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Don't Believe What You Read (Only Once): Comprehension Is Supported by Regressions During Reading

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Abstract

Recent Web apps have spurred excitement around the prospect of achieving speed reading by eliminating eye movements (i.e., with rapid serial visual presentation, or RSVP, in which words are presented briefly one at a time and sequentially). Our experiment using a novel *trailing-mask paradigm* contradicts these claims. Subjects read normally or while the display of text was manipulated such that each word was masked once the reader's eyes moved past it. This manipulation created a scenario similar to RSVP: The reader could read each word only once; *regressions* (i.e., rereadings of words), which are a natural part of the reading process, were functionally eliminated. Crucially, the inability to regress affected comprehension negatively. Furthermore, this effect was not confined to ambiguous sentences. These data suggest that regressions contribute to the ability to understand what one has read and call into question the viability of speed-reading apps that eliminate eye movements (e.g., those that use RSVP).

Keywords

reading, comprehension, eye movements

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With personal computing devices getting smaller, Website and app developers have recently been looking for ways to allow users to "read" texts on small screens (e.g., on smart watches). These methods (e.g., Spritz, a soon-to-be released app that has received a lot of media attention) are based on the rapid serial visual presentation (RSVP) method,[1] in which readers do not make eye movements (a natural part of reading), but rather, words are presented briefly one at a time, in the center of the screen, in sequential order. In a blog on their Web site, Spritz's developers claim that reading in this way can speed reading dramatically by making eye movements unnecessary, suggesting that "every saccade has a penalty in both time and comprehension" (Maurer & Locke, 2014). However, removing eye movements from the reading process is precisely the fatal flaw in such speed-reading apps and the reason why they will not be useful for reading any text that is not extremely easy or short; control over the sequence and duration of word processing is the most important variable that supports reading, and control of the oculomotor system is crucial to accurate comprehension of text.

In the study reported here, we demonstrated this point with a very simple manipulation: We had people read sentences both normally and in a condition in which words became masked after they moved their eyes away (i.e., with what we refer to as a trailing mask). This experimental manipulation prohibited readers from accessing further information from the words after initially reading them, as in the RSVP method. Comparing comprehension of the sentences between normal reading and reading with the trailing mask allowed us to assess how this lack of control over the sequence of the reading process affected comprehension.

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During reading, the eyes move rather systematically in the direction that the text is written (i.e., from left to right in English). But about 10% to 15% of the time, readers make *regressions*, in which they move their eyes back in the text to look at previously processed material (for reviews, see Rayner, 1998, 2009). There are several potential reasons (which are not necessarily mutually exclusive) why readers make regressions between words (for a review, see Bicknell & Levy, 2011). A detailed discussion of these different theories is beyond the scope of this article, but it bears noting that these explanations range from low-level oculomotor reasons to high-level linguistic reasons.

It is likely that an individual regression may be caused by any (or many) of these reasons. Although some explanations suggest that regressions are made in response to (i.e., in order to correct) oculomotor error causing a word to be unintentionally skipped, regressions in the cases in which the word was *not* skipped initially are more interesting and more informative. In general, explanations of such regressions suggest that higher-level linguistic processing causes the reader to go back and reread previous text in order to correct a failure in (or decreased confidence in; Bicknell & Levy, 2011) comprehension of the sentence or identification of an individual word. Thus, theories along these lines imply a close connection between comprehension processes and regression behavior, suggesting that readers are more likely to make a regression when they sense that their comprehension of the sentence has faltered. Indeed, regressions are more likely in sentences that tend to be misinterpreted, at least temporarily (e.g., in garden-path sentences; Frazier & Rayner, 1982; Levy, Bicknell, Slattery, & Rayner, 2009; see the Method section), and comprehension of these types of sentences is also generally lower than comprehension of normal sentences.

These findings lead to a critical question: Does making a regression increase a reader's understanding of a sentence, and consequently, does the inability to make a regression (e.g., when reading with the RSVP method) decrease the reader's understanding of a sentence? The answer to this question is not straightforward. For one thing, as we have mentioned, there is likely not one underlying cause to regressions and, therefore, regressions may be related to comprehension processes in some scenarios but not in others (i.e., when a regression corrects unintended skipping of a word). Moreover, regressions are a difficult phenomenon to study because they are difficult to manipulate experimentally. That said, most theories of regressions that make a connection to comprehension posit that the purpose of a regression is to obtain more visual input (e.g., Booth & Weger, 2013) in order to fix a comprehension failure (see Bicknell & Levy, 2011). Thus, we attempted to investigate regressions by making them more or less useful, using a modification of the moving-mask paradigm (Rayner & Bertera, 1979) that we refer to as the *trailing-mask paradigm* (i.e., words were masked after they were read initially so that regressions would not lead to the accumulation of more information about them). In this way, we were able to test the hypothesis that regressions support comprehension by allowing the reader to access more information about the text.

