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Ongoing Cognitive Processing Influences Precise Eye-Movement Targets in Reading

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Abstract
Reading is a highly complex learned skill in which humans move their eyes three to four times every second in response to visual and cognitive processing. The consensus view is that the details of these rapid eye-movement decisions—which part of a word to target with a saccade—are determined solely by low-level oculomotor heuristics. But maximally efficient saccade targeting would be sensitive to ongoing word identification, sending the eyes farther into a word the farther its identification has already progressed. Here, using a covert text-shifting paradigm, we showed just such a statistical relationship between saccade targeting in reading and trial-to-trial variability in cognitive processing. This result suggests that, rather than relying purely on heuristics, the human brain has learned to optimize eye movements in reading even at the fine-grained level of character-position targeting, reflecting efficiency-based sensitivity to ongoing cognitive processing.

Keywords
reading, eye movements, psycholinguistics, motor control, open data, open materials

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Reading is a complex learned skill that is near-ubiquitous in industrialized societies, requiring tight coordination among vision, language processing, and motor control. It is highly practiced, and although it emerged only 4,000 years ago—too recently and (until the past few centuries) in too small a fraction of the population of any society to have exerted selective pressure on brain evolution—skilled readers have a specialized brain area for it (Dehaene & Cohen, 2011). Given recent research suggesting near-optimality in other complex tasks requiring a tight link between information processing and motor control (Körding & Wolpert, 2004; Najemnik & Geisler, 2005; Todorov & Jordan, 2002), it is of considerable interest to what extent motor control in reading is optimized for ongoing processing. The current consensus view in reading research is that although most motor decisions in reading—when to make a saccade and which word to make a saccade to—are sensitive to ongoing cognitive processing (Rayner, 1998, 2009), decisions about the precise position within a word targeted by a saccade (referred to here simply as saccade targeting) are efficient only at a coarse level, being determined by a fast heuristic sensitive only to the length of the targeted word, not to the degree to which the word has already been processed (McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1998). In this article, we provide evidence against this view, suggesting that readers target positions within new words that optimize their reading efficiency. This result leads to a picture of all aspects of motor control in reading as being optimized for ongoing processing, thus unifying motor control in reading with that in other complex skills.

The basic facts about where saccades land on words are straightforward. Given a particular *launch site*—the origin of a saccade into a word—the distribution of *landing sites* on the word is unimodal, relatively broadly distributed across the word. The mode of this distribution depends on the launch site: the nearer to the word, the farther forward the mode of the distribution. Researchers agree that this distribution is the consequence of (possibly

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implicit) selection of a target position within the word, overlaid with roughly normally distributed random error from the motor system. The question taken up in this research was what factors influence a saccade's precise target position. The answer to this question is important for determining the level at which eye-movement control in reading is optimized for real-time processing.

Saccade target position (henceforth, *target*) is commonly thought to be determined by a fast heuristic composed of two components (McConkie et al., 1988). The *functional target* of a saccade is always the center of the word, which is presumed to be a reasonable position from which to process the word on average on the basis of single-word-recognition experiments (cf. O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984). Then, *systematic error* biases the saccade length toward a preferred saccade size (e.g., seven characters), yielding an *actual target*. This bias is implemented as a simple weighted average of intended saccade length and the preferred saccade size, meaning that the actual position targeted within a word in this account is purely a function of word length and launch site, insensitive to cognitive processing. As pointed out by McConkie et al., this simple model can explain the central facts about landing sites. For a given launch site, landing sites are unimodally distributed (truncated normal distribution); because of systematic error, the mode shifts forward with the launch site. Given evidence that saccade target selection may often need to be completed prior to substantial processing of a new word (Becker & Jürgens, 1979), McConkie et al.'s model is also theoretically attractive because it computes saccade targets solely from word length, which is determined—for writing systems with spaces between words—solely by a word's low-spatial-frequency extent.[1]

An alternative to this fast-heuristic account is one in which readers target saccades to the most useful part of an upcoming word, given their current state of cognitive processing (Bicknell & Levy, 2010, 2012; Legge, Klitz, & Tjan, 1997; Rayner, McConkie, & Zola, 1980; Rayner, Well, Pollatsek, & Bertera, 1982). We refer to this as the cognitive-processing account of saccade targeting. To understand how this account works, note first that readers often start identifying an upcoming word while still fixating on a previous word (Rayner, 1998, 2009). This identification is often limited to a word's initial few letters (Rayner et al., 1980) because of the exponential decrease in visual acuity with distance from the fovea and also the increasing difficulty in identifying letters surrounded by other letters in peripheral vision (*visual crowding*; Stuart & Burian, 1962). The cognitive-processing account suggests that when readers have identified relatively more of the word's initial letters but have not yet identified the whole word, targeting a saccade forward into the word past the initial letters would be most efficient. This is because such a saccade target would place the fovea closer to the remaining new information: the word's remaining letters and the following word. This account can also qualitatively reproduce the empirical relationship between launch site and modal landing position: The farther forward the launch site, the higher quality visual input readers will have obtained about the word's initial letters and the farther into the word readers will target their saccade (Legge, Hooven, Klitz, Mansfield, & Tjan, 2002).

Both models, then, can account for the aggregate properties of saccade-landing-site distributions on words. However, the two models can be distinguished by the predictions they make about individual trials. In all major models of reading, there is trial-to-trial variability in how much identification a reader will perform of a new word while fixating on the word prior to it—even given a fixed launch site (Engbert, Longtin, & Kliegl, 2002; Reichle, Pollatsek, Fisher, & Rayner, 1998). Under the fast-heuristic account—in which saccade targeting depends only on the launch site—this variability in processing will be unrelated to variability in targeting the new word and thus unrelated to variability in the landing site. Under the cognitive-processing account, however, this variability will be related to saccade targeting: Readers should target their eyes farther forward into a word on trials in which they have already obtained more information about its initial letters prior to fixating on it. Thus, under the cognitive-processing account, trials in which readers land farther forward in a word should be more likely to be cases in which they have already identified more of the word prior to fixating on it. The fast-heuristic account predicts that there cannot be such a relationship. We tested these predictions about the relationship between landing position and how much processing readers have done prior to fixating on a word by measuring their eye movements after they fixate on the word.

