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Investigating the causes of wrap-up effects: Evidence from eye movements and E-Z Reader

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Abstract

Wrap-up effects in reading have traditionally been thought to reflect increased processing associated with intra- and inter-clause integration (Just & Carpenter, 1980; Rayner, Kambe & Duffy, 2000; cf. Hirotani, Frazier, & Rayner, 2006). We report an eye-tracking experiment with a strong manipulation of integrative complexity at a critical word that was either sentence-final, ended a comma-marked clause, or was not comma marked. Although both complexity and punctuation each had reliable effects, they did not interact in any eye-movement measure. These results and simulations using the E-Z Reader model of eye-movement control (Reichle, Warren, & McConnell, 2009) suggest that traditional accounts of clause wrap-up are incomplete.

Readers tend to spend longer reading sentence- or clause-final words than sentence- or clause-internal words (Aaronson & Scarborough, 1976; Just & Carpenter, 1980; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989). This phenomenon is referred to as sentence or clause wrap-up and has traditionally been thought to be due to integrative processing that occurs sentence- or clause-finally, such as the processing involved in relating sentences or clauses and updating a discourse model (Just & Carpenter, 1980; Rayner, Kambe, & Duffy, 2000). Recently however, this classic interpretation of wrap-up effects has been questioned. Hirotani, Frazier, and Rayner (2006) argued that wrap-up effects reflect pauses associated with implicit prosody. Hill and Murray (2000) proposed that they are a low-level hesitation response of the oculomotor system in response to the punctuation and/or longer spacing that often occurs at clause and sentence boundaries.

One way to test the integrative processing hypothesis is to check for an interaction between sentence complexity and wrap-up. If an increase in integrative processing drives wrap-up effects, then sentence complexity and the presence of a punctuation-marked boundary should interact such that wrap-up effects are greater for more complex sentences. This interaction could be predicted either because more integrative processing is likely to be off-loaded until the end of a complex than a simple clause, or because more complex clauses require more

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difficult integration. On the other hand, if wrap-up effects reflect implicit prosody or low-level reactions to visual cues then no such interaction would be expected.

Hirotani et al. (2006) reported an eye-tracking experiment testing for such an interaction. Their between-items complexity manipulation varied the presence of a few adjectives, adverbs, and/or prepositional phrases in an initial clause, the critical word of which (*fish* in the simple condition below) was either clause-internal (1a), clause-final and not comma-marked (1b), clause-final and comma-marked (c), or sentence-final (1d).

Simple:

(1a) The mother cooked the fish yesterday, after the boy caught it. He was excited.

(1b) The mother cooked the fish after the boy caught it. He was excited.

(1c) The mother cooked the fish, after the boy caught it. He was excited.

(1d) The mother cooked the fish. After the boy caught it he was excited.

Complex:

(2a) Jeremy prepared the marinade for the venison steaks last night, while…

At the critical region *the fish* or *venison steaks* above, first-pass reading measures indicated effects of punctuation/structural boundaries with similar patterns and effect sizes in the simple and complex conditions. Fixations on the critical word were longest in the sentence-final condition, shorter in the comma-marked condition, and shortest in the non-comma-marked clause-final and clause-internal conditions. These results weigh against an interaction between sentence complexity and the presence of a boundary, contrary to the predictions of the integrative processing hypothesis. However, this complexity manipulation may not have been strong enough to modulate wrap-up effects.

The current paper reports an experiment and a computational simulation using the E-Z Reader model of eye movement control in reading (Reichle, Warren, & McConnell, 2009). The experiment followed up on Hirotani et al. (2006), but used better-controlled items and a stronger within-items manipulation of sentential complexity. In the simple conditions, the initial clause included a conjunction and an optionally transitive or reciprocal verb (Figure 1, conditions a-c). In the complex conditions, the conjunction was rearranged as an object cleft (Figure 1, conditions d-f). Previous research has demonstrated that the verb is a position of extreme complexity in object clefts in which both referents are referred to by name (Gordon, Hendrick, & Johnson, 2001; Warren & Gibson, 2005).

The critical word was the verb of the first clause (*phoned* in Figure 1). According to the integrative processing hypothesis, the complex conditions should show larger wrap-up effects than the simple conditions because they require more integrative processing, more of which will be off-loaded until the end of the clause or sentence. Warren and Gibson (2005) provide evidence that some integrative processing is delayed until the end of sentences with object cleft structures. In their study, reading time effects of processing complexity were manifest at the cleft verb, dissipated, and then reappeared at a sentence-final word.