Specifically, we attempted to systematically examine the relationship between regressions and reading comprehension by manipulating whether regressions actually did provide additional visual information. In the normal-reading condition, when readers looked back to words, the words remained visually available. In the trailing-mask condition, the letters in a word were replaced with *x*s once a forward saccade was made off the word, so regressions did not allow readers to obtain any additional visual information about words after initially moving past them. In addition, we compared whether this trailing-mask condition affected the ability to understand ambiguous language (i.e., garden-path sentences with a temporary structural ambiguity) more than the ability to understand more straightforward language (i.e., sentences without a structural ambiguity).

Method

Subjects

Forty undergraduates at the University of California, San Diego, participated in this experiment for course credit. All were native English speakers, had normal vision, and were naive to the purpose of the experiment.

Apparatus

Eye movements were recorded with an SR Research Ltd. (Mississauga, Ontario, Canada) Eyelink 1000 eye tracker (sampling rate of 1000 Hz) in a tower setup that restrained head movements with forehead and chin rests. Viewing was binocular, but only the movements of the right eye were recorded. Subjects were seated approximately 60 cm away from an HP (Palo Alto, CA) p1230 CRT monitor with a screen resolution of 1024 × 768 pixels and a refresh rate of 150 Hz. The sentences were presented in the vertical center of the screen in black Courier New 12-point font (2.99 characters subtended 1° of visual angle) on a white background. Complete sentences were always presented in one line of text (maximum of 109 characters). Display changes were completed, on average, within 4 ms (range = 0–7 ms) of the tracker detecting a saccade away from a word.

```
  *
While the man drank the water that was clear and cold overflowed from the toilet.
           *
xxxxx xxx man drank the water that was clear and cold overflowed from the toilet.
                *
xxxxx xxx xxx drank the water that was clear and cold overflowed from the toilet.
                          *
xxxxx xxx xxx xxxxx xxx water that was clear and cold overflowed from the toilet.
                                *
xxxxx xxx xxx xxxxx xxx xxxxx that was clear and cold overflowed from the toilet.
                          *
xxxxx xxx xxx xxxxx xxx xxxxx that was clear and cold overflowed from the toilet.
                                         *
xxxxx xxx xxx xxxxx xxx xxxxx xxxx xxx clear and cold overflowed from the toilet.
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Fig. 1. Illustration of the trailing-mask condition. From top to bottom, the lines show successive displays of an example sentence. Asterisks represent the locations of fixations. Once a subject made a forward saccade out of a word, that word was masked (i.e., each letter was replaced with an *x*); it remained masked for the remainder of the trial, even if the subject looked back to it (e.g., the second-to-last line of the figure).

Materials and design

Twenty ambiguous garden-path sentences (e.g., "While the man drank the water that was clear and cold overflowed from the toilet") were obtained from Christianson, Hollingworth, Halliwell, and Ferreira (2001). In these sentences, the noun that is the subject of the main clause (hereafter, the *subject noun*; e.g., *water*) following the first verb (e.g., *drank*) can initially be interpreted as the direct object of that verb (e.g., what the man was drinking). However, this interpretation is rendered structurally impossible when the reader reaches a disambiguating verb (e.g., *overflowed*), the verb in the main clause. In reading such a sentence, readers generally make a regression back to the subject noun (e.g., *water*) and reread the sentence in order to reparse it and form a correct