet et al., 2009). Although the span encompasses a significant number of letters to the right of fixation, the level of analysis drops off substantially from the fovea – from recognizing words to identifying letters to merely determining the length of the upcoming parafoveal word(s).

In "boundary" studies, only a single word of the text changes. While reading, participants parafoveally view either a valid or invalid preview in the target location, which then changes to the target when the reader saccades across a pre-specified (invisible) boundary located just before the target word. "Boundary" experiments have varied the visual, phonological, and semantic similarity between the foveated target and its initial parafoveal preview and have generally shown that orthographic and phonological, but not semantic, information is extracted parafoveally (e.g., McConkie and Zola, 1979; Rayner et al., 1980; Balota et al., 1985; Pollatsek et al., 1992). The fixation time advantage on a target word (fixation  $n$ ) when parafoveal information associated with that target (obtained from fixation  $n - 1$ ) is valid vs. invalid is termed *parafoveal preview benefit*. Rayner et al. (1982) found that when the first three letters (i.e., word-initial trigram) of the parafoveal preview were identical to those of the (eventual) target word and when the remaining letters of the preview were replaced by letters that were visually similar to the target, reading rate was only slightly impaired compared to when the preview was completely identical to the target (i.e., the valid preview condition). The implication is that the identification of word-initial letters is fundamental to

obtaining a parafoveal preview benefit (c.f. Inhoff et al., 1989; Inhoff, 1990; Johnson et al., 2007). Given that the first few letters of the parafoveal word are nearest the fovea and that the space before the parafoveal word serves to decrease lateral masking of its beginning letters, such findings are not unexpected.

If the identification of the word-initial trigram facilitates reading, as evidenced by parafoveal preview benefit, the question arises whether the level of lexical constraint conferred by the trigram can affect word identification. Within the auditory word recognition literature, the homologous issue of word beginnings and their role in spoken word identification has been the topic of innumerable studies. Marslen-Wilson and Welsh (1978; see also Marslen-Wilson, 1987) proposed the *cohort* model of spoken word recognition. In this model, the initial acoustic information activates a large number of candidate words (i.e., a cohort) in parallel, but as further evidence accumulates, the activation of words that are no longer compatible with the input decays until a single candidate remains (the point in a spoken word which delivers a single candidate is called the *uniqueness point*). Although the signal is produced and processed in a more continuous and sequential way in the auditory compared to the visual domain, parafoveal preview nevertheless gives emphasis to the initial letters of an upcoming word. Thus, it is reasonable to expect similar activation and selection processes to occur in visual word recognition during fluent reading. High constraint (HC) initial trigrams rarely appear in words whereas low constraint (LC) initial trigrams often do. For example, the HC trigram *dwa-* includes very few words in its cohort (e.g., *dwarf*, *dwarves*, *dwam*); in contrast, the LC trigram *clo-* has many words in its cohort (e.g., *clown*, *close*, *clock*, *cloud*, *cloth*, *cloak*, *clone*, *clout*, *clove*, *clog*, *cloy*, *clothes*, *clover*, *closet*, *cloister*, *clobber*; N.B., this excludes morphologically related suffixed words).

To determine whether such cohort effects operated in the visual domain, Lima and Inhoff (1985; Experiment 1), in an eye movement reading study, tested whether the constraint of a word-initial trigram affected reading behavior. They hypothesized that lexical access would be facilitated when a word's candidate set was limited by its initial letters. Target words were either HC (e.g., *dwarf*) or LC (e.g., *clown*) words of similar length and frequency presented in single-line neutral sentences. Lima and Inhoff additionally varied parafoveal preview across three conditions: one- and two-word moving window conditions (with strings of Xs replacing text outside the window), and a full-line condition (i.e., normal reading). In the one-word condition, readers were prevented from obtaining a valid parafoveal preview of the target; in both the two-word and full-line conditions, a valid parafoveal preview of the target was available. In accordance with prior findings, Lima and Inhoff found a preview benefit whereby targets were read faster with a valid (two-word and full-line conditions) vs. invalid (one-word condition) parafoveal preview. In contrast to their predictions, however, preview benefit did not interact with target constraint. They had expected to find greater preview benefit for HC than LC words. In terms of target fixation time, they did find an effect of constraint. The effect, however, was in the opposite direction of their prediction – HC words were fixated *longer* than LC words. It is important to note that this effect was only significant in the more immediate first fixation duration (FFD) measure (i.e., the duration

of the initial fixation on a target word, regardless of whether that word is refixated); the effect did not reach significance in the relatively delayed gaze duration (GD) measure (i.e., the sum of all consecutive fixations, including the first, before moving to another word). Lima and Inhoff concluded that higher trigram familiarity (LC words) could benefit lexical access by increasing the efficiency of foveal processing.

Although past eye movement research has explored the effects of whole-word orthographic (and phonological) regularity (Inhoff and Topolski, 1994; Sereno and Rayner, 2000), more recent studies have examined the effects of word-initial orthographic regularity on eye movement behavior. In particular, the focus of these studies has been on whether the orthographic regularity of a target word's beginning letters, viewed parafoveally from the prior fixation, can affect the location of the ensuing fixation on the target (i.e., landing position). Evidence for the influence of word-initial orthographic regularity on fixation location (with more regular word beginnings giving rise to more rightward landing positions), however, has been equivocal (for a review, see White and Liversedge, 2004).

White and Liversedge (2004) suggested that prior studies had confounded two variables associated with word-initial orthographic regularity, namely, "orthographic familiarity," and "informativeness." These two variables represent different ways of measuring the frequency of a word's beginning letter sequence. Orthographic familiarity is calculated by summing the frequency of all words (tokens) beginning with that letter sequence, while informativeness is calculated by summing the number of words (types) beginning with that letter sequence. White and Liversedge (2004) conducted two experiments that manipulated these variables by misspelling the beginning letter sequences of words. They found that landing position was closer to the beginning of misspelled words (i.e., nearer the location of the misspelling; e.g., *aoricultural*, *akricultural*, *ngricultural*) compared to correct words (e.g., *agricultural*), even when the misspelling employed a highly frequent word-initial trigram (e.g., *agricultural*). They also found no difference in landing position between correctly spelled words having informative word-initial trigrams (e.g., *escalator*) and misspelled informative (e.g., *eacalator*) or uninformative (e.g., *encalator*) controls. Although these manipulations permit a high degree of control over certain orthographic characteristics of the stimuli, the use of misspelled words, however, limits the generalizability of such results to normal reading.

The purpose of the present experiment was to further investigate the effect of word-initial letter constraint in reading. Like Lima and Inhoff (1985), we compared fixation time on HC (e.g., *dwarf*) and LC (e.g., *clown*) words in text. Unlike Lima and Inhoff (1985), however, we additionally manipulated two key variables known to affect word recognition, namely, word frequency, and contextual predictability. When lexical variables such as word length are controlled, high frequency (HF) words are read faster than low frequency (LF) words, and words preceded by a contextually biasing context are read faster than those in a neutral context (see, e.g., Hand et al., 2010; for reviews, see Rayner, 1998, 2009). In Lima and Inhoff's study, target words were mainly LF words embedded in neutral contexts. Prior research using gaze-contingent display change paradigms, however, has demonstrated

increased parafoveal preview benefit to HF vs. LF words (Inhoff and Rayner, 1986) as well as to contextually predictable vs. less predictable words (Balota et al., 1985). Thus, we implemented a 2 (Constraint: HC, LC)  $\times$  2 (Frequency: HF, LF)  $\times$  2 (Context: Biasing, Neutral) design. Because parafoveal preview benefit is modulated both by frequency and contextual predictability, it is possible that HC words will, in fact, show a processing advantage over LC words when favorable parafoveal preview conditions are present. Accordingly, we expected to find an interaction between Constraint and Frequency and/or Constraint and Context. In line with Lima and Inhoff's (1985) findings, we anticipated *longer* fixations on HC vs. LC words for LF targets in Neutral contexts. However, we predicted *shorter* fixations on HC vs. LC words for HF targets, for targets in Biasing contexts, or, minimally, for HF targets in Biasing contexts.

## MATERIALS AND METHODS

### PARTICIPANTS

Forty-eight members of the University of Glasgow community (30 females; mean age 23) were paid £6 or given course credit for their participation. All were native English speakers with normal or corrected-to-normal vision and had not been diagnosed with any reading disorder.

### APPARATUS

Eye movements were monitored via an SR Research Desktop-Mount EyeLink 2K eyetracker, with a chin/forehead rest. The eyetracker has a spatial resolution of 0.01° and eye position was sampled at 1000 Hz using corneal reflection and pupil tracking. Text (black letters on a white background, using 14-point Bitstream Vera Sans Mono, a non-proportional font) was presented on a Dell P1130 19" flat screen CRT (1024  $\times$  768 resolution; 100 Hz). At a viewing distance of 72 cm, approximately four characters of text subtended 1° of visual angle. Viewing was binocular with eye movements recorded from the right eye.

### DESIGN AND MATERIALS

A 2 (Constraint: HC, LC)  $\times$  2 (Frequency: HF, LF)  $\times$  2 (Context: Biasing, Neutral) design was used. All target words were five letters long. With a total of 88 experimental items, there were 11 items in each of the eight conditions. All experimental items are listed in the Appendix. An example set of materials, showing all eight target conditions, is presented in **Table 1**. Target words were always positioned near the middle of a line of text. Because each participant only read a given target word in one of its Context conditions (Neutral or Biasing), two participant groups were used. One group read half of the materials in Neutral and the other half in Biasing contexts; the second group read the materials in their opposing context conditions. In addition, experimental items were blocked by Context condition, with all Neutral materials presented first followed by all Biasing materials. Within each block, experimental items were presented in a different random order to each participant. Stimulus specifications across conditions are presented in **Table 2**.

### Constraint

Half of the target words had HC and half had LC initial trigrams. We calculated several measures to characterize the constraint of

**Table 1 | Example materials.**

Condition	Example
<b>NEUTRAL CONTEXT</b>	
LF LC	He had enjoyed being a <u>clown</u> but it was time to retire.
HC	In gym class, he felt like a <u>dwarf</u> next to his classmates.
HF LC	He bought tickets for the <u>train</u> to Waterloo on the internet.
HC	She wanted to talk to the <u>girls</u> about the incident.
<b>BIASING CONTEXT</b>	
LF LC	Pierre had entertained kids at the circus for 50 years. He had enjoyed being a <u>clown</u> but it was time to retire.
HC	Jamie loved basketball but he was very short for his age. In gym class, he felt like a <u>dwarf</u> next to his classmates.
HF LC	Stuart did not want to travel to London by bus or plane. He bought tickets for the <u>train</u> to Waterloo on the internet.
HC	At school, Miss Jones told only the boys to leave early. She wanted to talk to the <u>girls</u> about the incident.

Target words are underlined.

LF, low frequency; HF, high frequency; LC, low constraint; HC, high constraint.

the trigram neighborhood for each (five-letter) target. These were performed on both length-invariant (i.e., only five-letter words) and length-variant (i.e., words of any length or  $x$ -letter words) trigram neighborhoods. All measures included the target word. Similar to White and Liversedge (2004), we computed the number of words (type frequency, per million) and the summed frequency of words (token frequency, per million) that shared the initial trigram. We also calculated the percentage that each target represented of its trigram neighborhood, dividing each target word's frequency of occurrence by the summed frequency of all five- or  $x$ -letter words (including the target) that shared a given trigram. Finally, we obtained the rank position of the target within the trigram neighborhood based on its frequency relative to the frequency of its trigram neighbors. To determine these neighborhood profiles for  $x$ -letter words, we used the Brigham Young University on-line resource<sup>1</sup> (Davies, 2004) for the British National Corpus (BNC). Average values for each of these measures across conditions are presented in **Table 2**. Overall, in both five- and  $x$ -letter trigram neighborhoods, HC words, in comparison to LC words, had far fewer neighbors, had much smaller neighborhood frequencies, accounted for a much higher percentage of their neighborhood, and were ranked much closer to the top of their neighborhood.

