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Temporal Overlap in the Linguistic Processing of Successive Words in Reading: Reply to Pollatsek, Reichle, and Rayner (2006a)

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Abstract

A. Pollatsek, E. D. Reichle, and K. Rayner (2006a) argue that the critical findings in A. W. Inhoff, B. M. Eiter, and R. Radach (2005) are in general agreement with core assumptions of sequential attention shift models if additional assumptions and facts are considered. The current authors critically discuss the hypothesized time line of processing and indicate that the success of Pollatsek et al.'s simulation is predicated on a gross underestimation of the pretarget word's viewing duration in Inhoff et al. and that the actual data are difficult to reconcile with the strictly serial attention shift assumption. The authors also discuss attention shifting and saccade programming assumptions in the E-Z Reader model and conclude that these are not in harmony with research in related domains of study.

Keywords

saccade; attention; word recognition; reading

In our article on the time course of extracting information from consecutive words during eye fixations in reading (Inhoff, Eiter, & Radach, 2005), we concluded that the time course of parafoveal information usage in Experiment 2 of our study favored a theoretical conception according to which extraction of linguistic information from spatially adjacent words in the text need not be strictly serial, as maintained by sequential attention shift (SAS) models of eye movement control in reading. Instead, we favored an attentional gradient conception.

In their comment on our article, Pollatsek, Reichle, and Rayner (2006a) defend the strictly serial word-processing assumption. They point to theoretical shortcomings in our critical Experiment 2, notably our neglect of a 50-ms visual transmission (VT) time that is also referred to as *eye-to-mind lag*. They also express some methodological reservations. Critically, they present an E-Z Reader model simulation that appears to be in agreement with our Experiment 2 data once VT time is considered.

In their comments on our study, Pollatsek et al. (2006a) first reiterate central theoretical claims of SAS models, including the E-Z Reader model, to clarify their position on serial processing and thus to illuminate what the controversy is about. They go on to critique several specific

method-related aspects of our study and then introduce arguments aimed at providing a justification of their E-Z Reader simulation of our Experiment 2 data. We first clarify our theoretical position, then respond to Pollatsek et al.'s specific concerns—that is, our neglect of VT time and their reservations vis-à-vis aspects of our methods. In response to their more general critique of our work, we also discuss some theoretical issues regarding the relationship between attention allocation and oculomotor control in reading.

The Attentional Gradient Conception

As we noted in our original study (Inhoff et al., 2005), our results did not support a conception according to which there is parallel processing of spatially adjacent words within the perceptual span. Instead, we argued for a “middle way,” according to which the linguistic processing of consecutive words can overlap in time rather than being strictly serial or strictly parallel. We advocate a theoretical conception, which we refer to as *attention gradient hypothesis*, according to which more than one word can be attended at a time but preferential processing will be given to a particular unit or subunit of text within the perceptual span at any point in time. The gradient is shifted so that consecutive words in the text can be recognized (Inhoff et al., 2005; Inhoff, Radach, Starr, & Greenberg, 2000).

According to our theoretical position, linguistic processing of two consecutive words in a sentence, such as *home run* or *run home*, overlaps in time but is *not* parallel. The attention gradient of *home* is likely to reach its peak at an earlier point in time than the gradient of *run* when the compound word *home run* is read, and the time line of the gradient shift for *run home* will follow the opposite temporal order. Confusion of *home run* with *run home* would thus be an exception rather than the rule, according to our attentional gradient conception. It is also plausible to assume that readers are sensitive to the actual spatial ordering of consecutive words. The spatial location of words on a line of print dictates word order, and spatial location may guide, for instance, meaning construction when complex compound words are read (Inhoff, Radach, & Heller, 2000).