interpretation (Frazier & Rayner, 1982). To increase the statistical power of the experiment, we created another set of 20 garden-path sentences using the same initial verbs but different sentence frames. For example, from the sentence quoted at the beginning of this paragraph, we created, "While the child drank the milk that was on the table spilled." To create an unambiguous version of each of the 40 ambiguous sentences, we replaced the initial verb from the garden-path sentence (e.g., *drank*) with an intransitive verb (e.g., *slept*), so that it was unlikely that readers would interpret the following noun (e.g., *water, milk*) as a direct object (e.g., "While the man slept the water that was clear and cold overflowed from the toilet").[2] The factor of sentence ambiguity was crossed with display condition (trailing mask vs. normal reading) in a 2 × 2 design.

Thus, our final stimulus set consisted of 40 experimental sentences (each with an ambiguous and an unambiguous version). A given subject saw one version of each experimental sentence, and these sentences were intermixed with 40 simple filler sentences (e.g., "It was very hard to find the truck inside of the messy toybox"). We had determined the numbers of subjects and sentences a priori, on the basis of prior experiments of eye movements in reading, which generally indicated that having 10 subjects and sentences per condition generally leads to sufficient power. Furthermore, once the data were collected, all statistical models successfully converged (an issue also related to power), which suggested that our study was sufficiently powered.

Procedure

Subjects were instructed to read the sentences for comprehension. They were told that the words in some sentences would be replaced by *x*s as they read and that they should read the sentences as naturally as possible. Prior to the experiment, the eye tracker was calibrated using a three-point calibration scheme. The tracker was recalibrated if calibration error was more than 0.3°.

Sentences were displayed either normally or in the trailing-mask condition, in which each word was masked (i.e., each letter was replaced with an *x*) after the reader made a forward saccade away from it (see Fig. 1). Prior to each trial, a fixation point appeared in the center of the screen; the subject was required to fixate this point before the trial began. Next, a black box appeared on the left side of the screen in a location corresponding to the first character of the upcoming sentence. The size of the box indicated the display condition. A tall box (30 pixels × 130 pixels) indicated the trailing-mask condition, and a short box (30 pixels × 60 pixels) indicated the normal-reading

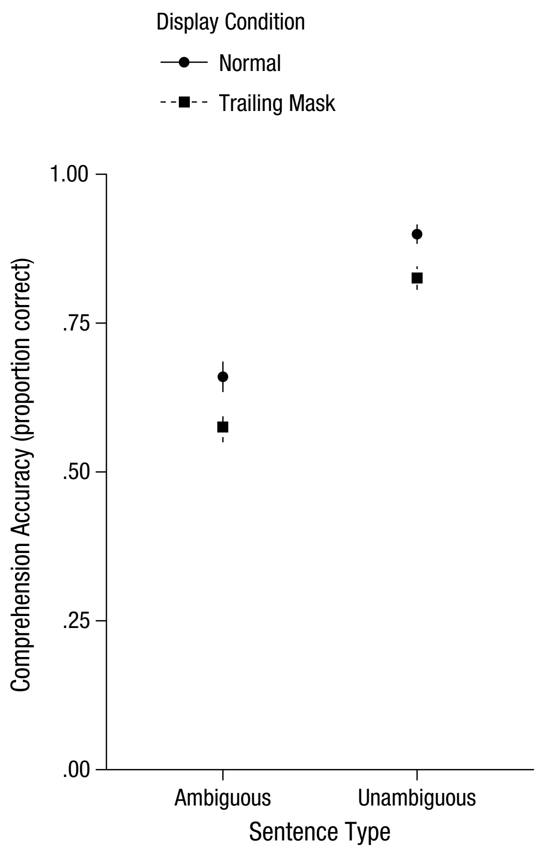

Fig. 2. Comprehension accuracy as a function of sentence type and display condition. Error bars represent ±1 *SEM*. Chance performance is .50.

condition (i.e., no visual manipulation). Once the eye tracker detected a fixation longer than 250 ms inside that box, it disappeared and the sentence was presented. Each sentence was followed by a yes/no comprehension question, which subjects answered by pressing the "yes" or "no" button on a response pad. As in Christianson et al. (2001), the questions about the ambiguous sentences directly probed whether subjects had misparsed the sentences. For example, the comprehension question following the first ambiguous sentence quoted earlier was, "Was the man drinking water from the toilet?" (correct answer: "no"). For the unambiguous sentences, the comprehension questions probed the intransitive verbs (e.g., "Was the man sleeping?" correct answer: "yes").

Results