Naively, then, we could compare word-identification time as a function of landing site. However, fixation position within a word has robust effects on word-identification measures—demonstrated not only in standard eye-movement measures in reading (Vitu, O'Regan, & Mittau, 1990) but also in isolated visual word-recognition studies in which fixation position is under full experimental control (O'Regan et al., 1984). So, instead, we used a gaze-contingent display-change paradigm (McConkie & Rayner, 1975; Rayner, 1975) to shift the text during a saccade, experimentally dissociating where a saccade would have landed from its actual landing site (Feng, 2009; Inhoff, Weger, & Radach, 2005; McConkie, Zola, & Wolverton, 1980; Nuthmann, 2006; O'Regan, 1981). Because of visual saccadic suppression, participants could not see the changes that occurred during these saccades. This manipulation allowed us to compare saccade populations with different original destinations while holding actual landing site constant.

Method

In our experiments, we tracked readers' eyes while they read individual sentences in fixed-width font. Each sentence contained a seven-letter target word. When the readers' eyes crossed an invisible boundary immediately prior to the space preceding the target word (Rayner, 1975), the display was updated with one of three possible outcomes: *no shift*, in which no change occurred; *text-right shift*, in which the text was shifted three characters to the right, so that the eyes landed farther back in the text than they normally would have; or *text-left shift*, in which the text was shifted three characters to the left, so that the eyes landed farther forward in the text than they normally would have.

We distinguished seven different original destinations, one for each letter of the target word, numbered 1 through 7 (Fig. 1). For example, a saccade with Original Destination 2 would actually land on Letter 5 after a text-left shift, which is the same actual landing position as a saccade with Original Destination 5 in the no-shift condition. Thus, we could compare these two saccade populations (one with Original Destination 2, one with Original Destination 5) at a constant actual landing position of Letter 5 (in the text-left-shift and no-shift conditions, respectively). Similarly, we could compare these same two populations at an actual landing position of Letter 2 (in the no-shift and text-right-shift conditions, respectively).

Because our manipulation shifted the text by three characters, we could compare each pair of populations with original destinations that differed by three while holding actual landing position constant, yielding four comparisons in total on our seven-letter target word (1 vs. 4, 2 vs. 5, 3 vs. 6, and 4 vs. 7). In each of these comparisons, we describe the population with the smaller numbered original destination as *farther behind* and the population with the larger numbered original destination as *farther forward*. As in the previous example, we could make each of these four comparisons at two actual landing sites. Thus, the total analysis design can be viewed as being similar to a 4 × 2 × 2 crossing of 4 comparisons (1 vs. 4, 2 vs. 5, 3 vs. 6, 4 vs. 7) × 2 types of original destinations (farther behind, farther forward) × 2 actual landing sites per comparison.[2]

In this design, the main prediction of the cognitive-processing account is that in each of these comparisons, measures of postsaccade word processing should show less subsequent processing for the farther-forward original destination, while holding constant actual landing site. In contrast, the fast-heuristic account of saccade targeting predicts that there should be no effect of original destination as long as launch site and actual landing site are held constant. The experiment's main goal, then, was to assess whether there is an effect of original destination on target-word processing, controlling for actual landing site.

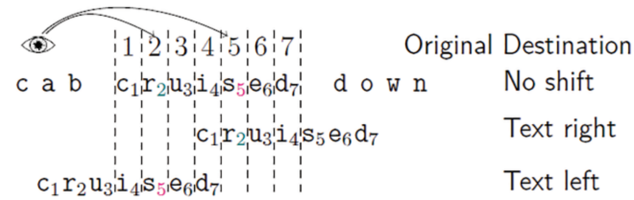


Fig. 1. Illustration of the actual landing positions of two saccade populations across all three conditions, for the experimental sentence, "A yellow cab cruised down the highway." Columns show original destinations in the target word "cruised," indexed in Row 1 by Target-Word Letter Numbers 1 through 7. (Subscripts and extra spaces between letters in this figure were not displayed to participants.) Arrows show Original Destinations 2 and 5. Rows 2 through 4 show the postsaccade location of the text in each experimental condition, with target-word letters numbered by subscripts. (Row 2 also shows one word of context on each side; for visual simplicity, context words are omitted in Rows 3 and 4.) In the no-shift condition, the text is not shifted, and the actual landing site is the original destination. In the text-right-shift condition, Original Destinations 1 through 3 do not land on the target word; for Original Destinations 4 through 7, the actual landing site is three letters farther back. In the text-left-shift condition, Original Destinations 5 through 7 do not land on the target word; for Original Destinations 1 through 4, the actual landing site is three letters farther forward. Combining the three conditions makes possible two comparisons of Original Destinations 2 and 5 while holding actual landing site constant: one at Actual Landing Site 2 (comparing text-right-shift Original Destination 5 and no-shift Original Destination 2; green subscripts) and one at Actual Landing Site 5 (comparing text-left-shift Original Destination 2 and no-shift Original Destination 5; magenta subscripts).

Participants and materials

We conducted three experiments, which were identical except that one of them did not include the text-left-shift condition. We included 40 participants in the first experiment, which contained only the no-shift and text-right-shift conditions. This initial sample size was chosen intuitively on the basis of our experience in research on eye movements in reading and is at the upper end of the range of participants commonly run in such experiments. Although this first experiment revealed a strong and clear effect, it became clear that the theoretical interpretation of this effect was limited by the absence of a text-left-shift condition. So we then ran 40 additional participants in a second experiment with all three conditions. (Sample size was chosen to match that of the first experiment.) The second experiment also yielded strong and clear effects. Finally, we found a way to speed the display change in our experiment software, so we conducted a third experiment with a faster display change (otherwise this experiment exactly replicated the second experiment) with a final group of 40 participants.[3] Here, we collapsed the data over the three experiments, yielding 120 total students from the University of California, San Diego, with normal or corrected-to-normal vision who participated for course credit and were included in our analyses (for results of the individual experiments, which are highly consistent with the collapsed analysis, see the Supplemental Material available online).

An experiment consisted of 160 sentences, each of which contained a seven-letter verb (target word), immediately preceded by a three- or four-letter noun (pretarget word; for complete materials, see https://osf.io/kgmpy). This number of items was about the largest number that can be reliably read during a single 1-hr experimental session, yielding the maximum possible power.