Specific Concerns

According to Pollatsek et al. (2006a), consideration of VT time could “quite drastically” (p. 1487) change our critical predictions for Experiment 2 of our study (Inhoff et al., 2005). The experiment included two complementary temporal manipulations of a parafoveal target preview. In a beginning-of-fixation preview condition, the target word was visible to the right of a fixated pretarget word for 140 ms and was masked after that. In an end-of-fixation preview condition, the target preview was masked during the beginning 140 ms of pretarget viewing and was visible throughout the remainder of pretarget viewing. A full-target preview and a full-target mask change condition were used as baselines. We considered two results problematic for SAS models, including recent versions of the E-Z Reader model: (a) End-of-fixation previews were not significantly more effective than beginning-of-fixation previews, and (b) parafoveal preview benefits in the end-of-fixation preview condition did not approximate preview benefits in the full-target preview condition when pretarget gazes were relatively long.

Pollatsek et al. (2006a) take issue with our conclusion that roughly equivalent preview benefits in the beginning- and end-of-fixation preview conditions of our study pose problems for the E-Z Reader model. They argue that had we considered effects of the E-Z Reader model's obligatory 50-ms VT time, then we would have arrived at the correct prediction, that beginning- and end-of-fixation previews would yield just a small advantage of the beginning- over the end-of-fixation preview condition or roughly equivalent preview benefits in the two conditions.

As Pollatsek et al. (2006a) point out, VT time may extend the usability of preattentively obtained information by approximately 50 ms. Hence, useful information will not arrive at the lexical module (“the mind”) until 190 ms after fixation onset in the beginning-of-fixation preview condition. A shifting of attention to this stream of parafoveal target information after 150–160 ms can thus extract useful linguistic information for 30–40 ms. This may yield some processing benefit when the target is subsequently fixated.

The end-of-fixation target preview is available 140 ms after the onset of pretarget viewing. If VT time is factored in, then useful target information will arrive approximately 190 ms after the onset of pretarget viewing (attention should be allocated to the target location at that point in time). As can be seen in Table 4 of our Experiment 2 data, typical pretarget single fixation durations and gaze durations exceeded 300 ms in the beginning- and end-of-fixation preview conditions. This means that useful linguistic information could be obtained from a target preview starting 190 ms after the onset of pretarget viewing until the end of pretarget viewing, which was roughly 325 ms after the onset of pretarget viewing in the beginning- and end-of-fixation preview condition. Generally, linguistic information thus should have been extracted from the parafoveally visible target preview for approximately 135 ms in the end-of-fixation preview condition. Moreover, if VT time is factored in, then the linguistic processing of a target preview could continue during the following saccade to the target (approximately 25 ms) and during the subsequent VT time during the first target fixation (see Pollatsek, Reichle, & Rayner, 2006b). Another 75 ms thus need to be added to the time line of parafoveal information use in the end-of-fixation preview condition, which should amount to a typical duration of parafoveal information use of slightly more than 200 ms. With or without consideration of VT time, the serial attention shift conception must predict substantially larger preview benefits in the end-of-fixation preview condition, which was not the case. There was a small numeric bias toward larger preview benefits in the end-of-fixation preview condition, but as we pointed out in our original study, it did *not* reach statistical significance in either the first fixation duration, the single fixation duration, or the gaze duration measure.

Pollatsek et al. (2006a) arrived at a much shorter estimate of the duration of linguistic information extraction in the end-of-fixation preview condition, and it is this much shorter estimate, 65–85 ms, that is key to their successful simulation of our beginning- and end-of-fixation preview effects. We consider their estimate flawed, however, in that it ignores the actual data. That is, rather than using pretarget viewing duration from our Experiment 2 to estimate the time line of information use from the parafoveally visible target, Pollatsek et al. imported a hypothesized “typical fixation time” of 225–235 ms¹ and used that to determine the time line of linguistic information extraction in the end-of-fixation preview condition. This gross underestimation of the actual temporal availability of the parafoveal target preview, by more than 100 ms, is critical to the success of the E-Z Reader simulation. Had it used the actual data, the outcome may well have been problematic for the SAS assumption.