### Frequency

In addition, half of the targets were HF and half were LF words. Word frequencies were obtained using BNC<sup>2</sup>, a corpus of 90 million written word tokens. Mean frequencies were 88 occurrences per million for HF targets and nine occurrences per million for LF targets (see **Table 2**).

### Predictability

Finally, half of the targets were presented in a Neutral context and half in a Biasing context. As illustrated in **Table 1**, Neutral

<sup>1</sup><http://corpus.byu.edu/bnc>

<sup>2</sup><http://www.natcorp.ox.ac.uk>

**Table 2 | Means (with SDs) of target specifications across experimental conditions.**

Measure	LF		HF	
	LC	HC	LC	HC
<i>N</i>	22	22	22	22
Length	5 (0)	5 (0)	5 (0)	5 (0)
Frequency	8 (5)	10 (6)	86 (69)	90 (84)
<b>NUMBER OF NEIGHBORS</b>				
Five-letter	20 (8)	2 (2)	19 (7)	5 (3)
x-Letter	209 (135)	17 (14)	269 (142)	50 (46)
<b>FREQUENCY OF NEIGHBORHOOD</b>				
Five-letter	429 (470)	11 (7)	1035 (1630)	93 (88)
x-Letter	1615 (1759)	31 (29)	5396 (15867)	358 (281)
<b>% OF NEIGHBORHOOD</b>				
Five-letter	4 (5)	95 (5)	15 (7)	96 (4)
x-Letter	1 (2)	38 (21)	5 (3)	33 (25)
<b>RANK IN NEIGHBORHOOD</b>				
Five-letter	7 (4)	1 (0)	3 (1)	1 (0)
x-Letter	28 (22)	1 (1)	8 (10)	2 (2)
<b>CLOZE</b>				
Neutral	0.03 (0.09)	0.04 (0.07)	0.04 (0.11)	0.03 (0.09)
Biasing	0.64 (0.23)	0.60 (0.19)	0.64 (0.25)	0.60 (0.32)
<b>PREDICTABILITY RATING</b>				
Neutral	3.70 (0.89)	3.43 (1.04)	4.21 (1.19)	3.98 (1.15)
Biasing	5.87 (0.52)	5.76 (0.60)	6.01 (0.40)	5.92 (0.61)

LF, low frequency; HF, high frequency; LC, low constraint; HC, high constraint; *N*, number of items; Length, word length (number of letters); Frequency, frequency of occurrence (per million); Number of Neighbors, number of trigram neighbors for five-letter or x-letter (any length) words; Frequency of Neighborhood, summed frequency (per million) of trigram neighborhood; % of Neighborhood, word frequency percentage that each target represents of its five-letter or x-letter trigram neighborhood; Rank in Neighborhood, rank of target in neighborhood, based on its frequency; Cloze, Cloze value of target, on a scale of 0 (target word not guessed) to 1 (target word correctly guessed); Predictability Rating, predictability rating of target in text, on a scale of 1 (highly unpredictable) to 7 (highly predictable); Neutral, neutral context condition (target sentence only); Biasing, biasing context condition (context plus target sentence).

conditions comprised one single-line sentence. Biasing conditions, however, comprised two single-line sentences: for a given target, the first sentence contained contextually biasing information for that word; the second sentence was the Neutral sentence in which the target was embedded. In this way, biasing information was established in and confined to the first of two sentences. In addition, the identical sentence containing the target could be used across the Neutral and Biasing context conditions (between participant groups).

The level of contextual predictability was determined by two norming tasks – a Cloze probability task and a predictability rating task. For both tasks, the materials were divided into two sets with equal numbers of Neutral and Biasing sentences and were presented to two participant groups to avoid repetition of the target sentence across conditions. In the Cloze task, two groups of 13 participants (none of whom participated in the main experiment

or the predictability rating task) were given each experimental item up to but not including the target word. Their task was to generate the next word in the sentence. Items were scored as “1” for correct responses and “0” for all other guesses. A 2 (Constraint: HC, LC) × 2 (Frequency: HF, LF) × 2 (Context: Biasing, Neutral) analysis of variance (ANOVA) on Cloze probabilities by items ( $F_2$ ) revealed, as expected, a main effect of Context, with more targets generated in Biasing (0.62) than in Neutral (0.04) contexts (see **Table 2**) [ $F_2(1,21) = 991.25$ ,  $MSE = 0.02$ ,  $p < 0.001$ ]. No other main effects or interactions were significant [all  $F_2s < 1$ ].

In the predictability rating task, two groups of 13 participants (again, none of whom participated in the main experiment or Cloze task) were presented with each item in its entirety with the target word underlined. Ten percent of the materials were non-experimental filler items (one- and two-line texts) that were clearly anomalous. The participants’ task was to indicate how predictable they considered the target word to be on a scale of 1 (highly unpredictable) to 7 (highly predictable). A 2 (Constraint: HC, LC) × 2 (Frequency: HF, LF) × 2 (Context: Biasing, Neutral) ANOVA on predictability ratings by items ( $F_2$ ) revealed, as expected, a main effect of Context, with targets rated more predictable in Biasing (5.89) than in Neutral (3.83) contexts (see **Table 2**) [ $F_2(1,21) = 590.73$ ,  $MSE = 0.32$ ,  $p < 0.001$ ]. The relatively high ratings of targets in Neutral contexts reflected the fact that they were designed to be *less* predictable (and not implausible or anomalous) compared to targets in Biasing contexts. The main effect of Frequency, although numerically small, was also significant, with higher ratings for HF (5.03) than for LF (4.69) targets [ $F_2(1,21) = 4.64$ ,  $MSE = 1.08$ ,  $p < 0.001$ ]. Most likely, this reflects the underlying fact that HF words are, by definition, more likely to occur than LF words within any context (see, e.g., Scott et al., 2012). The main effect of Constraint was not significant [ $F_2(1,21) = 2.45$ ,  $MSE = 0.55$ ,  $p = 0.132$ ], nor were any of the interactions [Frequency × Predictability:  $F_2(1,21) = 1.51$ ,  $MSE = 1.04$ ,  $p > 0.20$ ; Constraint × Frequency, Constraint × Predictability, and Constraint × Frequency × Predictability: all  $F_2s < 1$ ].

## PROCEDURE

Participants were given written and verbal instructions about the eyetracking task. They were told to read for comprehension, as they would normally, and that questions would appear after half of the trials to ensure they were paying attention.

The experiment involved the initial calibration of the eyetracking system, reading five practice one-line (Neutral) sentences, recalibration, reading the 44 Neutral experimental sentences, recalibration, reading five practice two-line (Biasing) passages, recalibration, and reading the 44 Biasing experimental passages. The nine-point calibration display comprised a series of calibration points extending over the maximal horizontal and vertical range of the display. After participants fixated each point in a random order, the accuracy of the calibration was checked (validation). The experiment proceeded only when the calibration was highly accurate (average error  $< 0.30^\circ$ ; maximal error on any one point  $< 0.50^\circ$ ). If necessary, participants could be recalibrated at any time during the experiment.

Each trial began with a black square which corresponded to the position of the first letter of the experimental item. An accurately

calibrated fixation at this location triggered the presentation of the item. After reading each item, participants moved their eyes to the lower, right corner of the screen and pressed a button to clear the screen. On half of the trials, a *yes–no* comprehension question followed. Participants had no difficulty in answering these questions (average over 92% correct). Prior to each new trial, participants were required to fixate a central point allowing the experimenter to implement a drift-correction routine.

## RESULTS

The target region comprised the space before the target word and the target itself. Lower and upper cut-off values for individual fixations were 100 and 750 ms, respectively. Data were additionally eliminated if there was a blink or track loss on the target, or if the fixation on the target was either the first or last fixation on a line. Overall, 2% of the data were excluded for these reasons. In reading, most content words are generally fixated once – sometimes words are immediately refixated, sometimes they are skipped altogether. In the present study, the probabilities for target word single fixation, immediate refixation, and skipping were 0.67, 0.07, and 0.24, respectively.

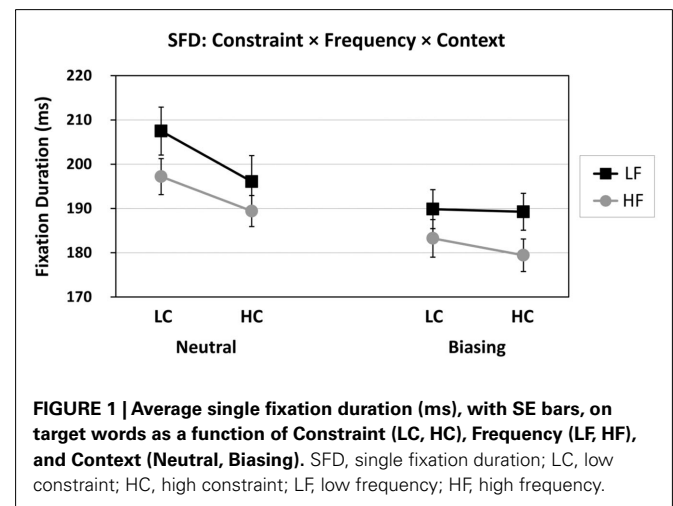
The resulting data were analyzed over a number of standard fixation time measures on the target word: (1) FFD; (2) single fixation duration (SFD; fixation time when the word is only fixated once); (3) GD; and (4) total fixation time (TT; the sum of all fixations, including later regressions made to that word). We also examined several other commonly used measures: (5) the duration of the next forward-going fixation from the target ( $T + 1$ ) as a measure of processing spillover; (6) the duration of the pre-target fixation ( $T - 1$ ; the last fixation before the target) as a measure of parafoveal pre-processing of the target; (7) the probability of making a first-pass fixation on the target (PrF); and (8) the landing position (LandPos) or location of the first fixation on the target. The average values across all measures (with SDs) are presented in **Table 3**.