Procedure

Participants silently read each sentence, presented on a single line of the screen in 14-point Courier New font. In all experiments, half of the sentences were in the no-shift condition. For one experiment, the other half of the sentences were in the text-right-shift condition, and for the other two experiments, the other half were evenly split between the text-right-shift and text-left-shift conditions. Assignments of items to shift conditions was counterbalanced. Sentences were presented in an order randomized separately for each participant. To encourage attentive reading, we presented a simple comprehension question after a random 56 of the 160 trials. Breaks were offered halfway through the experiment and were available at other times on request.

Apparatus

Participants' eye movements were monitored with an EyeLink 1000 eye tracker (SR Research, Kanata, Ontario, Canada) sampling at 1,000 Hz. The eye-tracking camera was mounted above a chin rest, on which participants rested their heads during the experiment. Participants read binocularly, but only the right eye was tracked. Sentences were displayed on an HP p1230 20-in. CRT monitor with a 150-Hz refresh rate and 1,024 pixel × 768 pixel resolution. Viewing distance was 60 cm, so 1° of visual angle spanned about 2.4 characters.

Analysis

As is standard in studies of eye movements in reading, fixations shorter than 80 ms that occurred within a single character width (11 pixels) of an adjacent fixation were combined with that fixation, and fixations shorter than 80 ms that did not were removed. Trials containing a fixation longer than 1,000 ms or track loss (e.g., a blink) on, immediately preceding, or following the target-word region were also excluded because they do not yield trustworthy data.[4] Trials were also excluded if the display change was completed more than 9 ms after the beginning of the following fixation; this was done because a display change that occurs during fixation may disrupt reading. Participants who had excessive data loss, defined as more than one third of trials being excluded for track loss or more than half of trials being excluded for late display changes, were excluded and replaced. This procedure left 120 participants without excessive data loss who were included in the analyses (40 per experiment) and an additional 26 participants across the three experiments whose data were excluded (16 for track loss and 10 for late display changes). For the 120 participants who were left in the analysis, 14% of trials were excluded for these reasons.

We analyzed two measures of word processing: (a) gaze duration, the summed duration of all fixations on a region prior to leaving it, and (b) refixation probability, the probability of making more than one fixation on a region prior to leaving it. We analyzed the effect of original destination on gaze duration with linear mixed-effects regression (Pinheiro & Bates, 2000) and on refixation probability with logistic mixed-effects regression (Agresti, 2002). In addition to a fixed effect of original destination, all models included random intercepts and random slopes for original destination for both participants and items. As control variables, the actual (postshift) landing site and launch site were included as unordered categorical fixed effects. Because of concerns of data sparsity, we excluded launch sites with fewer than 20 observations (0.8% of trials). We do not report control-variable effects. Outlier gaze durations were excluded by removing all gaze durations more than 3 standard deviations from a participant's mean, without respect to experimental condition.

For the analyses of both gaze duration and refixation probability, we fitted two separate mixed-effects models designed to reflect our study's similarity to a 4 (comparisons) × 2 (types of original destination) × 2 (actual landing site) factorial design. These two models within each set differed only in how the effect of original destination was parameterized. The *main-effect* model included a main effect of original destination, averaging over the four comparisons, along with three interaction terms, allowing this effect to differ arbitrarily across comparisons. The main-effect model determined the estimates and confidence intervals (CIs) of the overall-average effect. The *independent model* was parameterized