A second finding, also involving the end-of-fixation preview condition, is also difficult to reconcile with the strictly serial attention shift assumption of the E-Z Reader model; this finding was not addressed in Pollatsek et al.’s (2006a) critique. An inspection of the frequency distributions of pretarget viewing in the end-of-fixation preview condition and the matched corresponding full-target change preview condition revealed two distinct modes, one with relatively short pretarget viewing durations ranging from 140 ms to 300 ms and one with relatively long viewing durations of more than 300 ms. This natural partitioning of our pretarget viewing was of theoretical interest in that it should have generated two distinct time lines of

¹Pollatsek et al. (2006a) indicate that our reasoning for predicting larger preview benefits in the end- than in the beginning-of-fixation preview condition assumes a typical (pretarget) fixation duration of 225–235 ms. This is incorrect. We made no such claim in our original study. The actual pretarget gaze duration is much longer than that.

attention shifting from the pretarget word to the parafoveal target preview. Specifically, relatively short pretarget viewing durations should be diagnostic of relatively easy pretarget processing, which should have led to a rapid shift of attention to the target according to SAS models. Attention should often arrive at the parafoveal target location before useful target information is available (to recall, the target is presented 140 ms after the onset of pretarget viewing, and useful target information can be extracted 50 ms later, after VT is completed). In these cases, end-of-fixation previews should be less effective than full-target previews. In harmony with that, our supplementary analyses revealed a 30-ms advantage for the full-target preview condition. Conversely, according to SAS models, relatively long pretarget gaze durations indicate that pretarget processing was difficult and that the shifting of attention to the parafoveal target preview must occur relatively late, generally later than 190 ms after the onset of pretarget viewing. Typically, attention should thus arrive at the parafoveal target location after the target word replaced the mask in the end-of-fixation preview condition (and after useful target information has undergone VT). Consequently, the difference between the end-of-fixation preview condition and the full-target preview condition should thus be relatively small or negligible when pretarget viewing durations are relatively long. Yet this was not the case. Full-target previews were more effective than end-of-fixation previews, with an effective size of 30 ms. The relationship between pretarget gaze durations and target gaze durations in the full-target and end-of-fixation preview conditions is shown in Figure 1 (Figure 8 of the original study; Inhoff et al., 2005).

Although Pollatsek et al. (2006a) do not directly address these findings, they mention two scenarios that could provide a plausible account for the relatively large advantage of full-target previews over end-of-fixation previews irrespective of pretarget viewing duration: The display change itself may disrupt processing, thus rendering end-of-fixation previews less effective, or the initially displayed pseudoword mask may inhibit the subsequent use of the target preview. They note that intrafixation display change effects or inhibitory effects between mask and target previews during a fixation could explain why beginning- and end-of-fixation preview benefits do not add up to full-target preview benefits.

We explicitly tested the first scenario. Experiment 2 included two experimental conditions that were designed to test the consequences of a target display change during a fixation. In the *full-preview change* condition, preview of the target *cOfFeE* was replaced, for instance, with *CoFfEe* 140 ms after the onset of pretarget viewing. Likewise, *vAtiD* was replaced with *VaTId* in the *full-mask change* condition. No intrafixation changes occurred in *full-preview constant* and *full-mask constant* conditions. Comparison of the intrafixation display change and no-change conditions showed that a change increased target viewing durations. Critically, however, the display change did not influence target preview benefits, which were virtually identical irrespective of the occurrence of a target change during a fixation.

We did not test the second scenario in the Inhoff et al. (2005) study, but three conditions of Inhoff's (1989) study provide relevant information. In these conditions, parafoveal preview of a six-letter target word consisted either of the first three letters, the last three letters, or the full word. These previews were available throughout pretarget viewing, that is, there was no intrafixation display change. Nevertheless, preview benefits from the first three and last three letters were substantially smaller than preview benefits from the intact six-letter target word. That is, the sum of the spatially defined partial-target previews was not equivalent to the whole target preview even when there was no display change during a fixation. It thus appears unlikely that intrafixation display change artifacts compromised our results.