The different measures can be viewed as a series of snapshots over the temporal course of processing the target – from pre-target, to target, and then to post-target measures. The earliest measures are  $T - 1$ , PrF, and, to some extent, LandPos, which can reflect varying degrees of target pre-processing. These measures should, however, be interpreted with some caution as the pre-target text differed across conditions in our study (N.B. most pre-target words were HF function words). With respect to PrF, although the decision to skip a word occurs on the pre-target fixation, target processing can occur on both pre- and post-target fixations (e.g., Reichle et al., 2003; Kliegl and Engbert, 2005). With respect to LandPos, although it represents fixation location on the target, itself, the saccade target is determined from the pre-target fixation (e.g., McConkie et al., 1988; Rayner et al., 1996). Target measures include FFD, SFD, and GD during which the target is foveated. These measures tend to be highly correlated because the majority of data points contributing to each measure are shared – that is, most FFDs are SFDs, and most GDs are FFDs. As GD includes cases when an additional (consecutive) fixation is made on the target, in this respect, it is not as immediate as FFD or SFD. Finally,  $T + 1$  and TT represent relatively delayed, later stages of target word processing, since these measures comprise fixations

**Table 3 | Means (with SDs) of fixation time measures, fixation probability, and landing position across conditions.**

Measure	Context	LF		HF	
		LC	HC	LC	HC
FFD	Neutral	204 (32)	194 (32)	195 (26)	187 (23)
	Biasing	189 (29)	189 (29)	182 (29)	180 (25)
SFD	Neutral	207 (38)	196 (41)	197 (28)	189 (24)
	Biasing	190 (31)	189 (29)	183 (29)	179 (25)
GD	Neutral	223 (47)	208 (46)	206 (30)	201 (35)
	Biasing	201 (36)	196 (32)	188 (29)	184 (26)
TT	Neutral	261 (64)	234 (75)	233 (43)	223 (47)
	Biasing	212 (42)	204 (31)	207 (35)	196 (32)
$T + 1$	Neutral	216 (33)	201 (34)	207 (35)	202 (32)
	Biasing	199 (27)	198 (28)	199 (30)	191 (27)
$T - 1$	Neutral	202 (31)	191 (31)	193 (28)	191 (25)
	Biasing	191 (27)	190 (27)	188 (24)	181 (20)
PrF	Neutral	0.82 (0.14)	0.79 (0.16)	0.86 (0.14)	0.80 (0.15)
	Biasing	0.71 (0.19)	0.69 (0.19)	0.66 (0.21)	0.67 (0.20)
LandPos	Neutral	2.81 (0.62)	2.64 (0.54)	2.78 (0.59)	2.63 (0.57)
	Biasing	2.82 (0.68)	2.88 (0.63)	2.86 (0.58)	3.02 (0.56)

FFD, first fixation duration; SFD, single fixation duration; GD, gaze duration; TT, total fixation time;  $T + 1$ , next forward-going fixation from target;  $T - 1$ , pre-target fixation duration; PrF, probability of target fixation; LandPos, landing position on target; LF, low frequency; HF, high frequency; LC, low constraint; HC, high constraint.



**FIGURE 1 | Average single fixation duration (ms), with SE bars, on target words as a function of Constraint (LC, HC), Frequency (LF, HF), and Context (Neutral, Biasing).** SFD, single fixation duration; LC, low constraint; HC, high constraint; LF, low frequency; HF, high frequency.

occurring after the initial fixation(s) on the target. Nonetheless, TT tends to be correlated with GD as there is a high degree of data overlap.

As the majority of target word fixations were single fixations, SFD condition means, including SE bars, are displayed in **Figure 1**. For all measures, 2 (Constraint: HC, LC)  $\times$  2 (Frequency: HF, LF)  $\times$  2 (Context: Biasing, Neutral) ANOVAs were conducted both by participants ( $F_1$ ) and by items ( $F_2$ ). A summary of all main effects and interactions across all measures is presented in **Table 4**.

**Table 4 | Main effects and interactions by participants ( $F_1$ ) and by items ( $F_2$ ) on all measures.**

Factor	$F_1$	MSE	$p$	$F_2$	MSE	$p$
<b>CONSTRAINT</b>						
FFD	7.56	357	<0.01	5.31	242	<0.05
SFD	7.38	453	<0.01	4.46	321	<0.05
GD	12.87	411	<0.001	5.25	500	<0.05
TT	15.51	1267	<0.001	15.74	675	<0.001
$T + 1$	20.73	248	<0.001	11.37	211	<0.01
$T - 1$	12.46	240	<0.001	7.86	173	<0.05
PrF	3.98	0.02	=0.052	1.94	0.02	>0.15
LandPos	<1			<1		
<b>FREQUENCY</b>						
FFD	12.75	451	<0.001	11.49	276	<0.01
SFD	12.57	532	<0.001	9.13	304	<0.01
GD	21.25	682	<0.001	13.34	537	<0.01
TT	11.15	1454	<0.01	12.82	608	<0.01
$T + 1$	3.97	331	=0.052	3.48	191	=0.076
$T - 1$	8.12	291	<0.01	6.46	180	<0.05
PrF	<1			<1		
LandPos	<1			1.03	0.18	>0.30
<b>CONTEXT</b>						
FFD	16.89	610	<0.001	30.53	139	<0.001
SFD	20.42	688	<0.001	32.48	132	<0.001
GD	24.30	1191	<0.001	38.65	304	<0.001
TT	41.51	2531	<0.001	77.98	612	<0.001
$T + 1$	16.74	527	<0.001	19.71	216	<0.001
$T - 1$	9.30	480	<0.01	12.72	157	<0.01
PrF	96.04	0.02	<0.001	65.15	0.01	<0.001
LandPos	10.18	0.30	<0.01	11.62	0.12	<0.01
<b>CONSTRAINT × FREQUENCY</b>						
FFD	<1			<1		
SFD	<1			<1		
GD	1.40	465	>0.20	1.00	570	>0.30
TT	1.19	1170	>0.25	<1		
$T + 1$	<1			<1		
$T - 1$	<1			<1		
PrF	<1			<1		
LandPos	<1			<1		
<b>CONSTRAINT × CONTEXT</b>						
FFD	4.63	321	<0.05	4.56	154	<0.05
SFD	3.35	391	=0.074	4.74	174	<0.05
GD	1.69	557	>0.15	<1		
TT	1.65	1062	>0.20	1.20	730	>0.25
$T + 1$	1.66	456	>0.20	1.87	198	>0.15
$T - 1$	<1			<1		
PrF	2.04	0.02	>0.15	1.02	0.01	>0.30
LandPos	4.96	0.35	<0.05	2.77	0.18	=0.111
<b>FREQUENCY × CONTEXT</b>						
FFD	<1			<1		
SFD	<1			<1		
GD	<1			<1		
TT	4.98	820	<0.05	1.65	1177	>0.20
$T + 1$	<1			<1		

(Continued)

$T - 1$	<1			<1		
PrF	4.87	0.02	<0.05	4.75	0.01	<0.05
LandPos	<1			2.05	0.12	>0.15
<b>CONSTRAINT × FREQUENCY × CONTEXT</b>						
FFD	<1			<1		
SFD	<1			<1		
GD	<1			<1		
TT	1.99	1387	>0.15	<1		
$T + 1$	5.21	374	<0.05	4.19	228	=0.053
$T - 1$	4.31	316	<0.05	3.19	204	=0.089
PrF	1.19	0.02	>0.25	1.25	0.01	>0.25
LandPos	<1			<1		

FFD, first fixation duration; SFD, single fixation duration; GD, gaze duration; TT, total fixation time;  $T + 1$ , next forward-going fixation from target; PrF, probability of target fixation; LandPos, landing position on target.

Degrees of freedom are  $F_1(1,47)$  and  $F_2(1,21)$ . MSE, mean squared error.

## MAIN EFFECTS

### Constraint

In each of the fixation time measures (FFD, SFD, GD, TT,  $T + 1$ , and  $T - 1$ ), there was a significant main effect of Constraint (see **Table 4**). In contrast to Lima and Inhoff's (1985) earlier findings, HC words were fixated for less time than LC words (HC vs. LC: 187 vs. 193 ms for FFD, 189 vs. 194 ms for SFD, 197 vs. 205 ms for GD, 214 vs. 228 ms for TT, 198 vs. 205 ms for  $T + 1$ ; and 188 vs. 194 ms for  $T - 1$ ). For PrF, although the effect was not significant (marginal by participants, non-significant by items), the direction of the numerical effect was consistent with the fixation time results, with HC words (0.74) less likely to be fixated than LC words (0.76). Finally, the main effect of Constraint for LandPos was not significant.

### Frequency

The main effect of Frequency (see **Table 4**) was significant across all target fixation time measures (FFD, SFD, GD, TT) and the pre-target  $T - 1$  measure, but only marginally significant (both by participants and items) in the post-target  $T + 1$  measure. In line with numerous eye movement studies on word frequency, HF words were associated with shorter fixations than LF words (HF vs. LF: 186 vs. 194 ms for FFD, 187 vs. 196 ms for SFD, 195 vs. 207 ms for GD, 215 vs. 228 ms for TT, 200 vs. 204 ms for  $T + 1$ , and 188 vs. 193 ms for  $T - 1$ ). There was no reliable effect in the PrF and LandPos measures.

### Context

The main effect of Context (see **Table 4**) was significant across all measures, including fixation probability and landing position (FFD, SFD, GD, TT,  $T + 1$ ,  $T - 1$ , PrF, and LandPos). Again, similar to several eye movement studies investigating predictability, targets in Biasing contexts were fixated for less time than those in Neutral contexts (Biasing vs. Neutral: 185 vs. 195 ms for FFD, 185 vs. 198 ms for SFD, 192 vs. 210 ms for GD, and 205 vs. 238 ms for TT), were less likely to be fixated (Biasing vs. Neutral: 0.68 vs. 0.82 for PrF), and were associated with shorter pre- and post-target

fixations (197 vs. 207 ms for  $T + 1$ , and 188 vs. 194 ms for  $T - 1$ ). For LandPos, readers fixated further into targets when they were more predictable (Biasing vs. Neutral: 2.89 vs. 2.72 characters).

## INTERACTIONS

Although the interactions, in general, tended to be non-significant, there were a few exceptions (see **Table 4**).

### Constraint × Frequency

The Constraint × Frequency interaction was not significant across any measure.

### Constraint × Context

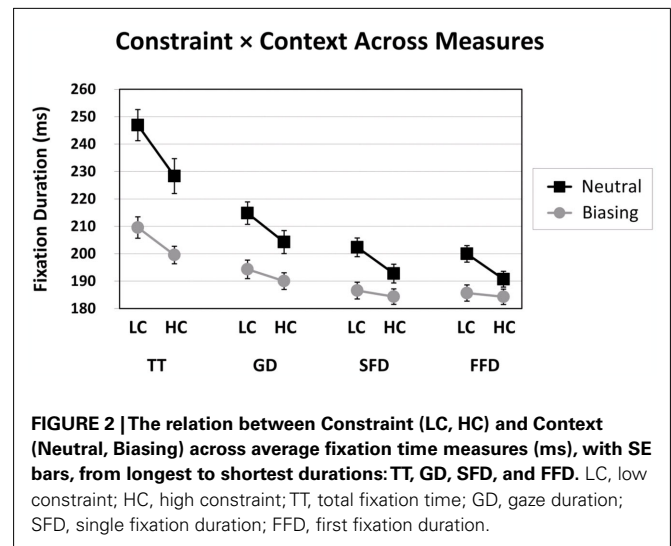
Constraint × Context, however, did reach significance in the more immediate fixation time measures of FFD and SFD (although this effect was marginal by participants for SFD) and, for LandPos, was significant by participants but only a statistical trend by items. In all other measures (GD, TT,  $T + 1$ ,  $T - 1$ , and PrF), Constraint × Context failed to reach significance.

For LandPos, although the numerical means suggested an opposing pattern of results, with landing positions for HC words nearer word beginnings in Neutral contexts (HC = 2.64 and LC = 2.80 characters), but nearer word endings in Biasing contexts (HC = 2.95 and LC = 2.84 characters), this pattern was not maintained statistically. Rather, the follow-up contrasts in general were more supportive of an interpretation in which the landing position for HC-Neutral targets (2.64 characters) was nearer the beginning of the word compared to the other three conditions (2.80, 2.95, and 2.84 characters for LC-Neutral, HC-Biasing, and LC-Biasing, respectively) (HC-Neutral vs. LC-Neutral:  $F_1 = 3.55$ ,  $p = 0.066$ ,  $F_2 = 2.14$ ,  $p = 0.158$ ; HC-Neutral vs. HC-Biasing:  $F_1 = 13.42$ ,  $p < 0.001$ ,  $F_2 = 9.68$ ,  $p < 0.01$ ; HC-Biasing vs. LC-Biasing:  $F_1 = 1.60$ ,  $p > 0.20$ ,  $F_2 < 1$ ; LC-Neutral vs. LC-Biasing: all  $F_s < 1$ ).