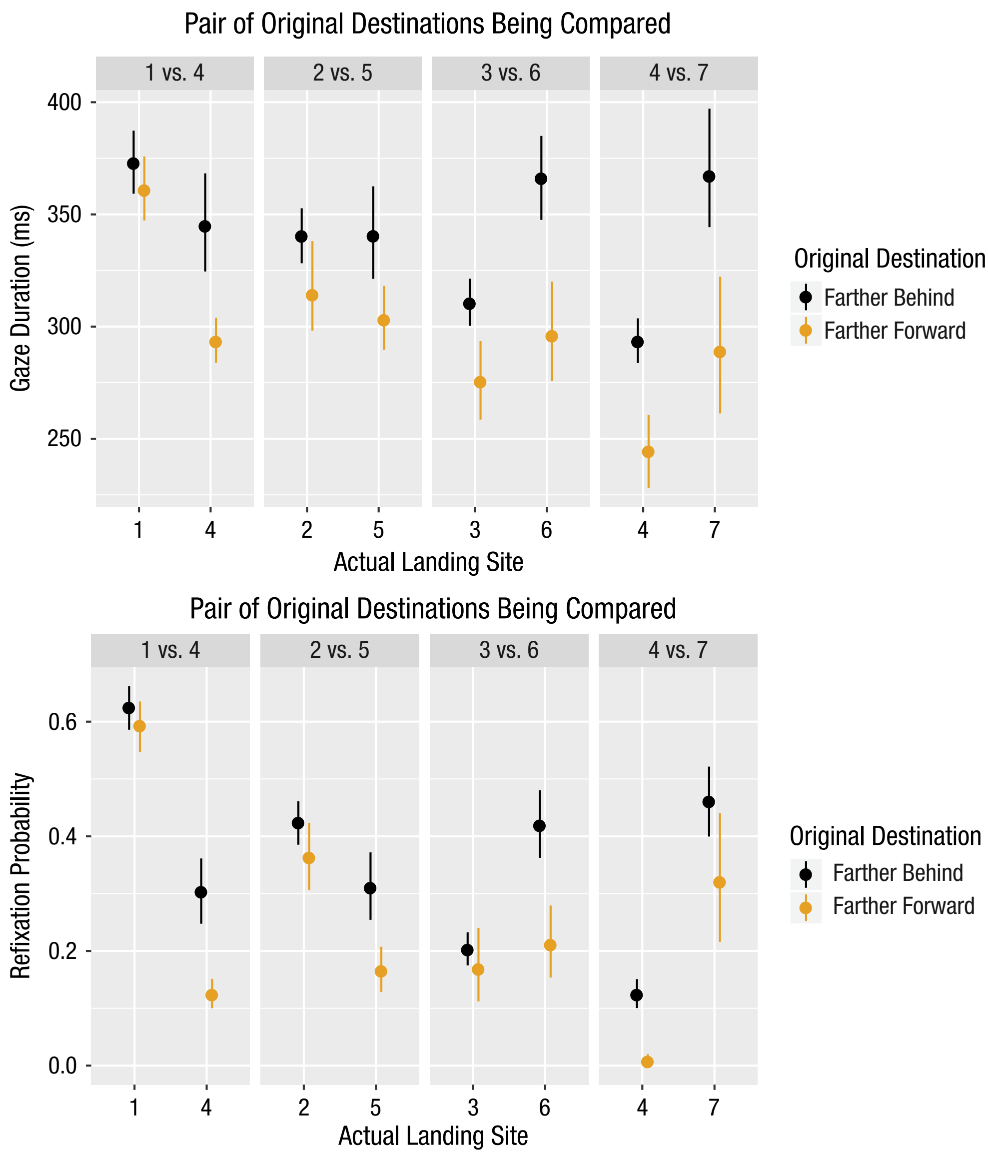


Fig. 2. Mean gaze duration (top) and refixation probability (bottom) as a function of the actual landing site of the saccade into the target word and whether the original destination of that saccade was farther behind or farther forward in the target word. Results are shown separately for each of the four comparison pairs of original destinations. Integers 1 through 7 refer to the letter number within the target word (see Fig. 1). Original destinations were defined within the target word prior to any shift. Error bars show bootstrapped 95% bias-corrected and accelerated confidence intervals over participant means (Efron, 1987).

to estimate the effect of original destination separately within each of the four pairs of saccade populations. All models included four terms allowing for arbitrary differences between the two actual landing sites within each population comparison, six terms for arbitrary differences between actual landing sites, and an effect of launch site. For more details on model parameterization, see Section S1 in the Supplemental Material. We computed *p* values via the likelihood-ratio test, comparing the full model with one without each fixed effect of interest. All raw data files and analysis scripts are available at https://osf.io/kgmpy.

Results

Overall analysis

Figure 2 shows gaze durations and refixation probabilities broken down according to the 4 × 2 × 2 factorial analysis described above. For every actual-landing-site-controlled

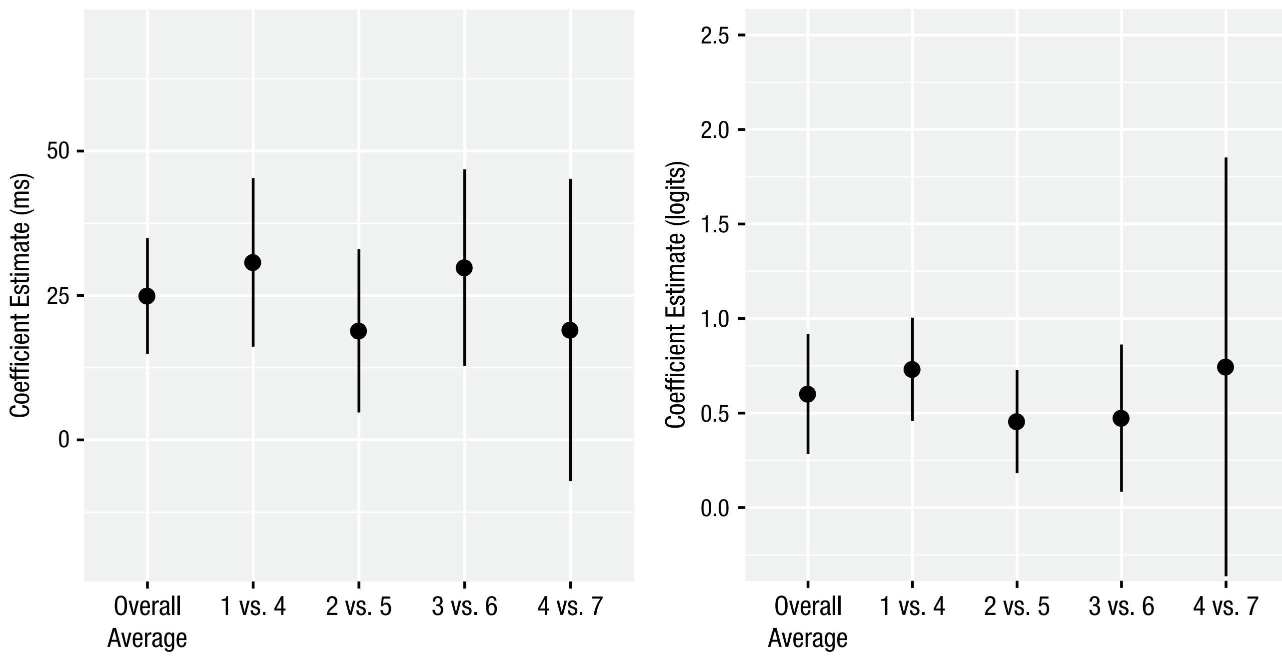


Fig. 3. Estimates of gaze duration (left) and refixation probability (right) from generalized mixed-effects regression of the effect on target-word processing of having a destination three letters farther behind in a word, while actual landing site is held constant. Error bars show 95% confidence intervals.

comparison, the original destination that was farther behind showed longer gaze durations and higher refixation probabilities on the target word, as predicted by the cognitive-processing account. This overall effect of original destination, averaged across all four comparisons and both landing sites for each comparison, was highly statistically reliable for gaze duration ($\hat{\beta} = 25$ ms, $p < .001$) and refixation probability ($\hat{\beta} = 0.6$ logits, $p < .001$). CIs on this overall effect, as estimated by generalized mixed-effects regression, are shown in Figure 3 in the leftmost column in each panel. An omnibus test of the interaction terms revealed no statistical evidence that the effect of original destination differed across comparisons (*p*s > .30).

In addition to the highly reliable overall effect of original destination, there were reliable effects of original destination for every comparison except the 4 vs. 7 comparison on gaze duration (1 vs. 4: $p < .001$; 2 vs. 5: $p < .01$; 3 vs. 6: $p < .001$; 4 vs. 7: $p = .18$) and refixation rate (1 vs. 4: $p < .001$; 2 vs. 5: $p < .01$; 3 vs. 6: $p < .05$; 4 vs. 7: $p = .19$). CIs for each of these comparisons are shown in Figure 3. This represents strong evidence that the original destination of the saccade is related to processing, even when the actual landing site is fixed.