Pollatsek et al. (2006a) point out that we use alternating case in our experiments and that target preview benefits were relatively large. This could be of concern in that readers could have had considerable difficulty reading our materials. To minimize disruptive effects of alternating

case, we augmented our experimental procedure in Experiments 1b and 2, in which readers received extensive practice reading alternating-case text prior to the experiment, and Experiment 1a showed that this practice was effective. Although the viewing duration for the pretarget word in Experiment 2 was relatively long, overall sentence reading was fluent and first target fixation duration and target gaze duration were roughly within the normal range.

Critically, use of alternating case did not impede the acquisition of useful linguistic information from a parafoveal target preview, which yielded benefits up to 99 ms in the gaze duration data of the full-target preview condition. The large majority of our pretarget–target word sequences consisted of two closely related nouns (e.g., *traffic light*). The same word pairs had yielded a 91-ms preview benefit in an earlier study in which all text was written in lower-case (Inhoff, Starr, & Shindler, 2000). In a somewhat related study with lowercase noun–noun Finnish compound words (which were written without internoun spacing in that language), Hyönä, Bertram, and Pollatsek (2004) obtained (target) preview benefits of slightly more than 100 ms. Preview benefits in the current study are thus commensurate with preview benefits in studies that used the same or similar lowercase materials. Rather than constituting a potential concern, the large size of preview benefits in the full-target preview condition gives our study a distinct advantage. The power of an experimental manipulation increases with effect size—that is, our experiment was ideally suited for the charting of the time line of parafoveal information use.

General Theoretical Considerations

From the discussion provided by Pollatsek et al.'s (2006a) comment on our original study and from their publications on recent versions of the E-Z Reader model (Pollatsek et al., 2006b; Rayner, Ashby, Pollatsek, & Reichle, 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006; Reichle, Rayner, & Pollatsek, 1999, 2003), the E-Z Reader model's attention shift claims can be summarized as follows: Attention is conceived as a focused spotlight of preferential processing in the spirit of Posner (1980). The extent of this spotlight coincides exactly with the boundaries of the word that is being attended at any given moment. Attention moves from word to word sequentially from left to right, and the departure and arrival of attention mark the end versus beginning of lexical (L1 and L2) processing. The movement of attention is “instantaneous”—that is, it requires no extra time for preparation and execution. An initial stage of lexical processing, L1, triggers the programming of a saccade, while a shift of attention has to wait until the second phase of lexical processing, L2, has been completed. Therefore, the act of *programming* a saccade going from word n to word $n + 1$ is decoupled from the act of shifting attention from word n to word $n + 1$ (Pollatsek et al., 2006b).

Although attention allocation in reading may be task specific to some extent, it is desirable for a theory of word processing and oculomotor control in reading to be compatible with other lines of reading research and with basic oculomotor and attention research in neighboring domains of study (see Findlay & Gilchrist, 2003, for integrative discussions of visual processing in different domains). Three areas of research are particularly relevant to the current theoretical debate in this regard. This work examined the time line of a spatial shift of attention, the relationship between attention shifting and saccade programming, and the allocation of attention to several to-be-identified parafoveal targets.

The Time Line of Attention Shifts

In the current versions of the E-Z Reader model, the shifting of attention from one word to another is assumed to consume no extra time. Computationally, the hypothesized movement of attention from the pretarget to the target word does not appear trivial, however. Before attention can be shifted, the system has to obtain information that the current word has been recognized, and it has to transfer this information from the word recognition module to the

attention shift module. Successful shifting requires the selection of the next to-be-attended visual object in the text, which may be one among several preattentively discerned visual objects, and it requires a movement of an attentional beam through visual space and the fitting of the beam to the area of the to-be-attended word, depending on its size. Within the sequential processing framework of SAS models, a zero time delay between the offset of pretarget processing and the onset of target processing appears implausible, especially in view of the computational complexity of the hypothesized attention shift operation.