For FFD and SFD, follow-up contrasts revealed significant differences between LC-Neutral and LC-Biasing conditions (FFD:  $F_1 = 6.19$ ,  $p < 0.05$ ,  $F_2 = 4.84$ ,  $p < 0.05$ ; SFD:  $F_1 = 8.68$ ,  $p < 0.01$ ,  $F_2 = 3.88$ ,  $p = 0.062$ ), HC-Neutral and HC-Biasing conditions (FFD:  $F_1 = 30.59$ ,  $p < 0.001$ ,  $F_2 = 27.25$ ,  $p < 0.001$ ; SFD:  $F_1 = 30.62$ ,  $p < 0.001$ ,  $F_2 = 25.48$ ,  $p < 0.001$ ), LC-Neutral and HC-Neutral conditions (FFD:  $F_1 = 12.76$ ,  $p < 0.001$ ,  $F_2 = 12.62$ ,  $p < 0.01$ ; SFD:  $F_1 = 11.29$ ,  $p < 0.01$ ,  $F_2 = 12.73$ ,  $p < 0.01$ ), but not between LC-Biasing and HC-Biasing conditions (all  $F_s < 1$ ). In sum, while the effect of Context was maintained for both LC and HC words, the effect of Constraint was only upheld in Neutral contexts. In **Figure 2**, we plotted the Constraint × Context data (collapsed across Frequency) over the different fixation time measures, from the longest to the shortest duration (TT, GD, SFD, FFD). It seems that the interaction in the early SFD and FFD measures may actually arise from floor effects. That is, fixation times in HC-Biasing conditions just cannot get any shorter.

### Frequency × Context

With respect to Frequency × Context, our results confirmed those of past eye movement studies that have typically demonstrated a lack of an interaction in fixation times but the presence of one in PrF (e.g., Rayner et al., 2004a; Hand et al., 2010). With the



**FIGURE 2 |** The relation between Constraint (LC, HC) and Context (Neutral, Biasing) across average fixation time measures (ms), with SE bars, from longest to shortest durations: TT, GD, SFD, and FFD. LC, low constraint; HC, high constraint; TT, total fixation time; GD, gaze duration; SFD, single fixation duration; FFD, first fixation duration.

exception of TT, in which the interaction was only significant by participants, all other measures (FFD, SFD, GD,  $T + 1$ ,  $T - 1$ , and LandPos) failed to show an interaction. For the reliable interaction in PrF, follow-up contrasts were significant for LF-Neutral vs. LF-Biasing ( $F_1 = 32.67$ ,  $p < 0.001$ ,  $F_2 = 32.02$ ,  $p < 0.001$ ) and HF-Neutral vs. HF-Biasing ( $F_1 = 78.07$ ,  $p < 0.001$ ,  $F_2 = 76.42$ ,  $p < 0.001$ ), were not significant for LF-Neutral vs. HF-Neutral ( $F_1 = 1.67$ ,  $p > 0.20$ ,  $F_2 = 1.59$ ,  $p > 0.20$ ), and were only marginally significant for LF-Biasing vs. HF-Biasing ( $F_1 = 3.34$ ,  $p = 0.074$ ,  $F_2 = 3.32$ ,  $p = 0.083$ ). Thus, Biasing contexts gave rise to a lower likelihood of fixating the target (or an increased probability of skipping it), and when the target was additionally HF, these effects were enhanced. This pattern of differences stands in partial contrast to prior research which has found fewer fixations (or increased skipping) only in the combined condition of high predictability and HF (Rayner et al., 2004a; Hand et al., 2010).

### Constraint × Frequency × Context

Finally, the three-way interaction was significant (although marginal by items) in the pre- and post-target measures,  $T - 1$  and  $T + 1$  (see **Table 4**). Recall that these measures are considered to reflect parafoveal pre-processing and post-target processing spillover. All other measures (FFD, SFD, GD, TT, PrF, and LandPos) failed to demonstrate an interaction. Follow-up contrasts for  $T - 1$  and  $T + 1$  revealed similar effects, with Neutral and Biasing contexts producing distinct patterns (for condition means, see **Table 3**). In general, in Neutral contexts, pre- and post-target fixations were longer with LF-LC words (e.g., *clown*) compared to any other condition; in Biasing contexts, pre- and post-target fixations were shorter with HF-HC words (e.g., *girls*) relative to the other conditions.

For  $T - 1$  in Neutral contexts, the three contrasts involving the LF-LC condition were significant by participants and items (LF-LC vs. LF-HC/HF-LC/HF-HC: all  $F_s > 4.50$ ,  $p_s < 0.05$ ). The remaining Neutral conditions did not differ from each other (LF-HC vs. HF-LC vs. HF-HC: all  $F_s < 1$ ). For  $T - 1$  in Biasing contexts, the three contrasts involving the HF-HC condition were significant by participants but marginal in two of the items contrasts



(HF–HC vs. LF–LC/LF–HC/HF–LC: all  $F_{1s} > 4.45$ ,  $p_{1s} < 0.05$ ; all  $F_{2s} > 3.00$ ,  $p_{2s} < 0.10$ ). The remaining Biasing conditions did not differ from each other (LF–LC vs. LF–HC vs. HF–LC: all  $F_s < 1$ ).

An identical pattern of means was obtained in  $T + 1$ , although the results tended to be less reliable. For  $T + 1$  in Neutral contexts, the three contrasts involving the LF–LC condition were significant by participants and items (LF–LC vs. LF–HC/HF–LC/HF–HC: all  $F_s > 4.75$ ,  $p_s < 0.05$ ). The remaining Neutral conditions did not differ from each other (LF–HC vs. HF–LC vs. HF–HC: all  $F_s < 1.80$ ,  $p_s > 0.15$ , except LF–HC vs. HF–LC with  $F_1 = 2.58$ ,  $p = 0.115$ ). For  $T + 1$  in Biasing contexts, the contrasts involving the HF–HC condition were largely significant by participants (significant in two, marginal in one), but marginal at best by items (marginal in two, trend in one) (HF–HC vs. LF–LC/LF–HC/HF–LC: all  $F_{1s} > 3.35$ ,  $p_{1s} < 0.08$ ; all  $F_{2s} > 2.47$ ,  $p_{2s} < 0.13$ ). The remaining Biasing conditions did not differ from each other (LF–LC vs. LF–HC vs. HF–LC: all  $F_s < 1$ ).

## SUMMARY

The overall pattern of results across all measures (FFD, SFD, GD, TT,  $T + 1$ ,  $T - 1$ , PrF, and LandPos), with a few notable exceptions detailed below, generally showed main effects of Constraint, Frequency, and Context with no interactions. For the main effects of Constraint and Frequency, with the exception of PrF and LandPos, all measures showed reliable facilitation for HC over LC and for HF over LF words, respectively. For the main effect of Context, all measures, including PrF and LandPos, showed significant facilitation in Biasing vs. Neutral conditions. In terms of the interactions, Constraint  $\times$  Frequency was statistically unreliable. Constraint  $\times$  Context generally reached significance (exceptions noted) in only three measures – LandPos (trend by items), FFD, and SFD (marginal by participants). However, the interaction in the early FFD and SFD measures seemed to be the result of a floor effect impeding HC–Biasing conditions. The Frequency  $\times$  Context interaction was only reliable in the PrF measure (TT was significant by participants but non-significant by items), replicating prior eye movement studies. Target words were more likely to be skipped when they were in Biasing contexts with an additional (marginal) advantage when the target was HF vs. LF. Finally, the Constraint  $\times$  Frequency  $\times$  Context was significant (marginal by items) only in  $T - 1$  and  $T + 1$ . Although some of the follow-up contrasts were marginal, in general, the longest pre- and post-target fixations occurred with LF–LC words in Neutral contexts and the shortest with HF–HC words in Biasing contexts, a pattern that substantiated the underlying main effects of Constraint, Frequency, and Context.

## DISCUSSION

The present study was carried out in order to investigate whether there was a difference in processing words beginning with LC initial trigrams (e.g., *clown*), having numerous trigram neighbors, vs. those with HC initial trigrams (e.g., *dwarf*), having few trigram neighbors. Previous work by Lima and Inhoff (1985) had found, contrary to their original predictions, that LC words received shorter fixations than HC words, but only in the FFD measure. In their study, however, LC and HC words were LF words embedded in Neutral contexts. Our study additionally manipulated the

word frequency (LF vs. HF) of LC and HC targets as well as their predictability (Neutral vs. Biasing preceding context). We had expected to replicate Lima and Inhoff's findings in our LF–Neutral condition, with LC words fixated for less time than HC words. However, in HF, Biasing, and/or HF–Biasing conditions, we had expected that HC words might demonstrate a processing advantage over LC words. If, as prior research has demonstrated, parafoveal processing is facilitated for words that are HF (Inhoff and Rayner, 1986) or predictable (Balota et al., 1985), then it seemed probable that HC words in these conditions would show a processing benefit relative to LC words. In general, our findings showed that, regardless of target frequency or predictability, HC words were reliably fixated for *less* time than LC words.

We first review our findings within the context of a time-course framework, delineating the effects in terms of pre-target ( $T - 1$ , PrF, and LandPos), target (FFD, SFD, and GD), and post-target ( $T + 1$  and TT) measures. We then present some further analyses in an attempt to address possible methodological concerns with our experiment. We return to Lima and Inhoff's (1985) study and discuss differences in methods that may have led to their different pattern of results. Finally, we examine recent eye movement studies investigating issues related to word-initial letter constraint whose results are more consistent with our findings.

## PATTERNS OF EFFECTS

### Pre-target effects

Pre-target fixation duration effects have been a focus of several recent eye movement studies, with both positive and null effects reported (e.g., Rayner et al., 2004b; Drieghe et al., 2005, 2008; Inhoff et al., 2005; Kennedy and Pynte, 2005; Kliegl et al., 2006; Kennedy, 2008; Miellet et al., 2009; Hand et al., 2010). Such effects are termed “parafoveal-on-foveal” effects because characteristics of the (parafoveal) target can begin to emerge in fixation time on the pre-target (foveal) word, before the target is directly fixated. There is no question that information about the upcoming parafoveal word is obtained prior to its fixation – moving window and boundary experiments have demonstrated that normal reading behavior is impaired when parafoveal text is altered. The issues of debate, however, concern (1) the level of parafoveal pre-processing (whether it is limited to lower-level, perceptual analysis or can extend to higher-level, semantic activation); and (2) the implications for models of eye movement control in reading (whether visual attention is allocated in a serial or parallel manner which, consequently, determines if parafoveal information can affect the duration of the current fixation). In our study, pre-target fixations ( $T - 1$ ) demonstrated sensitivity to the target word's constraint, frequency, and predictability, with shorter durations when the parafoveal target was HC, HF, or in a Biasing context. The three-way interaction (marginal by items) showed, in Neutral contexts, a relative disadvantage to LF–LC parafoveal targets and, in Biasing contexts, a relative advantage to HF–HC parafoveal targets. Although such effects apparently support the notion of parafoveal-on-foveal processing at a deep level, we are reluctant to draw any firm conclusions. The aim of our study was not to investigate parafoveal-on-foveal processing. As such, unlike most investigations of parafoveal-on-foveal processing, we did not insure that targets were preceded by longer, content words. We will

return to this issue when we additionally examine whether launch site (i.e., the location of the pre-target fixation) affected target fixation duration.