Mislocated fixations

One limitation of the interpretive logic outlined above is that its predictions regarding the fast-heuristic account assumed that all saccades landing on the target word were intended for the target word. However, some of these saccades may have been intended for other words, landing on the target word only because of motor error, and there could be differences in the proportions of such mislocated fixations across different original destinations. Such mislocated fixations would come from two populations: (a) saccades that were intended for the pretarget word but overshot and (b) saccades that were intended to skip over the target word and land on the posttarget word but undershot. The former population can be further subdivided into cases in which the pretarget word was not yet fixated (intended initial fixations) and cases in which the pretarget word had already been fixated (intended refixations). Under the fast-heuristic account, in which intended refixations always move the eyes in the direction of the word center, we could eliminate all mislocated fixations of type (a) by restricting our analysis to a subset of trials in which the saccade going to the target word was preceded by a single fixation on the right half of the pretarget word.

Subset analysis. To ensure that these results could not be explained under the fast-heuristic account by mislocated fixations intended for the pretarget word, we performed the same analysis as above on this subset of the data (representing 49% of the full data set). Figure 4 shows the raw data in this subset, and CIs for each of the

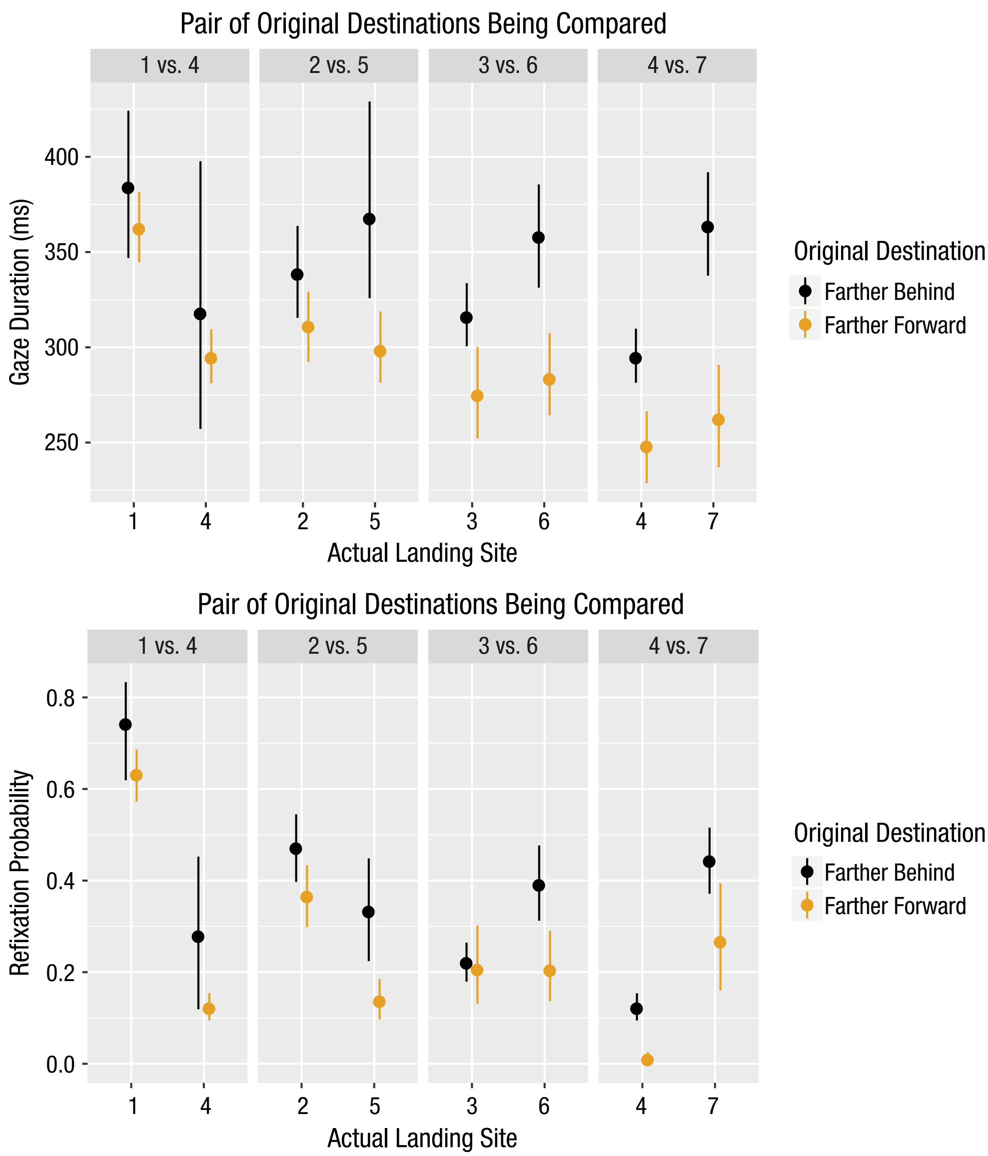


Fig. 4. Mean gaze duration (top) and refixation probability (bottom) for the subset of data in which the saccade to the target word was preceded by a single fixation on the right half of the pretarget word. Values are shown as a function of the actual landing site of the saccade into the target word and whether the original destination of that saccade was farther behind or farther forward in the target word. Results are shown separately for each of the four comparison pairs of original destinations. Integers 1 through 7 refer to the letter number within the target word (see Fig. 1). Original destinations were defined within the target word prior to any shift. Error bars show bootstrapped 95% bias-corrected and accelerated confidence intervals over participant means (Efron, 1987).

four comparisons are shown in Figure 5. Results were highly similar to those for the full data set. Again, we see that for every actual-landing-site-controlled comparison, the original destination that was farther behind showed longer gaze durations and higher refixation probabilities on the target word, as predicted by the cognitive-processing account. This overall effect of original destination, averaged across all four comparisons and both landing sites for each comparison, was statistically reliable for gaze duration ($\hat{\beta}$ = 34 ms, $p < .001$) and refixation probability ($\hat{\beta}$ = 0.8 logits, $p < .001$). An omnibus test of the interaction terms revealed no statistical evidence that the effect of original destination differed across comparisons (ps > .4). There were reliable effects of original destination for nearly every comparison on gaze duration (1 vs. 4: p = .34; 2 vs. 5: $p < .001$; 3 vs. 6: $p < .001$; 4 vs. 7: $p < .01$) and refixation rate (1 vs. 4: $p < .05$; 2 vs. 5: $p < .001$; 3 vs. 6: p = .087; 4 vs. 7: $p < .05$). This represents strong evidence that these results cannot be explained by mislocated fixations intended for the pretarget word.