All relevant theories predict effects of both complexity and punctuation. However, the magnitude and time course of these effects in the present experiment, as well as their interaction or lack thereof, may help distinguish between theories of wrap-up. Additionally, interpreting the current results within the framework of the E-Z Reader model will allow us to consider potential co-influences of different mechanisms that have been proposed to explain wrap-up and test explicit hypotheses about how increased integrative processing and visual cues like punctuation might influence eye movements in reading.

Methods

Participants

48 undergraduates at the University of Pittsburgh participated for course credit. All were native English speakers with normal or corrected-to-normal (via contact lenses) vision.

Apparatus

An Eyelink 1000 eye-tracker monitored the gaze location of participants' right eyes during reading. The eye tracker has a spatial resolution better than 30′ arc and a 1000 Hz sample rate. Participants viewed the stimuli binocularly on a monitor 63 cm from their eyes; 3.3 characters equaled approximately 1° of visual angle.

Materials

The materials consisted of 54 items in a 2 × 3 design crossing syntactic complexity (simple vs. complex) with punctuation (period, comma, null). All content words were the same for each item across conditions. The critical verb and the following word were always 5 or 6 letters long. In the period condition, the critical verb was sentence-final; in the comma condition it ended a comma-marked clause; and in the null condition it finished a clause but was not comma-marked. Spacing between every word was the same, regardless of the presence or absence of a punctuation mark. This was accomplished by manipulating a bolded mono-spaced font: text was 14 point font, punctuation was 10 point font, and all inter-word spaces with or without punctuation summed to 15 points (see Figure 1). These specifications held for every sentence each participant saw in the experimental session, including fillers and practice. This control of spacing is in contrast to previous eye-movement studies of wrap-up, in which either: (1) words separated by punctuation were twice as far apart as words not separated by punctuation (e.g., Rayner et al., 2000;Hirotani et al., 2006), or (2) a condition with no punctuation had a double space where other conditions had a punctuation mark and a space (Hill & Murray, 2000).

The 54 experimental items were combined with 36 filler items and 32 items from an unrelated experiment. Conditions were counterbalanced across six presentation lists using a Latin square design. After 33% of the sentences in the experimental session, participants answered a yes/no comprehension question using a button response. Half required a “yes” response.

Procedure

The experiment lasted 40-55 minutes. A chinrest and forehead rest minimized head movements. Participants were asked to read normally, for comprehension, and were told that after some passages they would need to answer a comprehension question. After the participant was seated at the eye tracker and had been instructed as to the format of the experiment, the tracker was aligned and calibrated. Calibration was checked between trials and the tracker was recalibrated as necessary.

Results

Two analysis regions were defined. The critical region was the verb in the first sentence (*phoned*). The post-critical region consisted of the following word (*before*).

Comprehension rates were high (M = 91%, SD = 5.8%). Approximately 7% of trials were excluded from analysis due to track losses, blinks in or near the critical region, and/or incomplete trials. Fixations shorter than 80 ms that fell within 1.5 characters of another fixation were grouped; other fixations under 80 ms and all fixations over 1000 ms were excluded. The critical word was fixated on approximately 90% of trials during first pass reading across all conditions. Data loss affected all conditions similarly.

Four eye-movement measures reflecting first pass reading were computed on the critical verb (Rayner, 1998). *First-fixation duration* is the duration of the first fixation on a word during first pass reading. *Gaze duration* is the sum of all fixations from first fixating a word during first pass reading until leaving it. *Go-past time* (also called *regression-path duration*) is the sum of all fixations from first fixating a word during first pass reading until leaving it to the right, including regressive fixations. *Regressions out* is the percentage of trials a region was regressed from during first pass reading. Additionally, we investigated the length of saccades from the critical verb to the post-critical word during first pass reading of the post-critical word, and the position of the first fixation on the post-critical word. Data were subjected to *ANOVA*s using participants (F_1) and items (F_2) as random factors.