For PrF, readers were more likely to skip targets that were HC (vs. LC) or were embedded in a Biasing (vs. Neutral) context. Although there was no main effect of Frequency, there was a Frequency  $\times$  Context interaction. The pattern of effects, in general, replicated past studies (Rayner et al., 2004a; Hand et al., 2010) in which HF-Biasing targets were skipped more often than targets in the other conditions. No other PrF effects were significant.

For LandPos, readers' fixation location on the target (determined from the pre-target fixation) was further into the word in Biasing (vs. Neutral) contexts. Although some eye movement studies show similar findings (e.g., Lavigne et al., 2000; McDonald and Shillcock, 2003; Kennedy et al., 2004), others do not (e.g., Rayner et al., 2001; Vainio et al., 2009). The only other effect was a Constraint  $\times$  Context interaction (significant by participants, trend by items), which generally showed that landing position within HC-Neutral words were further to the left than those in the other conditions (see, e.g., Hyönä, 1995).

### Target effects

The three target fixation time measures (FFD, SFD, and GD) all exhibited a significant effect of Constraint, with shorter fixation times associated with HC (vs. LC) targets. The other main effects of Frequency and Context were also significant, replicating past eye movement studies that demonstrate an advantage for HF vs. LF words and for words in Biasing vs. Neutral contexts, respectively. The lack of a Frequency  $\times$  Context interaction also replicated past studies. The only significant interaction was Constraint  $\times$  Context in the earlier FFD and SFD measures (although marginal by participants in SFD), showing a null effect of Constraint selectively in Biasing contexts. We suggested, however, that the lack of any difference here was most likely due to a floor effect in which individual fixation times on words in the HC-Biasing condition had reached their lower limit.

### Post-target effects

Refixations on the target made after first leaving the target only contributed to 6% of the total possible data. Thus, TT effects tended to be similar to those of GD, demonstrating main effects of Constraint, Frequency, and Context. The only difference was a Frequency  $\times$  Context interaction that was significant by subjects but not by items, a result similar to that reported in Hand et al. (2010).

$T + 1$  also showed main effects of Constraint, Frequency (marginal by participants and items), and Context. As with  $T - 1$ , there was a three-way interaction (significant by participants, marginal by items). The pattern of results from the follow-up contrasts (several of which were statistically marginal) revealed increased processing spillover in the LC-LF-Neutral condition and decreased spillover in the HC-HF-Biasing condition, the "hardest" and "easiest" conditions, respectively, as defined by the direction of main effects.

### FURTHER ANALYSES

There are two issues with our current experiment that demand further attention. The first is related to our experimental method, the

second to our interpretation. A potential confound of our study was that Neutral, single-line sentences were always presented as a first block, followed by a second block of Biasing, two-line materials. We adopted this approach for several reasons. We thought that having the Neutral materials first would enable a more cautious comparison to Lima and Inhoff's (1985) original study which involved only single-line sentences. We also thought it would be less confusing to the participants if similar materials were presented together. Finally, we reasoned that presenting the Biasing materials first may have induced participants to engage in different strategies when subsequently presented with Neutral materials. At the outset, we had originally started to construct "empty" contexts to be presented as the first sentence for our Neutral materials and had intended to randomized all materials within a single block. However, the "empty" contexts generally served to introduce a certain degree of incoherence. Nevertheless, the issue remains that if participants tend to speed up over the course of the experiment, it is possible that our effect of Context may be due to practice effects and not our manipulation.

In general, we do not think that our Context effect is an order effect – past eye movement studies that have manipulated the predictability of targets in fully randomized designs have found similar effects (e.g., Rayner et al., 2004a; Hand et al., 2010; see also, Rayner, 1998, 2009). Additionally, effects from fatigue could offset those of practice over the course of an experiment. To address this concern, however, we performed separate Constraint  $\times$  Frequency ANOVAs on FFD and SFD for Neutral and Biasing conditions. FFD and SFD represent the earliest measures of processing. If participants sped up from Neutral to Biasing blocks, then it is possible that effects of Constraint or Frequency would likewise be attenuated. Recall, however, that Constraint interacted with Context for the early measures, with Biasing contexts functionally eliminating effects of Constraint. The separate ANOVAs confirmed this [Constraint: neutral-FFD  $F_1(1,47) = 11.11$ ,  $MSE = 368$ ,  $p < 0.01$ ,  $F_2(1,21) = 12.91$ ,  $MSE = 150$ ,  $p < 0.01$ ; Neutral-SFD  $F_1(1,47) = 8.00$ ,  $MSE = 552$ ,  $p < 0.01$ ,  $F_2(1,21) = 9.55$ ,  $MSE = 232$ ,  $p < 0.01$ ; Biasing-FFD and Biasing-SFD all  $F_s < 1$ ]. These results cannot distinguish between an interaction (possibly due to floor effects) and a general acceleration of fixation times over the experiment. However, Frequency did not interact with Context and such effects were maintained in both halves of the experiment [Frequency: neutral-FFD  $F_1(1,47) = 6.49$ ,  $MSE = 471$ ,  $p < 0.05$ ,  $F_2(1,21) = 6.38$ ,  $MSE = 272$ ,  $p < 0.05$ ; Neutral-SFD  $F_1(1,47) = 5.40$ ,  $MSE = 638$ ,  $p < 0.05$ ,  $F_2(1,21) = 4.37$ ,  $MSE = 260$ ,  $p < 0.05$ ; Biasing-FFD  $F_1(1,47) = 6.22$ ,  $MSE = 435$ ,  $p < 0.05$ ,  $F_2(1,21) = 6.00$ ,  $MSE = 241$ ,  $p < 0.05$ ; Biasing-SFD  $F_1(1,47) = 7.47$ ,  $MSE = 434$ ,  $p < 0.01$ ,  $F_2(1,21) = 5.90$ ,  $MSE = 283$ ,  $p < 0.05$ ].

We also examined the first-pass reading time on each region of the target sentence (i.e., the only sentence in the Neutral condition; the second sentence in the Biasing condition) across Context conditions. Sentences were divided into four regions: the target, itself, including the space preceding it (always six characters); a pre-target region before the target (always 10 characters); a beginning region of text occurring before the pre-target region (13 characters on average); and a post-target region of all text occurring after the target (27 characters on average). For each region, the

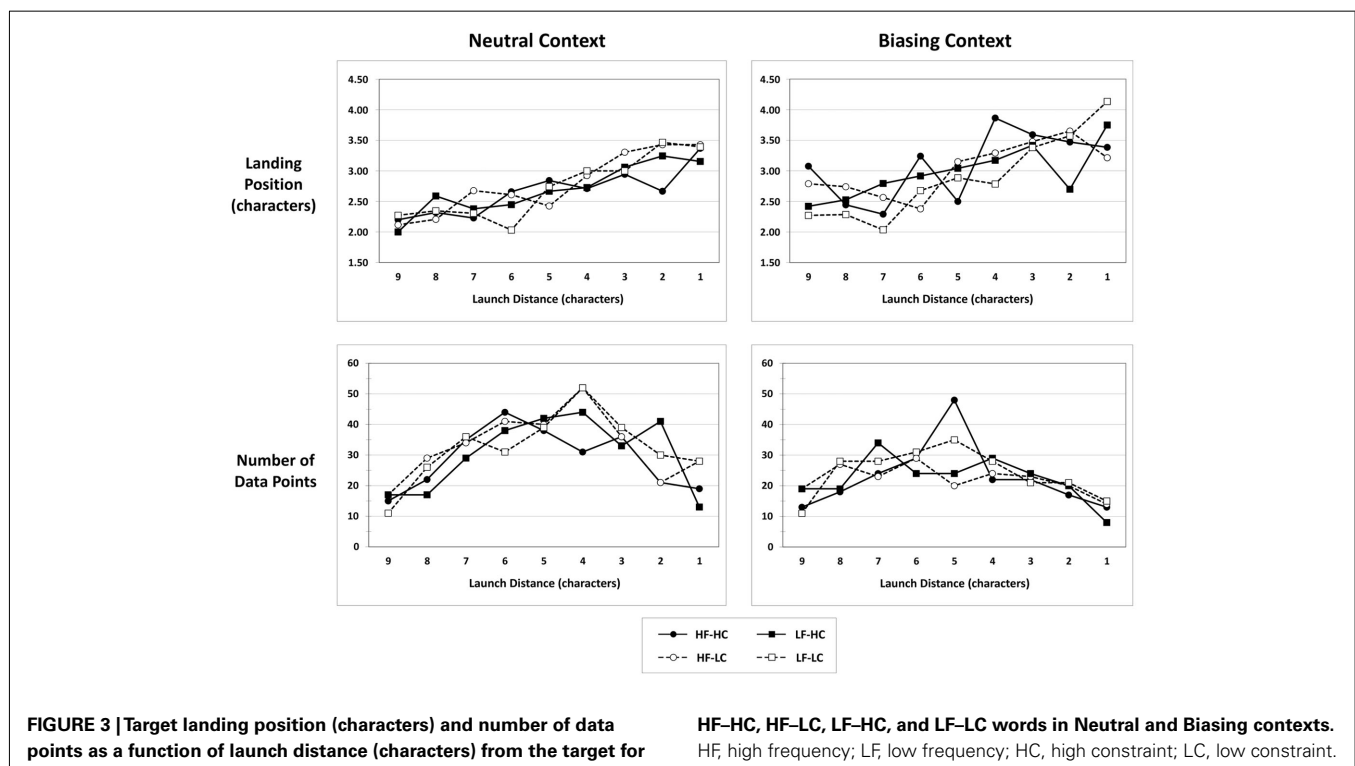
first-pass reading time was divided by the number of characters in that region to yield a reading time per character (ms/char) measure. The averages for beginning, pre-target, target, and post-target regions were 33.1, 26.9, 35.2, and 32.7 ms/char for the Neutral condition and 37.5, 23.4, 32.7, and 24.1 ms/char for the Biasing condition, with corresponding differences (Neutral–Biasing) of –4.4, 3.5, 2.5, and 8.6 ms/char. While most regions were read faster in the Biasing compared to the Neutral condition, the first region was read slower. The greatest numerical advantage for the Biasing condition arose from the final region, where discourse integration processes would be most facilitated. While the current data cannot unequivocally demonstrate that our Context effect is *solely* due to the target's predictability (and not the by-product of an order effect), the overall weight of evidence, including that from prior eye movement studies investigating contextual effects, seems to favor an interpretation in which reading behavior across several measures is facilitated by more predictable contexts.

A final point regarding Neutral vs. Biasing conditions is related to anaphor resolution. The concern is that in the Neutral condition, pre-target anaphoric references (e.g., pronouns) have no antecedents, whereas in the Biasing condition, some do. Unresolved anaphors could serve to increase processing time selectively in the Neutral condition, and thus masquerade as a context effect. The conditions under which anaphor resolution proceeds with relative ease or difficulty is, itself, not fully resolved, nor is the issue of how isolated pronouns are processed in context-free circumstances. Nevertheless, the data do not seem to support the contention that the context effect is the result of unresolved anaphors. We examined the Neutral sentences containing unresolved anaphors. Some of these anaphors were located in the

beginning region, others were located in the pre-target region, and some spanned these two regions. Our comparison of reading times in these early target sentence regions (above), however, revealed no evidence of systematic differences. Given that the unresolved anaphors were fairly equally distributed across these two regions, it seems unlikely that they are responsible for the pattern of effects.