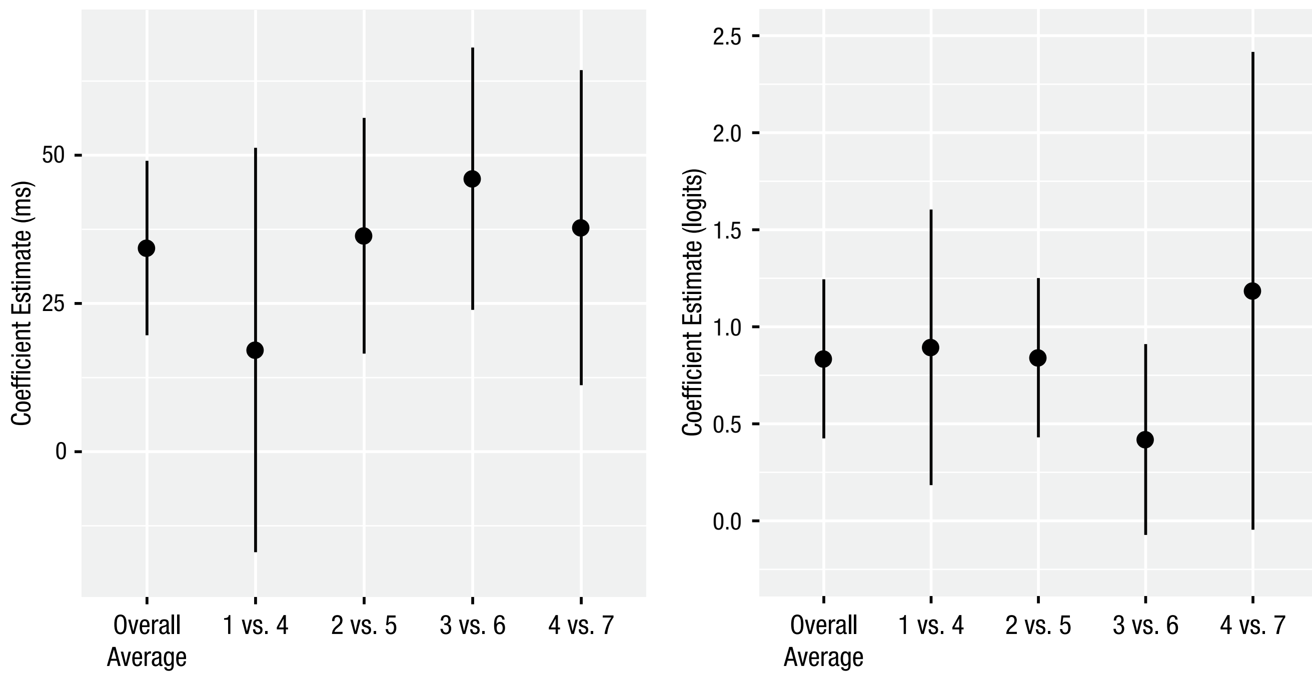
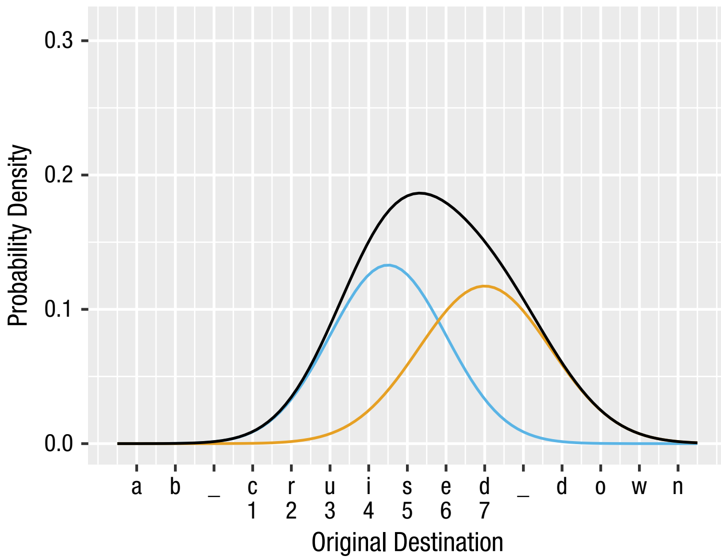


Fig. 5. Estimates of gaze duration (left) and refixation probability (right) for the subset of data in which the saccade going to the target word was preceded by a single fixation on the right half of the pretarget word. Estimates are from generalized mixed-effects regression of the effect on target-word processing of having a destination three letters farther behind in a word, while actual landing site is held constant. Error bars show 95% confidence intervals.

Mixture-of-Gaussian modeling. Although according to the fast-heuristic account, this subset of data does not contain mislocated fixations intended for the pretarget word (saccades that were intended for the pretarget word but overshot), it is possible that it contains mislocated fixations intended for the posttarget word (saccades that were intended to skip over the target word and land on the posttarget word but undershot). Under the fast-heuristic account, the set of saccades landing on the target may thus be a mixture of two normally distributed populations: one intended for the target word, the other for the posttarget word (*intended-skip* saccades; Fig. 6). For a given original destination, the proportion of intended-skip saccades in the population would depend on the parameters of the mixture distribution: the two normal components' means, variances, and mixing probabilities. For example, the set of saccades with Original Destination 4 may have contained a lower proportion of intended-skip saccades than the set of saccades with Original Destination 7, and similarly for 1 versus 4, 2 versus 5, and 3 versus 6. Assuming that saccades intended for the posttarget word reflect trials in which there has been more processing of the target word prior to landing on it, differences in the proportion of intended-skip saccades between original-destination populations for a given landing site could potentially explain our results within the fast-heuristic account.