Critical word

Figure 2 shows the mean eye-movement measures on the critical verb[1]. Punctuation and complexity did not interact in any measure (all Fs≤1; ps>.3). However, every measure showed a main effect of punctuation, with the period conditions having the longest durations/most regressions, the comma being intermediate, and the null shortest/least (First-Fixation: $F_1(2,94)=6.8$, $MS_e=1405.4$, $p<.005$, $p_{rep}=.984$; $F_2(2,106)=8.3$, $MS_e=1439$, $p<.001$, $p_{rep}>.99$; Gaze: $F_1(2,94)=15.0$, $MS_e=3361$, $p<.001$, $p_{rep}>.99$; $F_2(2,106)=16.3$, $MS_e=3309$, $p<.001$, $p_{rep}>.99$; Go-Past: $F_1(2,94)=29.2$, $MS_e=20341$, $p<.001$, $p_{rep}>.99$; $F_2(2,106)=31.4$, $MS_e=21628$, $p<.001$, $p_{rep}>.99$; Regressions Out: $F_1(2,94)=25.1$, $MS_e=.02$, $p<.001$, $p_{rep}>.99$; $F_2(2,106)=22.3$, $MS_e=.03$, $p<.001$, $p_{rep}>.99$). Complexity effects, with complex conditions having longer durations/more regressions than simple ones, were reliable primarily in measures that indexed or included regressions (Go-Past: $F_1(1,47)=17.9$, $MS_e=43896$, $p<.001$, $p_{rep}>.99$; $F_2(1,53)=31.4$, $MS_e=26617$, $p<.001$, $p_{rep}>.99$; Regressions Out: $F_1(1,47)=39.7$, $MS_e=.03$, $p<.001$, $p_{rep}>.99$; $F_2(1,53)=34.7$, $MS_e=.04$, $p<.001$, $p_{rep}>.99$). First fixation showed this same pattern, but the effect was reliable only by participants ($F_1(1,48)=4.5$, $MS_e=967$, $p<.05$, $p_{rep}=.883$; $F_2(1,53)=2.1$, $MS_e=1782$, $p=.16$). Gaze duration had a numerically reversed pattern (Fs<1), with simple conditions longer than complex conditions. This reversal may have occurred because: (1) gaze duration averaged 45 ms shorter for trials with a first pass regression from this region (cf. Altmann, Garnham, & Dennis, 1992;Mitchell, Shen, Green, & Hodgson, 2008), and (2) there were more regressions from the complex conditions.

Post-critical word

Previous studies investigating wrap-up have found effects of landing position on the post-critical word (Hirotani et al., 2006). The current study found no such effects (means ranged from 2.7 to 3.0 characters from the end of the critical word). However, saccades from the critical word to the post-critical word on first pass fixation of the post-critical word averaged .3 of a character longer in the complex conditions ($F_1(1,47)=12.0$, $MS_e=.65$, $p=.001$, $p_{rep}=.99$; $F_2(1,53)=12.8$, $MS_e=.48$, $p=.001$, $p_{rep}=.99$). There were no effects of punctuation or interactions (Fs<1) in this measure. This pattern, namely an effect of complexity on saccade length but not landing position, suggests a launch site difference from the critical word, likely related to differences in regression patterns from, or refixations on, the critical word in the simple and complex conditions.

[1]Due to experimenter error, one stimulus item was presented twice. The analyses reported below include the item, but analyses excluding it are almost identical.

Modeling

To further examine our results, we simulated them using E-Z Reader 10 (Reichle et al., 2009). As Figure 3 shows, this model assumes that the completion of an early stage of lexical processing, called the *familiarity check*, causes the oculomotor system to begin programming a saccade to the next word. Following lexical access, attention shifts to the next word so that it can be processed, and simultaneously the meaning of the identified word is integrated into a higher-level representation. This post-lexical processing is broadly consistent with the "good enough" processing approach (e.g., Ferreira & Patson, 2007) and represents the syntactic, semantic, referential, and discourse processing necessary for whatever level of comprehension satisfies the reader. In most cases, this integration stage requires time $t(I)$ to complete, although in some cases $t(I)$ reflects the integration time that elapses before the system takes action on a signal indicating likely upcoming difficulty. After $t(I)$ has elapsed, with some probability, p_F, integration fails (e.g., as might happen when a reader is garden-pathed) or a cue like punctuation anticipates that integration will take longer, indicating a likely imminent breakdown in coordination between lexical and post-lexical processing. If integration fails, a cue indicates impending trouble, or the integration of word n does not complete before the completion of lexical processing on word n+1, the forward progression of the eyes is halted, leading to longer fixations and more regressions. These regressions target the problematic word with probability p_N, or an earlier word with probability $1.0 - p_N$. Because integration failure can occur or a cue can have its effect during the labile stage of saccadic programming, either of these can cancel a planned progressive saccade and thereby increase first-fixation and gaze durations (see Reichle et al., 2009 for details).