The second issue concerns how much we can conclude about parafoveal processing in the absence of employing a boundary paradigm. An invalid parafoveal preview (a letter string different from the target that changes to the target when eyes cross a pre-target boundary) can be used to insure foveal-only processing. By its nature, however, an invalid preview does not simply deny parafoveal processing; it permits parafoveal processing of an incorrect stimulus. Nevertheless, the complexity of our existing design ( $2 \times 2 \times 2$ ) made an additional parafoveal preview manipulation impractical. We can, however, make some tentative conclusions about parafoveal processing based in part on our pre-target ( $T - 1$ ) findings of parafoveal-on-foveal effects as well as on further analyses of our data.

Launch distance (i.e., the number of characters from the pre-target fixation to the beginning of the target region) can be used as a proxy measure of the degree of parafoveal processing of the target (see, e.g., Hand et al., 2010). This argument assumes that nearer launch sites allow for better parafoveal pre-processing than further ones. We first calculated descriptive statistics for our launch site analysis. **Figure 3** shows the landing position as well as the number of data points on target words as a function of launch distance across all conditions. The pattern of target landing position data shows that closer launch sites resulted in saccades further into the target. The pattern of data points shows that launch



distance was relatively normally distributed. These patterns are confirmed by past eye movement research (e.g., McConkie et al., 1988; Rayner et al., 1996). There are more data points in Neutral context conditions as the target was more likely to be skipped in Biasing context conditions. While the data are somewhat noisy, there do not seem to be any systematic differences between the experimental conditions.

We performed a 2 (Launch Distance: Near, Far)  $\times$  2 (Constraint)  $\times$  2 (Frequency)  $\times$  2 (Context) ANOVA on the FFD data by participants [ $F_1(1,47)$ ] and by items [ $F_2(1,21)$ ]. For Launch Distance, we defined Near as saccades originating from one to three characters and Far as saccades originating from seven to nine characters. For missing data (less than 2% overall; 11 of 768 participant and 7 of 352 item cells), appropriate condition means adjusted by participant or item were substituted. As in our original analyses, the main effects of Constraint, Frequency, and Context were all significant (Constraint:  $F_1 = 8.89$ ,  $p < 0.01$ ,  $F_2 = 5.75$ ,  $p < 0.05$ ; Frequency:  $F_1 = 13.40$ ,  $p < 0.001$ ,  $F_2 = 13.49$ ,  $p < 0.01$ ; Context:  $F_1 = 15.24$ ,  $p < 0.001$ ,  $F_2 = 33.17$ ,  $p < 0.001$ ). FFDs were shorter on HC vs. LC targets (181 vs. 188 ms), on HF vs. LF targets (180 vs. 188 ms), and on targets in Biasing vs. Neutral contexts (178 vs. 191 ms). Launch Distance was also significant, with shorter FFDs associated with Near vs. Far launch sites (175 vs. 193 ms) ( $F_1 = 33.61$ ,  $p < 0.001$ ,  $F_2 = 40.99$ ,  $p < 0.001$ ). Two interactions were significant by participants but not by items (Launch Distance  $\times$  Constraint and Frequency  $\times$  Context:  $F_1s > 9.10$ ,  $p_1s < 0.01$ ,  $F_2s < 1$ ). No other interactions approached significance. Thus, it seems that Launch Distance (within a range of nine characters) did not modulate any of the reported main effects. However, these effects should be considered with caution as they only represent a relatively small sample of the data (see **Figure 3**).

### RECONCILING DIFFERENCES

Recall that Lima and Inhoff (1985) only found an advantage for LC words in the FFD measure. Our finding of a processing advantage for HC words was demonstrated across several eye movement measures. The issue remains, however, as to how we can best account for the pattern of our results, both in light of Lima and Inhoff's study as well as in the broader theoretical context of recent related research. It is possible that differences in results between the current experiment and Lima and Inhoff's were due to differences in aspects of materials and methods.

First, the specifications for the number of five- and  $x$ -letter neighbors across conditions in their study was 9 and 80 for LC, and 1 and 5 for HC, respectively; in our study, the corresponding values (for comparable LF targets) were 20 and 209 for LC, and 2 and 17 for HC, respectively. Thus, it seems that our LC words were more "unconstrained" than theirs, having denser neighborhoods. In terms of the *lexical constraint hypothesis* – Lima and Inhoff's (1985) initial position, in which word-initial letter information acquired parafoveally is used to constrain the number of possible candidates – LC words having bigger trigram neighborhoods should be additionally disadvantaged. Our findings lend support to this account. According to Lima and Inhoff's revised view, however, larger trigram neighborhoods should lead to even greater subsequent foveal processing efficiency. While both accounts seem

plausible, we believe that the weight of evidence, as discussed below, favors an interpretation in which a higher constraining parafoveal trigram, when clearly visible, acts to facilitate that word's recognition.

Second, in terms of methods, a combination of an expanded experimental design and a greater number of participants in our experiment ( $N = 48$ ) compared to Lima and Inhoff's (1985) ( $N = 18$ ) resulted in over five times more data points available for analysis in our study compared to theirs (4224 vs. 756 observations, respectively). Although the difference between studies in the number of data points per participant per condition was moderate (11 in ours vs. 7 in theirs), it does represent a 57% increase which, nonetheless, serves to enhance the reliability of our results.

Third, Lima and Inhoff (1985) always preceded their target word by a content word that had an average length of seven characters. In our study, the pre-target word tended to be a HF function word. The average length of our pre-target words was four letters (which did not differ across conditions). Although our analysis of launch distance and landing position (**Figure 3**) shows that fixations were made on the pre-target word (launch sites of one to four characters), the median launch site in our sample was five characters. It seems reasonable, then, to assume that our pre-target words were skipped more often than those used in Lima and Inhoff's experiment. The consequences, however, are not straightforward. On the one hand, a single fixation on a longer, content, pre-target word would result in less parafoveal pre-processing of the subsequent target (e.g., Henderson and Ferreira, 1990). However, if a second fixation were made on that pre-target word (the probability of which increases with word length), then a greater degree of target pre-processing could occur (e.g., Sereno, 1992). On the other hand, a higher degree of skipping a shorter, function, pre-target word entails that, although launch distance to the target word is maintained, the parafoveal preview of the target would include an intervening word. Without knowing the frequencies of the different fixation scenarios in Lima and Inhoff's study, it is difficult to speculate further about how the variation in pre-target words between our experiments differentially affected target processing. Nevertheless, when launch distance is taken into consideration, our target word data provide evidence to suggest that pre-target skipping did not interact with the variables of interest. Although the mean pre-target word length was four characters, the median value was three characters. Consequently, our launch distances of Near (one to three characters) vs. Far (seven to nine characters) correspond, to a large extent, to having fixated or skipped the pre-target word, respectively. In the Launch Distance  $\times$  Constraint  $\times$  Frequency  $\times$  Context analysis detailed above, only the main effects reached significance (with shorter target fixation times associated with Near launch distances or with words that were HC, HF, or in Biasing contexts). We can tentatively conclude that, with respect to the experimental manipulations, skipping the word before the target in general only additively modulated subsequent FFDs on the target.

Fourth, Lima and Inhoff's (1985) materials were presented on a Hewlett-Packard 1300A CRT with letters plotted in a dot-matrix font (cyan letters on a black background) in a darkened room. Under these conditions, the text can appear quite pixelated and is more difficult to read. Our materials were presented in a situation

more akin to natural reading – a high quality font (black letters on a white background) in a well-lit room. The difficulty reading a dot-matrix font is substantiated by the longer fixation times in Lima and Inhoff's study. The average FFD and GD in their full-line (i.e., normal reading) condition was 225 and 253 ms, whereas the average FFD and GD in our LF-Neutral condition (i.e., the condition most comparable to their stimuli) was 199 and 216 ms, a reduction of 26 and 37 ms, respectively. Assuming that both experiments sampled typical university students with similar abilities in reading relatively simple short lines of text, it seems that the most plausible explanation for the slower reading times in the Lima and Inhoff study is related to the intelligibility of the font used.

In terms of the speed of identifying parafoveal letters in a dot-matrix font, it is possible that LC trigrams would show an advantage over HC trigrams for reasons related to differential lower-level visual processing. Recently, Kveraga et al. (2007) used low resolution (blurred) and high resolution (clear) stimuli to bias processing toward the magnocellular (M) and parvocellular (P) pathways, respectively. They found that M-stimuli were projected rapidly from early visual areas to the orbitofrontal cortex (OFC) which, in turn, sent rapid feedback in the form of predictions to inferotemporal (object identification) areas. P-stimuli, however, were only projected from occipital cortex to the fusiform gyrus, without the rapid mediation via the OFC. In the current context, a blurred (dot-matrix) parafoveal stimulus, in comparison to a clear one, paradoxically would lead to faster top-down processing. That is, top-down processing predicting a parafoveal word-initial trigram would be easier for common or prototypical (LC) trigrams than for rare (HC) ones.

Finally, a recent eye movement experiment by White (2008) examined the effects of word-initial orthographic familiarity, using HF-familiar, LF-familiar, and LF-unfamiliar words as targets in sentences. The comparison of interest for the current study is that between LF-familiar and LF-unfamiliar words. White (2008) measured orthographic familiarity in terms of *n*-gram token frequencies (i.e., the summed frequency of all words containing a particular letter sequence). White (2008) obtained trigram token values from CELEX (Baayen et al., 1995). In particular, the token-initial trigram frequency was significantly larger for LF-familiar than LF-unfamiliar words. In this respect, these conditions are similar to our LF-LC and LF-HC conditions, respectively. White found that SFD was significantly longer for LF-unfamiliar words (FFD was significant by participants but trend by items; GD was significant by participants and marginal by items; TT was not significant). As with the Lima and Inhoff (1985) study, although the effect is less well expressed in fixation time measures in comparison to our study, the direction of the effect is, nevertheless, inconsistent with our findings.

In order to appropriately evaluate White's words, using the BNC (Davies, 2004), we calculated the same measures we had used to characterize the trigram (*x*-letter) neighborhoods, namely, the number of trigram neighbors (type frequency), the summed frequency of the trigram neighborhood (token frequency, per million), the percentage of the trigram neighborhood accounted for by the target based on its frequency, and the rank of the target within the trigram neighborhood, again, based on its frequency (see Table 2). Specifically, our LF-LC words (vs. White's

LF-familiar words) had substantially more trigram neighbors (209 vs. 121) and a slightly higher trigram neighborhood summed frequency (1615 vs. 1144 per million), while accounting for a similar percentage of the trigram neighborhood (1 vs. 2%) and relative rank within the trigram neighborhood (28 vs. 30). Our LF-HC words (vs. White's LF-unfamiliar words) had fewer trigram neighbors (17 vs. 31), had a lower summed frequency of trigram neighbors (31 vs. 192 per million), accounted for a greater percent of the trigram neighborhood (38 vs. 22%), and were higher ranking within the trigram neighborhood (1 vs. 9). In neighborhood terms, in comparison to White's words, our LF-LC words were unknown members lost in larger crowds and our LF-HC words were unique members conspicuous within smaller gatherings. In general, there was a greater difference between our LF-LC and LF-HC words than White's LF-familiar and LF-unfamiliar words which could have contributed to the different pattern of results.