Looking at the relevant literature, one finds several ways to estimate the “speed” of attention shifts. One way is to use the slopes of search functions in serial search tasks to estimate the amount of time spent per item in the visual display.² Estimates derived in this way are usually on the order of about 25–75 ms (Egeth & Yantis, 1997), with 50 ms as the value initially reported in the classic study by Treisman and Gelade (1980) that the authors of the E-Z Reader model refer to in various writings. Another technique, the attentional blink paradigm, yielded still longer estimates of “attentional dwell times” that are on the order of 150–300 ms and are thus similar to the range of typical fixation durations (Horowitz, Holcombe, Wolfe, Arsenio, & DiMase, 2004; Theeuwes, Godijn, & Pratt, 2004; Ward, 2001). Chun and Wolfe (2001) and Logan (2005) discussed the apparent contradiction between vastly different estimates by distinguishing the time spent allocating attention (processing time) and the time spent shifting attention, both of which are assumed to take up a nontrivial amount of time. According to Logan, who sought to discriminate attention shift and visual encoding times, attention shifting takes approximately 75–100 ms when peripheral cues are used to signal the location of a to-be-detected target. We are not aware of any study that claims a 0-ms or near 0-ms spatial attention shift duration.

Even if the duration of the horizontal attention shift was relatively short, 30–50 ms, preview benefits in the beginning-of-fixation preview condition of our Experiment 2 should have become negligible, which was not the case. In the absence of other parameter changes, implementation of an attention shift duration is also likely to impede the success with which the model can simulate word skipping. Skipping is assumed to occur when the L1 processing of an upcoming word can be completed before the saccade to the word is committed to action. Time spent shifting attention must delay the completion of L1 by a corresponding duration, thus decreasing the likelihood of a parafoveal word’s L1 completion before a saccade to it is committed to action.

The Relationship Between Attention Shifting and Saccade Programming

By decoupling the shift of attention from one word to the next word in the text from saccade programming, the E-Z Reader model is also decoupled from a large body of literature that has shown a close functional relationship between the two. In this literature, there appears to be consensus that attentional orienting either precedes or coincides with saccade programming and that there is a strong and mandatory link between the two. As an example, Deubel and Schneider (1996) reported experiments using stimulus materials that were somewhat similar to a reading situation in that they presented a horizontal string of letters separated by blanks. In their paradigm, a central cue designated a specific member of the string as the target for the saccade. Before the onset of a saccade toward this goal, a discrimination stimulus was presented briefly within the string of items. Results indicated a high degree of spatial selectivity. Discrimination performance was almost perfect when the saccade was directed to the critical item but was close to chance level when the saccade target was located only one item to the left or right of the critical discrimination stimulus. Of note, conditions designed to provoke

²This approach rests on the assumption that visual search is indeed strictly serial and involves a rapid scan over successive items. Alternatives involving mechanisms of parallel processing have been proposed, however, by Duncan and Humphreys (1989), Wolfe (1994), and others.

decoupling of “recognition” attention from saccade programming failed to alter the pattern of results (see also Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986). Together, results from this line of research suggest that object-specific coupling of saccade programming and object discrimination is strong and mandatory.³

This has led to the currently dominant view that a presaccadic shift of attention guides the *selection* of a peripheral item as the target of the saccade, thus constituting the initial step in the programming of a saccade (see Deubel, O’Regan, & Radach, 2000, for a recent discussion in the context of reading research). In contrast, the E-Z Reader model assumes that a saccade target is selected *before* an attention shift takes place. Although attention generally arrives at the target earlier than the eyes in the E-Z Reader model, this is basically a consequence of the assumption that saccade programming is relatively time consuming whereas the subsequently executed shift of attention does not require any time. Therefore, the position of the model is that the eyes are directed to a word that is unattended at that time, rather than to a word that attention has been directed to.

To our knowledge there is no empirical work in the literature on attention and saccade programming that can be taken to support the proposed decoupling of attention shifting and saccade programming during reading. To the contrary, general attention-allocating principles predicted eye movements in reading in a recent study that used interindividual differences in an attentional cuing task to determine group-specific patterns in the temporal buildup of inhibition of return (Weger & Inhoff, 2006). This time course then effectively predicted the two groups’ regressive saccade amplitude in a separate sentence-reading task.