To model wrap-up effects, we set the frequencies and lengths of the pre-target, target, and post-target words equal to their mean empirical values, and their predictabilities equal to zero. These word triplets were embedded into the Schilling, Rayner, and Chumbley (1998) sentence frames (see Reichle et al., 2009, Footnote 3). All of the model's parameters were set to default values. Results generalized across a range of p_N values; we report simulations where p_N was set to 0.5. The values of $t(I)$ and p_F were orthogonally varied to identify the values that best predicted the regression probabilities and minimized the absolute mean deviations between the observed and simulated first-fixation and gaze durations in each condition. (Although we report simulated go-past times for completeness, we ignored them in selecting parameters because re-reading has not yet been fully specified within the model.) Figure 2 shows the simulation results using the best-fitting values of $t(I)$ and p_F and 1,000 statistical subjects per condition. Note that these results confirm that E-Z Reader (Reichle et al., 2009) can simulate behaviors (e.g., inter-word regressions spurred by post-lexical processing) that have here-to-fore been ignored by eye-movement models.

An examination of the best-fitting parameter values allows inferences about how sentence-processing difficulty and punctuation influence on-going lexical and post-lexical processing and eye guidance. If $t(I)$ indexes the time required for the integration stage to either complete, fail, or be cued to likely upcoming disruption, then the increase in $t(I)$ associated with complexity could reflect longer/more post-lexical processing and the decrease in $t(I)$ associated with punctuation could reflect quicker use/implementation of the cue to anticipated disruption. Increases in p_F associated with punctuation could be interpreted as increases in the likelihood of anticipating difficulty, while increases associated with complexity could be interpreted as increases in the likelihood of integration failure.

General Discussion

The results of this experiment were inconsistent with the hypothesis that wrap-up effects are solely due to increased integrative processing. Unlike in previous studies (e.g., Rayner et al., 2000; Hill & Murray, 2000), wrap-up effects were reliable as early as the first fixation on the critical word. This implicates a mechanism other than increased integrative processing, because such additional processing would be expected to occur after normal integrative processing and be evident only in later measures. Additionally, although both complexity and punctuation caused reliable effects, they did not interact. This also weighs against a single mechanism account of wrap-up (cf., Just & Carpenter, 1980; Rayner et al., 2000).

The early effects of punctuation implicate a mechanism that operates quickly, likely relying on the fact that punctuation marks, and in the case of periods, the attendant capitalization of the next word, are strong, early-available cues to the oculomotor and language systems. Consistent with Hill and Murray (2000), and with our interpretation of E-Z Reader's p_F increase and *t(I)* decrease associated with punctuation, this could be a low-level oculomotor response conditioned to the presence of punctuation, allowing time for additional processing, but not driven by the need for additional processing per se. It could alternatively be an oculomotor response conditioned to implicit prosody (Hirotani et al., 2006).

Although some report that saccades crossing punctuation are longer (Rayner et al., 2000; Hirotani et al., 2006), the current data did not show this. Such effects may thus be due to differences in spacing usually associated with punctuation [see Hill & Murray (2000) for a similar argument]. However, the current results rule out the possibility that such spacing differences drive wrap-up effects (cf., Hill & Murray, 2000).

An E-Z Reader 10 simulation of the current data accurately predicted gaze durations, first-pass regressions out of the critical word, and most first fixation durations. However, first fixations were slightly under-predicted in two of the complex conditions. This is because the model almost always predicts that first fixation effects will also appear in gaze duration. If the reliable-by-participants complexity effect in first fixation is real, then the observed dissociation between first fixation and gaze indicates a shortcoming of the model.

The results of the current experiment and simulations weigh against single-mechanism accounts of wrap-up, and instead support an account combining an occulomotor hesitation mechanism, possibly related to implicit prosody (Hirotani et al., 2006) or the frequent co-presence of punctuation and difficulty (Hill & Murray, 2000), with a traditional increased integrative processing mechanism (Just & Carpenter, 1980).