Another possible reason for the different pattern of results between White's (2008) and our study, as with Lima and Inhoff (1985), may be related to the quality of the display used. Although White's LF words were slightly lower in frequency in comparison to ours (3 vs. 9 per million, as per the BNC), they were shorter (half four- and half five-letter words vs. all five-letter words). Nevertheless, fixation times were substantially longer (FFDs, SFDs, and GDs were 280, 284, and 309 ms for LF-familiar and 286, 294, and 324 ms for LF-unfamiliar, respectively) than those in our study (see Table 3, LF-LC/Neutral and LF-HC/Neutral conditions). As mentioned earlier, it seems that the intelligibility of the font used is the most likely driving force behind differences in reading speed between participant groups. If this were the case, then the pattern of results in White's study may have arisen in part for reasons of diminished visual clarity as discussed earlier.

## RELATED FINDINGS

Within the eye movement reading literature, two recent studies have examined issues related to word-initial letter constraint. In the first, Williams et al. (2006) investigated the role of orthographic neighbors as parafoveal previews to targets in a reading study using the boundary paradigm. A word's orthographic neighbors are words of the same length that differ by only a single letter from that word (Coltheart et al., 1977). For example, the neighbors of *sleet* are *fleet*, *sheet*, *sweet*, *slept*, *sleek*, and *sleep*. Williams et al. (2006) compared fixation time on targets when the parafoveal preview was identical to the target (e.g., *sleet*), an orthographic neighbor of the target (e.g., *sweet*), or an orthographically matched non-word (e.g., *speet*). In their first experiment, targets were LF and orthographic neighbor previews were HF words; in their second experiment, targets were HF and orthographic neighbor previews were LF words. They found that the amount of preview benefit depended on the frequency of the preview. When orthographic neighbor previews were HF, the preview benefit was equivalent to identical (LF) previews, with both conditions showing facilitation relative to the non-word preview condition. When orthographic neighbor previews were LF, only the identical (HF) preview condition was facilitated. These results, in partial contrast to those of Lima and Inhoff (1985), demonstrate that when parafoveal information is orthographically similar as well as lexical

(word vs. non-word) and salient (HF vs. LF), lexical processing, as reflected in the subsequent fixation time on the parafoveal word, is facilitated.

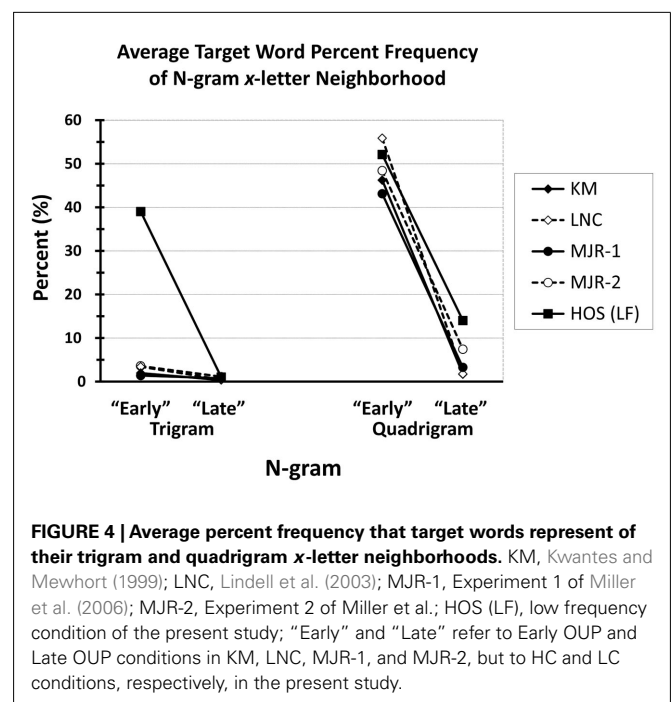
The second study examined the *orthographic uniqueness point* (OUP) in fluent reading (Miller et al., 2006). The OUP is the visual analog of the spoken word uniqueness point, that is, the letter position in a word that differentiates that word from other words based on orthography. For example, a typical early OUP word has its uniqueness point at letter position 4 (e.g., *actress*) whereas a late OUP word cannot be specified until letter 6 or 7 (e.g., *cartoon* or *curtail*). Prior research had used foveally presented words for naming (Kwantes and Mewhort, 1999) and lateralized presentation for a lexical decision task (Lindell et al., 2003) to investigate the OUP. Both studies found an RT advantage for early compared to late OUP words, providing evidence that a word's letters are at some point processed serially, in a left-to-right manner (in English). Specifically, according to Kwantes and Mewhort (1999), the seriality in processing occurs when a reader begins searching for the word in memory, not at the earlier stage of letter identification. Miller et al. (2006), however, raised several methodological concerns with these studies which they addressed in two experiments. First, they used early and late OUP words in the context of a normal reading task while recording participants' eye movements. Second, they generally used different words than those that had been previously tested (Lindell et al.'s words were a subset of those used by Kwantes and Mewhort). In Experiment 1, Miller et al. expanded and altered the stimulus list from the earlier studies. In Experiment 2, Miller et al. further refined their stimuli to address Lamberts' (2005) prior criticism that early OUP words tended to have fewer orthographic neighbors than late OUP words. Finally, using the boundary paradigm, Miller et al. manipulated the parafoveal preview of early and late OUP words across three conditions. The preview could be identical to the subsequent target, have the same first four letters as the target with the remaining letters visually different, or be entirely visually different from the target. Across both experiments, Miller et al. found no evidence to support the notion of serial processing. Late OUP words were read as fast as early OUP words, regardless of the amount of preview available. They attributed the lack of an OUP effect to differences in methodology and stimuli employed in the prior studies.

In the context of our current findings, a positive OUP effect could be interpreted as a relative advantage for words beginning with HC four-letter (quadrigram) combinations (i.e., early OUP words, whose OUP is at letter position 4) vs. words beginning with LC quadrigrams (i.e., late OUP words, whose OUP is at letter position 6 or 7). Because the eye movement experiments (Miller et al., 2006) which did not find an OUP effect used different stimuli than the naming (Kwantes and Mewhort, 1999) and lexical decision (Lindell et al., 2003) studies which did, the differing results may have arisen from the level of constraint conferred by the word-initial quadrigram. One of our measures of constraint was the percentage that each word represented of its entire ( $x$ -letter) trigram neighborhood (see Table 2). For this measure, we divided the frequency of each target word by the summed frequency of all words (including the target) of any length that shared that word-initial trigram. Using this same procedure, we

calculated (as per Davies, 2004) the average percentage that a given target represented of its quadrigram neighborhood in early and late OUP conditions. We found that, across all three of the above studies, early OUP words represented a far greater proportion of their quadrigram neighborhoods (average 48%, range 43–55%) than late OUP words (average 3%, range 2–7%). The percentages for each study are presented in Figure 4. While early OUP words, by definition, should comprise a larger percentage of their quadrigram neighborhoods than late OUP words, there was no apparent difference in these means across the different studies.

The possibility remains, however, that the experiments reporting an advantage for early over late OUP words (Kwantes and Mewhort, 1999; Lindell et al., 2003) may have used early OUP words that had higher constraining *trigram* neighborhoods than the experiments that found no such difference (Miller et al., 2006). For each study, we calculated (using Davies, 2004) the percentage that each early and late OUP word represented of its trigram neighborhood. These percentages are presented in Figure 4. In terms of trigrams, both early and late OUP words represented only a negligible percentage of their neighborhoods, with a minimal difference between early OUP (average 2.6%, range 1.4–3.6%) and late OUP (average 0.7%, range 0.4–1.1%) words. As with the quadrigram neighborhoods, these proportions did not differ between studies. Thus, although the results of RT and eye movement experiments were in conflict, the profiles of quadrigram and trigram neighborhoods for early and late OUP words were similar.

Assuming that the presence of an OUP effect in naming and lexical decision is due to task effects and that the lack of one in fluent reading more accurately reflects processes associated with recognizing words in text (for an extended discussion, see Miller et al., 2006), the question remains why we found a fixation time



advantage for words with HC trigrams while Miller et al. found no such advantage for words with HC quadrigrams. As noted previously, the stimuli used in the prior OUP studies were generally LF words; thus, any comparisons to our study will be limited to our LF–HC and LF–LC conditions. With respect to trigrams, our (LF) HC words represented a much larger proportion of their neighborhoods than did our LC words (see **Table 2**; **Figure 4**). In contrast, Miller et al.'s early OUP words were equally as unrepresentative as their late OUP words in corresponding neighborhoods. With respect to quadrigrams, we first calculated (using Davies, 2004) the percentage that our HC and LC words represented of their quadrigram neighborhoods. Similar to Miller et al.'s early and late OUP stimuli, respectively, our HC words comprised a large proportion (52%) and our LC words a relatively small proportion (14%) of their quadrigram neighborhoods (see **Figure 4**). In short, our stimulus conditions became differentiated one letter position prior to those used in Miller et al. These differences in *n*-gram profiles and in the empirical findings, taken together, would seem to suggest that word-initial letter constraint is only effective if it occurs within the first three (and not four) letters of a word.

Although this is a rather bold claim, eye movement research on the use of parafoveal information does provide support for the attentional relevance of word beginnings (e.g., Rayner et al., 1982; McConkie and Zola, 1987). Nonetheless, we do not want to imply that *no more than* the first three letters of a word are processed in a certain way. Rather, we would suggest that the rate of gain of parafoveal information levels out the further the distance (in letters) from the beginning of the parafoveal word (see, e.g., Engbert et al., 2005; Kliegl et al., 2006; Miellet et al., 2009). Other issues, however, would also come into play. First, fixations to a target can originate from closer or further launch distances which would affect the amount of parafoveal preview obtained (e.g., Hand et al., 2010). Also, on any given fixation, more or less parafoveal preview can be acquired as a function of the difficulty of the currently fixated, foveal word (e.g., Henderson and Ferreira, 1990). One way to test the limits of parafoveal information capture of word-initial quadrigrams in early and late OUP words would be – as we suggested at the outset regarding Lima and Inhoff's (1985) findings – to additionally manipulate word frequency and contextual predictability. That is, an early OUP word may be facilitated if it were both an HF and highly predictable word. As mentioned previously, OUP stimuli tend to be LF words. In the Miller et al. (2006) study, OUP targets appeared in contextually neutral sentences (average Cloze values were less than 0.01). If increased frequency and predictability of the parafoveal word enhances the parafoveal preview benefit of that word, as prior research has demonstrated (e.g., Balota et al., 1985; Inhoff and Rayner, 1986), then it is possible that the highly constraining quadrigrams of such early OUP words would facilitate that word's recognition.

Theoretically, our results have implications for models of eye movement control in reading (e.g., E–Z Reader of Reichle et al., 2003; SWIFT of Engbert et al., 2005). It is beyond the scope of this paper, however, to detail the different mechanisms which may account for our findings (see, e.g., White, 2008). Likewise, our

results have implications for a range of word recognition models. Nevertheless, caution must be exercised in making generalizations beyond the specific reading task employed. Effects do not always generalize from lexical decision, or even self-paced reading, to fluent reading conditions. With respect to orthographic neighborhood size (i.e., the number of words differing from the target by exactly one letter), Pollatsek et al. (1999) reported a pattern of results homologous to our own findings. They showed that a large neighborhood size facilitated lexical decision but had an inhibitory effect on reading, even when using the same experimental target words. Such differences in findings are sometimes explained by different mechanisms which are engaged by the different tasks. Norris (2006), on the other hand, adopts a more parsimonious approach in arguing that readers behave like optimal Bayesian decision-makers and exploit whatever statistical patterns that are available in order to deliver the most efficient result. In these terms, a word-initial HC trigram viewed parafoveally greatly raises the *post hoc* probability of the occurrence of that target. Proponents of Bayesian reading models would therefore suggest that the choice of a reading mechanism should be secondary to assuming that readers will learn to recognize visual words in an optimal manner.