Experimental conditions have been created in which participants could allocate attention parallel to more than one parafoveal target location. Godijn and Theeuwes (2003) recently examined the time line of attention allocation and saccade programming. They used a dual-task paradigm to manipulate saccadic target selection and the allocation of attention to a particular location in space for that purpose. In Experiment 1, the primary task required the execution of a sequence of saccades to two simultaneously cued object locations of a circular display with eight locations, and the secondary task required the identification of a letter that was presented for 47 ms either 35 ms, 82 ms, or 129 ms after the saccade cue. Under these conditions, letters at the locations of both the first and the second saccade target were recognized more accurately than letters presented at a noncued location, and this occurred even at the shortest dual-saccade cue-letter presentation interval. Four other experiments provide compelling evidence for the view that attention was allocated (in parallel) to more than one target location and that parallel allocation of attention to more than one target preceded the targeting of the initial saccade (see also Van der Stigchel & Theeuwes, 2005). Even though Godijn and Theeuwes’s (2003) task demands differ from those of reading, their findings favor a general theoretical conception according to which spatial attention can encompass more than one to-be-identified object.

In spite of the close link between attention shifting and saccade programming, the two differ in that the eyes can only be moved to one (attended) visual object at a time whereas visual attention can encompass more than one object at a time. The allocation of attention thus does not need to follow an all-or-none function. We favor a conception according to which it can be applied in a graded fashion to more than one object in simple identification tasks and to

³One study suggesting that some saccades *can* be programmed independently of attention shifts is by Stelmach, Campsall, and Herdman (1997), who used a temporal order judgment as the indicator for attention allocation. In agreement with most other studies, they found that under conditions of exogenous cuing, attention can “move” much faster than the eyes. Their finding that under endogenous cuing more than 300 ms is needed to redirect attention to the parafovea is interesting but perhaps irrelevant to a possible role of attention shifts during reading.

more than one word in reading tasks, as we assume in our gradient conception of attention allocation during reading (Inhoff et al., 2005; see Inhoff, Radach, Starr, & Greenberg, 2000, for a more detailed discussion).

We hope that the current methodological and theoretical debate is fruitful in that it will spark further empirical work on the time course of information extraction within the effective range of vision during a fixation in reading. It may well be the case that other techniques or other approaches yield more accurate estimates of the time course of linguistic information extraction. For instance, preliminary work from our laboratory suggests that the extraction of linguistic information from a parafoveal target preview, which occurred 70–140 ms after the onset of pretarget viewing in Experiment 1b of our original study, can occur earlier than that.

In spite of our theoretical differences, we also wish to acknowledge the heuristic value of SAS models and the success with which the E-Z Reader model has stimulated a large body of empirical work on information processing and eye movements in reading (see Radach, Kennedy, & Rayner, 2004, for a recent compilation with a focus on parafoveal processing). Currently, the E-Z Reader model can be considered the gold standard against which other successful computational models are tested (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Feng, 2006; McDonald, Carpenter, & Shillcock, 2005; Reilly & Radach, 2006; Richter, Engbert, & Kliegl, 2006; Yang, 2006). We hope that the current theoretical debate will add momentum to the discussion of key assumptions of this and other models of eye movement control in reading.

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Figure 1.

Target gaze durations as a function of pretarget gaze duration in two target preview conditions, one in which the target preview was visible throughout a fixation (with a case display change 140 ms after the onset of pretarget viewing) and one in which the target location was occupied by a pseudoword mask during the beginning 140 ms of pretarget viewing and by the target thereafter. Error bars represent mean standard errors. From “The Time Course of Linguistic Information Extraction From Consecutive Words During Eye Fixations in Reading,” by A. W. Inhoff, B. M. Eiter, & R. Radach, 2005, *Journal of Experimental Psychology: Human Perception and Performance*, 31, p. 992. Copyright 2005 by the American Psychological Association.