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(a)	Joe and Bob phoned. Before leaving Bob needed directions.	(Simple/Period)
(b)	Joe and Bob phoned, before leaving. Bob needed directions.	(Simple/Comma)
(c)	Joe and Bob phoned before leaving. Bob needed directions.	(Simple/Null)
(d)	It was Joe who Bob phoned. Before leaving Bob needed directions.	(Complex/Period)
(e)	It was Joe who Bob phoned, before leaving. Bob needed directions.	(Complex/Comma)
(f)	It was Joe who Bob phoned before leaving. Bob needed directions.	(Complex/Null)

Figure 1.
An example sentence with the same relative spacing and relative fonts as presented in the experiment (the figure has been reduced).

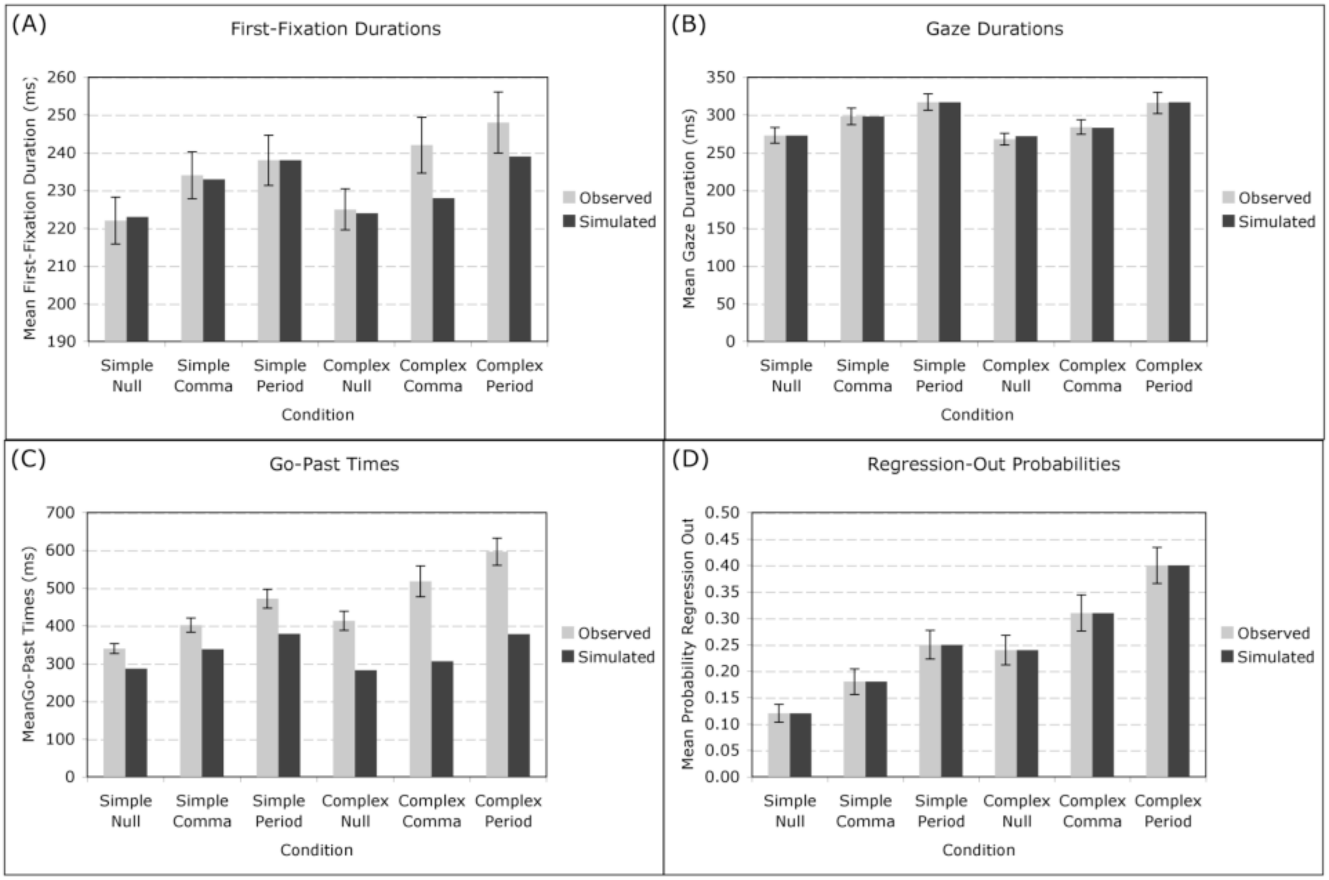

Figure 2.