## CONCLUSION

We examined the word-initial letter constraint of target words in an eye movement reading study that additionally manipulated the word frequency and contextual predictability of these targets. Several results replicated prior research – for example, demonstrating frequency and predictability effects in fixation times and an interaction of these effects in word skipping rates. In direct contrast to Lima and Inhoff (1985), however, we found an effect of trigram constraint in which HC words (e.g., *dwarf*) were consistently fixated for *less* time than LC words (e.g., *clown*). Although Constraint interacted with Context, it did so only in early fixation time measures and was most likely the result of a floor effect. We suggested that the differences in our findings in relation to those of Lima and Inhoff were due to differences in materials and methods. Finally, we evaluated recent related eye movement research in light of our findings. Although this research does not fully corroborate our results, neither does it refute our claims. Additionally, our findings are consistent with a Bayesian account (Norris, 2006) in which readers respond to the statistical information available to perform in an optimal fashion. In sum, this study reports evidence that supports the notion that the level of orthographic constraint conferred by the first few letters of an upcoming word is advantageously processed by the reader.

## ACKNOWLEDGMENTS

Portions of this research were supported by an Economic and Social Research Council (ESRC) postgraduate fellowship at the University of Glasgow to C. J. Hand and were presented at the 47th Annual Meeting of the Psychonomic Society, Chicago, November 2008. We thank Marc Becirspahic for help in calculating the five-letter trigram neighborhoods, Aisha Shahid for help with the experimental materials, Bo Yao for help with the figures, and Keith Rayner and Jukka Hyönä for their helpful comments on an earlier version of this article.

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- Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.
- Received: 31 October 2011; accepted: 05 March 2012; published online: 02 April 2012.
- Citation: Hand CJ, O'Donnell PJ and Sereno SC (2012) Word-initial letters influence fixation durations during fluent reading. *Front. Psychology* 3:85. doi: 10.3389/fpsyg.2012.00085
- This article was submitted to *Frontiers in Language Sciences*, a specialty of *Frontiers in Psychology*.
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## APPENDIX

### EXPERIMENTAL MATERIALS

The materials are listed as they would appear in the Biasing context condition. The Neutral condition is simply the second sentence of each item, containing the target word (underlined). Target words were low or high frequency (LF, HF) words with low or high constraint (LC, HC) word-initial trigrams. Items are sorted by these four conditions, with 22 items per condition. One participant group read half the items of each condition in a Biasing and half in a Neutral context. The other participant group read the same items in their opposite context condition.

#### LF-LC

1. Leon was unhappy with the tough bread he got with his soup. He complained that it was stale and the waitress apologised.
2. Jill's friends were drinking red wine all night in her flat. In the morning, she noticed an enormous stain on the carpet.
3. Robert was polishing his shoes before his big job interview. He wanted them to be shiny enough to see his face in them.
4. Maude added two brown sugars to her cappuccino. She put her spoon through the froth and stirred them in.
5. Sidney had tried a new shampoo for his terrible dandruff. He massaged it into his scalp before rinsing it out well.
6. Eve's cat had begun to scratch her new furniture. She would need to get his claws cut to prevent more damage.
7. Ray lived for six months with groups of pygmies in Africa. He studied each tribe and learned about their customs.
8. Albert thought he looked good with his new facial hair. His friends disagreed and thought his beard looked awful.
9. Lorna had gone on a five-mile run in the midday sun. You could see the sweat running down her face by the end.
10. Luke's first job was working at the supermarket. His responsibility was to stack the shelves.
11. When Geoffrey got a nosebleed, Dawn nearly keeled over. We thought she was going to faint at the sight of his blood.
12. The child couldn't sleep after watching the monster movie. It had been really scary and she was afraid to be alone.
13. Gavin placed the expensive necklace around his wife's neck. It was a string of pearl beads and she adored him for it.
14. There were fingerprints all over the handrail at the bar. They took away the shine from the brass and looked grubby.
15. Rory was going to dig all day in the potato fields. He picked up his spade and headed off to work.
16. Pierre had entertained kids at the circus for fifty years. He had enjoyed being a clown but it was time to retire.
17. The Big Ranch restaurant's specialty was high quality beef. Bill ordered their biggest steak and a pitcher of beer.
18. Emily had never seen such an enormous bowl of ice cream. She excitedly grabbed a spoon and began to stuff herself.
19. The shopkeeper suspiciously eyed the girl in the hooded top. He knew she was a thief and hoped to catch her red-handed.
20. The teacher scrawled sentences onto the blackboard. The noise of the chalk sent shivers up everyone's spine.
21. Tania first prepared the tomatoes, cucumber and lettuce. She finished making the salad with oil and vinegar dressing.
22. The letter Lucas had posted was returned to him. He had forgotten to put a stamp on it before posting it.

#### LF-HC

1. The heavy rain had washed the dirt and soil into the stream. This made the water muddy and unsafe to drink.
2. I couldn't stop sneezing as I cleaned out the storage room. Everything was dusty and it got up my nose as I worked.
3. 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.
4. Betty only needed the egg whites to make her meringue nests. Later, she used the yolks to make a separate dish.
5. Hounds used for hunting are trained in special kennels. They are taught to chase foxes out of their burrows.
6. Heroin addicts often tie a belt tightly around their arms. This makes it easier to find veins that they inject into.
7. Everyone was excited about going to see big cats at the zoo. The children wanted to see the lions and tigers most of all.
8. 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.
9. The cause of death was a hammer blow to the head. The damage to the victim's skull was quite sickening.
10. Valerie's neighbour's Alsatian kept coming into her garden. She got her son to build a fence to keep the dog out.
11. The boys got into a fist fight in the playground. They began to furiously punch each other in the face.
12. Andrea constantly suffered from severe eczema. Her skin was always itchy and she constantly scratched it.
13. The forecast warned drivers of poor visibility on the roads. As Will drove home, it became foggy and he could barely see.
14. At the ceilidh, Steven vigorously spun Emma round and round. This made her very dizzy but she still had a good time.
15. The grey squirrel was foraging at the foot of the oak tree. He recovered the acorn that he had buried last winter.
16. Jamie loved basketball but he was very short for his age. In gym class, he felt like a dwarf next to his classmates.

17. Poachers still illegally hunt elephants for their tusks.  
It is possible to buy ivory items on the black market.
18. Karen had jumped and landed awkwardly while ice skating.  
She badly hurt her ankle and would need to have an x-ray.
19. 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.
20. Maintaining a healthy digestive system requires roughage.  
Foods that are high in fibre are recommended by experts.
21. The music teacher hired removal men when he moved house.  
He couldn't move his piano on his own as it was too heavy.
22. Tara had taken heaps of photos of her Egyptian holiday.  
She would have to begin a new album to keep them together.
17. The park-keepers took good care of the lawns.  
They made sure that the grass was cut every day.
18. There had been a terrible crash at the weekend's Grand Prix.  
Oil had leaked onto the track and caused a massive pile-up.
19. The yacht crew were pleased with the favourable strong wind.  
They used it to gain speed and were sure to win the race.
20. I could feel something in my shoe which dug into my heel.  
It was a small stone which had come from the gravel path.
21. Johnny liked his father to read to him before bedtime.  
There was one particular story he liked about a tiger.
22. David increased his vocabulary by reading lots of books.  
His knowledge of difficult words was far better than others.

**HF-LC**

1. Maria's only son was graduating today from Oxford.  
As she watched, she felt so proud of his achievements.
2. Marcus almost hurt himself badly lifting weights at the gym.  
He had picked ones that were too heavy for him to lift.
3. During apartheid in South Africa, most races could not vote.  
Only people who were white could take part in the elections.
4. Susan was bored in the lecture and time passed slowly.  
She kept glancing at the clock and counted down the minutes.
5. The pirates located the spot where the treasure was buried.  
They opened up the chest and marvelled at the booty inside.
6. Mary's young son gave her a kick as she washed the dishes.  
She was so surprised, she dropped a plate and it smashed.
7. Tiger Woods was angry when he was distracted playing a shot.  
Apparently, someone in the crowd cheered as he hit the ball.
8. Stuart did not want to travel to London by bus or plane.  
He bought tickets for the train to Waterloo on the internet.
9. Terry went to the new gardening centre.  
He bought a rare plant for his garden.
10. Harry was slightly late for the play in the theatre.  
He missed the start but caught up with the plot quickly.
11. The toddler held onto the furniture to keep himself upright.  
On his own, he was unable to stand without falling down.
12. The joiner hadn't smoothed the edges of the cabinets yet.  
They were still quite rough and not ready to be varnished.
13. Nigel was struggling to cut the turkey with a blunt knife.  
He asked his wife for a sharp one and he continued to carve.
14. During the War, German submarines targeted supply convoys.  
They would attack the ships that carried weapons and food.
15. Every morning, Jeff would walk past the baker's shop.  
He enjoyed the smell of bread and frequently bought a loaf.
16. Everyone knew that "EastEnders" was just beginning.  
We recognised the familiar theme tune and sat down to watch.

**HF-HC**

1. Meg was driving and spotted a badly injured hedgehog.  
She tried to prevent it from dying but it was too late.
2. Special police units rushed to the bank robbery in progress.  
The men inside were armed and had taken customers hostage.
3. The couple finally got pregnant after trying for months.  
They were extremely happy when they eventually succeeded.
4. Derek asked for a bacon double cheeseburger at Burger King.  
He also ordered an extra large drink to wash it all down.
5. Sheena had to shop for many things in many different stores.  
She made up several lists so that she remembered everything.
6. Henry had been injured in a scrum at school.  
He was unable to play rugby for several weeks.
7. Ted was diabetic and had to monitor what he ate.  
If he ate too much sugar he could become unwell.
8. Dan was traumatised by seeing the mutilated body as a child.  
He could never get rid of the image from his mind's eye.
9. At school, Miss Jones told only the boys to leave early.  
She wanted to talk to the girls about the incident.
10. Keith liked to listen to Mozart, the Beatles, and techno.  
He liked all kinds of music with no particular preference.
11. The Sultan kept his gold bullion hidden in his palace.  
There was always someone there to guard it around the clock.
12. It had rained all night and the footpath was very muddy.  
Hannah's shoes were dirty and she trailed mud in the house.
13. The Queen has never voted in a General Election.  
Members of the royal family are not allowed to.
14. Seth could easily carry six plastic chairs at a time.  
They were incredibly light and could be stacked together.
15. Craig knew the law about carrying illegal weapons in public.  
He still carried a knife despite the risk of being caught.
16. Jack's aunt was supposed to pick him up after school.  
Instead, it was his uncle who was waiting for him.

17. The Ministry of Defence discovered a spy in their operation. It was a Russian agent who was relaying details to Moscow.
18. Sarah had saved money to have veneers fitted at the dentist. When they were finished, her teeth looked fabulous.
19. The DVD is now the most common form of movie entertainment. It seems that the video will soon be a thing of the past.
20. Claire's knee was causing her a lot of pain after exercise. The specialist said the joint was inflamed and needed rest.
21. It was a cold day and Barbara had forgotten her gloves. She decided to keep her hands in her pockets for warmth.
22. Jennifer tried a cigarette for the first time and loved it. She started to regularly smoke when she went out.