Determining the plausibility of this explanation for our data within the fast-heuristic account requires knowledge of the mixture parameters, and there is no general agreement on what values these parameters would take. The large amount of data we have about the distribution of forward saccades from the pretarget word, however, allows us to fit the mixture model directly. In the fast-heuristic account, the parameters of the distributions are a function of launch site, so we fitted mixture models separately for each of our two launch sites: two or three characters before the critical word (as our precritical words are always three or four characters in length). The maximum-likelihood mixture models for each launch site are presented in the left column of Figure 7 (for a range of other mixture-model estimates, all of which yield conclusions qualitatively similar to those reported here, see Section S2 in the Supplemental Material). From these fits, we calculated the proportion of intended-skip saccades for each original destination (Fig. 7, right column). In both cases, we found that the fast-heuristic account could potentially explain the differences between Populations 3 versus 6 and 4 versus 7, because the proportions of saccades intended for the posttarget word were substantially higher for the farther-forward original destinations. Crucially, however, this was not the case for the other two differences we observed—1 versus 4 and 2 versus



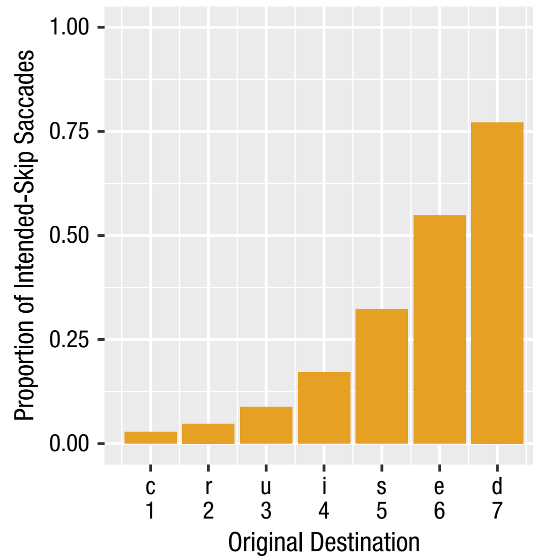


Fig. 6. Predictions of the fast-heuristic account. Saccades that land on the target word arise from a mixture of two normal distributions (left panel): one distribution intended for the target word (hypothetical distribution in blue) and one for the posttarget word (hypothetical distribution in orange; the resulting marginal distribution is in black). Populations of saccades with different original destinations have different probabilities of coming from each of these two distributions (right panel). For the two hypothetical distributions shown here, saccades with destinations of Character 1 would be very likely intended for the target word, and saccades with destinations of Character 7 would be likely intended for the posttarget word (*intended-skip* saccades).

5—because the proportion of intended-skip saccades was estimated as lower for Original Destination 4 than 1 and lower or virtually equal (within 1 percentage point) for 5 than 2. Thus, even the possibility of mislocated fixations cannot explain our data under the fast-heuristic account.

Discussion

These data provide strong evidence against the fast-heuristic account, in which all saccades to a word from a particular launch site are aimed at the same position. Contrary to this account's predictions, we found reliable differences in subsequent eye-movement behavior between saccades that would have landed at different locations within a word, holding constant the saccade's actual landing position and controlling for launch site. Additional analyses found that these results were still incompatible with the fast-heuristic account even under the assumption that some saccades to the target word were intended for another word. Rather, our key result—that saccades directed farther forward in the target word were associated with less subsequent target-word processing on landing—is highly consistent with the predictions of the cognitive-processing account of saccade targeting. According to this account, readers who have already identified more of a word's initial letters will preferentially direct their eyes farther forward in the word, so on trials with farther-forward original destinations, we should see less target-word processing when actual landing site is (experimentally) held constant. (For further discussion of alternative interpretations that can be ruled out, see Section S4 in the Supplemental Material.) The cognitive-processing account naturally explains the relationship between saccade targeting and subsequent eye-movement behavior in our data, suggesting that motor control in reading is optimized to maximize efficiency.

Our results provide clear evidence for a role of cognitive processing in within-word saccade targeting, but this leaves the role of fast heuristics unspecified. It could be that fast heuristics are usually relied on in saccade targeting but that in a subset of trials, cognitive processing intervenes to modulate saccade targeting. A more radical possibility is that saccade targeting in reading is always determined by cognitive processing. Which account should we prefer? The remarkable success of the fast-heuristic account in capturing a large amount of the variance in saccade targeting might suggest that the former account is preferred. However, it has been demonstrated that at least some cognitive-processing accounts can also explain these data (Legge et al., 2002). Given this, we suggest that the latter account may be preferred on grounds of parsimony. Additionally, because the fast-heuristic account is known not to provide good fits for data from the reading of scripts without spaces, such as Chinese (Li, Liu, & Rayner, 2011), a fully cognitive processing view of