Mean observed and simulated dependent measures on target words: (a) first-fixation durations; (b) gaze durations; (c) go-past times; and (d) regression probabilities. The following parameters were used in the simulated conditions: (1) Simple-Null: $t(I) = 102$, $p_F = 0.26$; (2) Simple-Comma: $t(I) = 84$, $p_F = 0.42$; (3) Simple-Period: $t(I) = 75$, $p_F = 0.62$; (4) Complex-Null: $t(I) = 139$, $p_F = 0.46$; (5) Complex-Comma: $t(I) = 116$, $p_F = 0.63$; and (6) Complex-Period: $t(I) = 93$, $p_F = 0.90$.

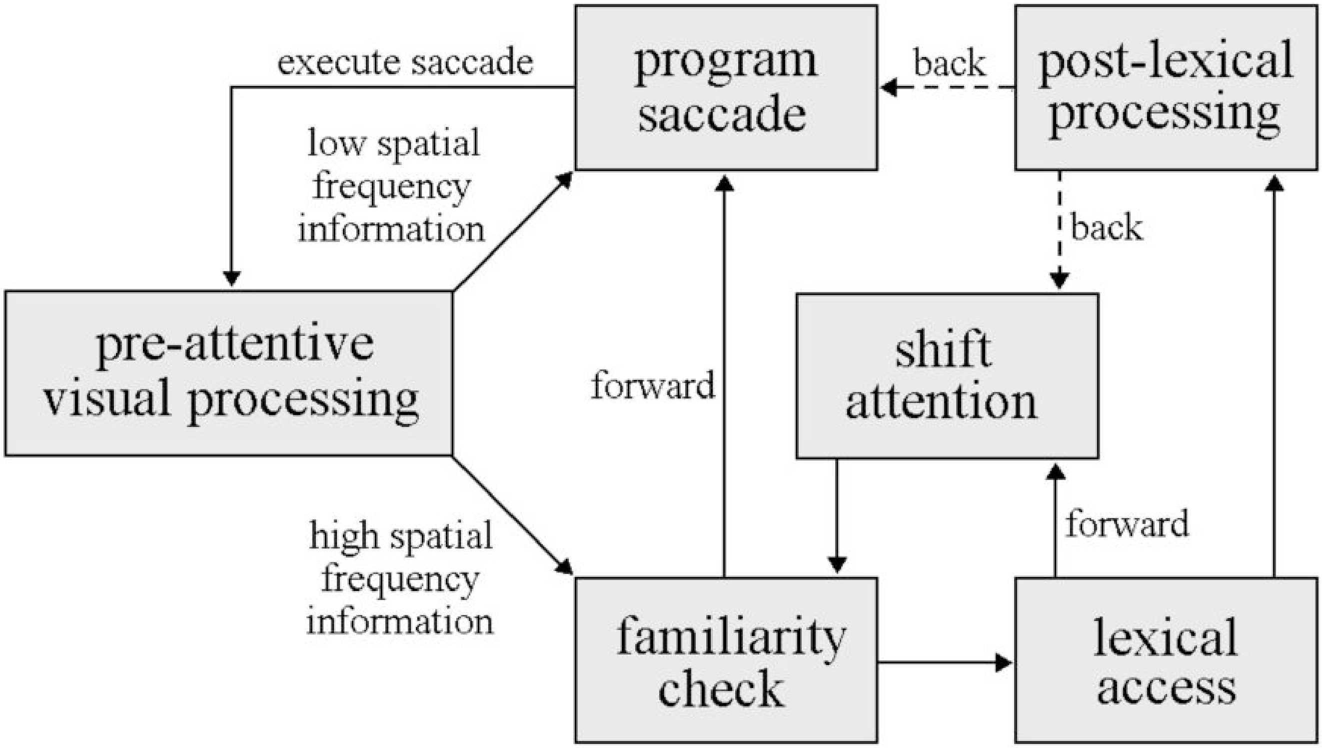

Figure 3.
A schematic diagram of *E-Z Reader* (Reichle et al., 2009). Solid lines indicate information flow/control among processes; dashed lines indicate probabilistic ($p < 1$) transitions.