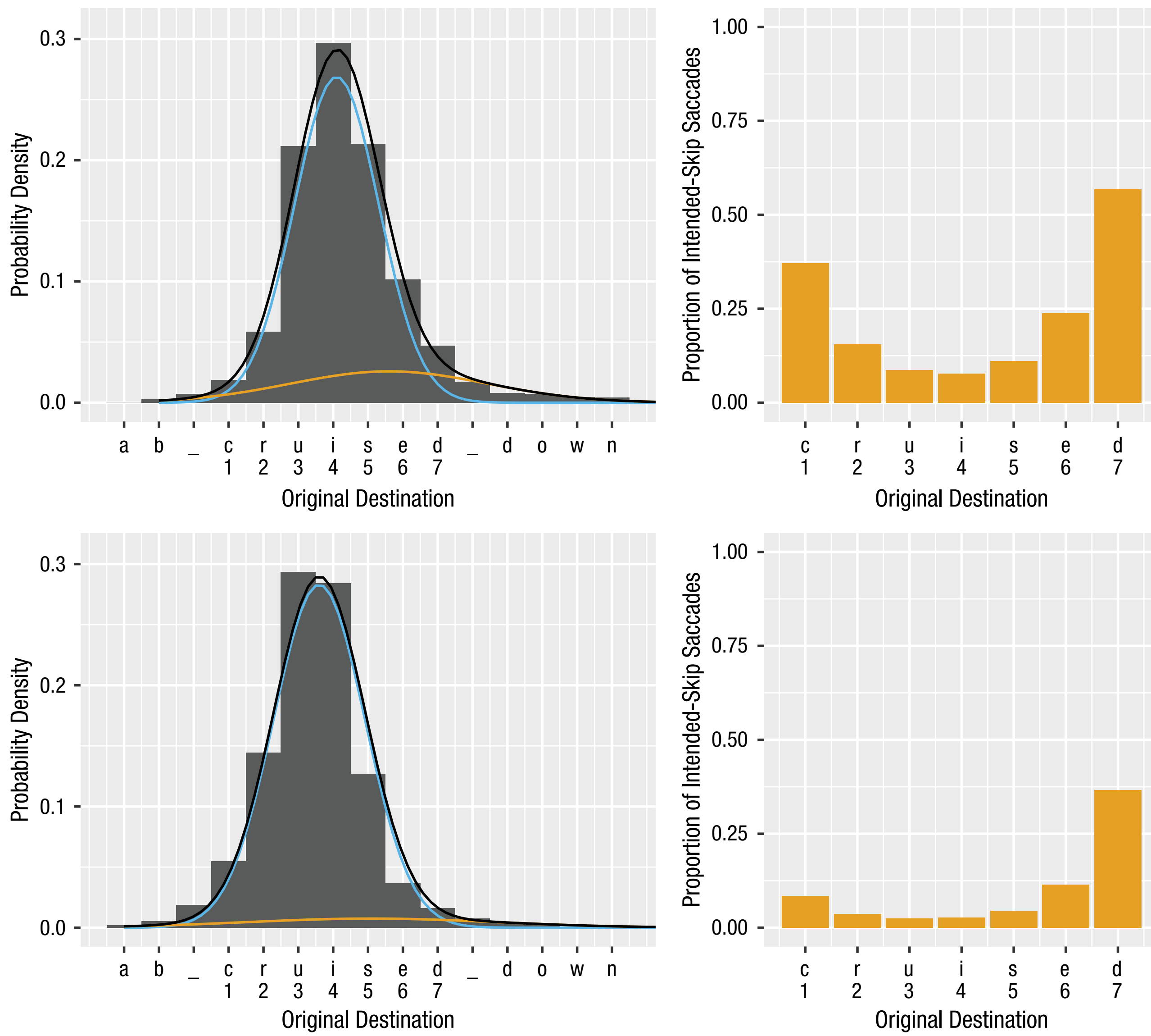


Fig. 7. Results from maximum-likelihood mixture-of-two-Gaussians models in forward saccades launched from three (top row) and two (bottom row) characters prior to the target word (left panel; saccades intended for target are blue, intended-skip saccades are orange, and marginal density is black) and the proportion of intended-skip saccades for each original destination (right panel).

saccade targeting also has the potential to provide a unified treatment of saccade targeting across languages and scripts. Future work teasing apart these possibilities will likely require quantitative comparisons of computational models of both accounts.

In summary, our results demonstrate a particular relationship between saccade targeting and ongoing cognitive processing. This relationship is counter to the predictions of the dominant fast-heuristic account of saccade targeting in reading, in which precise saccade-targeting decisions are the one type of decision in reading thought to be insensitive to ongoing cognitive processing. Instead, the nature of this relationship is just as would be predicted by a model in which saccade targeting is optimized for efficiency, in which readers' eyes scan farther forward into words when they have already obtained more information about the word's initial letters. Our findings thus open the door to a view of all eye-movement decisions in reading as reflecting goal-based optimization (Bicknell & Levy, 2010; Lewis, Shvartsman, & Singh, 2013) with respect to ongoing cognitive processing, in which fast heuristics have a limited role or none at all.

Our results also extend classic findings from other experimental studies of language processing, exemplifying how quickly the fine details of cognitive state during incremental word processing can influence behavior. In shadowing, in which participants repeat speech as they hear it, disrupted words are spontaneously restored to their original forms (e.g., hearing "tomorrane" and repeating it as "tomorrow") in syntactically and semantically supportive contexts, even when shadowing latency is as short as 250 ms (Marslen-Wilson, 1975). In the visual-world paradigm, listeners often initiate programs for saccades to objects in a visual scene that they hear named (e.g., *candle*) before they hear the end of the word (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Likewise, our present results indicate that in reading, within-word saccade targeting is guided by ongoing cognitive processing of that word itself, even when recognition is not yet complete. Given the present results for reading, we might expect ongoing cognitive processing to manifest a similar role in other fine-grained saccade-targeting decisions such as face processing (Peterson & Eckstein, 2012) and scene viewing (Henderson, 2017). Our experimental method and the logic of our predictions could be adapted to these and other settings in the study of oculomotor control.

Transparency

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K. Bicknell, R. Levy, and K. Rayner designed and performed the research and analyzed the data. K. Bicknell and R. Levy wrote the manuscript. All the authors approved the final manuscript for submission.
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All data, analysis scripts, and materials have been made publicly available via the Open Science Framework and can be accessed at https://osf.io/kgmpy. The design and analysis plans were not preregistered. The complete Open Practices Disclosure for this article can be found at http://journals.sagepub.com/doi/suppl/10.1177/0956797620901766. This article has received the badges for Open Data and Open Materials. More information about the Open Practices badges can be found at http://www.psychologicalscience.org/publications/badges.

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Supplemental Material

Additional supporting information can be found at http://journals.sagepub.com/doi/suppl/10.1177/0956797620901766

Notes

1. For writing systems that do not include spaces between words, a reader would have to make an educated guess about word length to use such a strategy.
2. This is not quite a standard factorial 4 × 2 × 2 design because 2 of the 16 cells were identical: The population with the farther-forward original destination in the 1 vs. 4 comparison assessed at Actual Landing Site 4 is the same as the population with the farther-behind original destination in the 4 vs. 7 comparison assessed at Actual Landing Site 4. The model specification we used for data analysis, which is summarized in the Results section and described in full detail in the Supplemental Material available online, takes into account this difference from a standard 4 × 2 × 2 design while maintaining factorial-design-like interpretability of the statistical analysis.
3. Before trials with late display changes were excluded, the median display change completed 9 ms before the start of the next fixation in the third experiment, compared with 3 ms after the start of the next fixation in the first two experiments. The speedup was achieved by setting the display_type parameter in the UMass EyeTrack software to "LCD."
4. Because the target word moved to different absolute positions on the screen depending on the shift condition, for the purposes of blink exclusion, we used a target-word region defined as the union of the locations occupied by the target word across all shift conditions.

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