Fixations that were shorter than 80 ms and within one character of a previous or subsequent fixation were combined with that previous or subsequent fixation. All remaining fixations shorter than 80 ms or longer than 1,000 ms were eliminated from analysis. Trials in which there was a blink or track loss on a word of interest (i.e., the subject noun or the disambiguating verb) or on an immediately adjacent word during first-pass reading were excluded. These exclusions left 1,409 trials (88% of the original data) available for analysis. To analyze gaze durations, we used linear mixed-effects regression models (LMMs; see Baayen, Davidson, & Bates, 2008), with the maximal random-effects structure (Barr, Levy, Scheepers, & Tily, 2013); we report regression coefficients, which estimate the effect sizes (in milliseconds) of the reported comparisons, along with the standard errors and t values of the coefficients. For binary dependent variables (accuracy and regression probabilities), we used logistic generalized mixed-effects regression models and report regression coefficients, which represent effect sizes in log-odds space, along with z values of the coefficients. It is not clear how to determine the degrees of freedom for the t statistics estimated by the LMMs, so it is difficult to estimate p values (Baayen et al., 2008), and we do not report degrees of freedom and p values. Statistical significance at approximately the .05 level is indicated by values of the t and z statistics greater than or equal to 1.96.

Comprehension accuracy

To assess the general effect of not being able to reread words, we compared comprehension accuracy between trials in which subjects read normally and trials in which they read with the trailing mask. We crossed this display-condition factor with sentence type (ambiguous vs. unambiguous) to determine whether the effect of the trailing mask was confined to difficult language, or whether it had a general effect on comprehension regardless of how difficult the language was to understand. There was a significant effect of sentence type ($b = -1.64$, $z = 6.34$, $p < .001$); subjects answered the questions for ambiguous sentences less accurately than the questions for unambiguous sentences. There was also a main effect of display condition ($b = -0.92$, $z = 5.09$, $p < .001$); subjects were less accurate at answering comprehension questions in the trailing-mask condition than during normal reading (Fig. 2). The interaction was only marginally significant ($b = 0.70$, $z = 1.90$, $p = .06$), which suggests that restricting the opportunity to reread words with the trailing-mask paradigm decreased comprehension globally, and not exclusively for ambiguous (i.e., garden-path) sentences (see The Effects of Rereading on Comprehension Accuracy).

Duration of gaze on the subject noun

Duration of initial gaze on the subject noun (i.e., initial reading time before leaving it) was significantly longer in

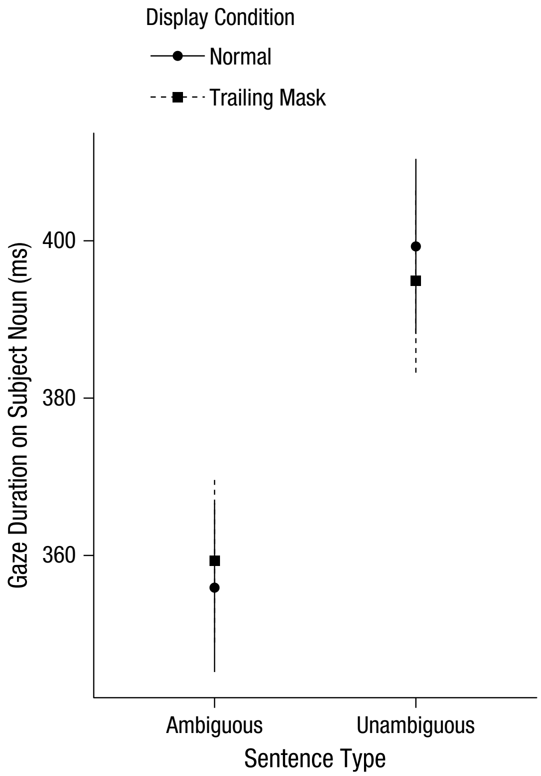

Fig. 3. Duration of initial gaze on the subject noun as a function of sentence type and display condition. Error bars represent ±1 *SEM*.

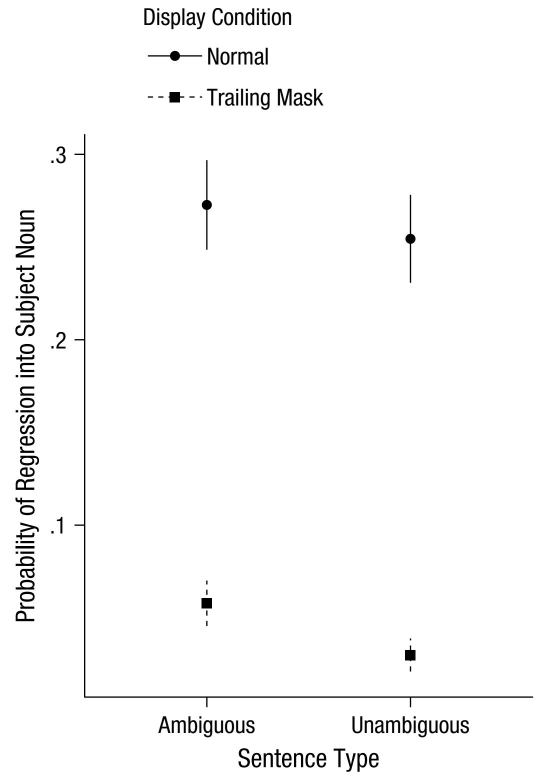

Fig. 4. Probability of a regression to the subject noun as a function of sentence type and display condition. Error bars represent ±1 *SEM*.

unambiguous sentences than in ambiguous sentences (b = 41.89, SE = 11.32, t = 3.70), which indicates that subjects had more difficulty reading the subject noun in unambiguous sentences than in ambiguous sentences. This finding may initially seem counterintuitive but is not surprising given that this noun likely was initially interpreted as the object of the initial verb; this syntax seems sensible in the ambiguous sentences, which have a transitive initial verb that can take an object (e.g., "While the man drank the water . . ."), but seems strange in the unambiguous sentences because their intransitive verbs cannot take objects (e.g., "While the man slept the water . . ."). However, this difficulty is only temporary and should be resolved later in the sentence, once the reader sees the disambiguating verb (e.g., ". . . overflowed from the toilet"), so that an unambiguous sentence becomes easier to understand. Gaze duration was unaffected by display condition; neither the main effect of display condition nor the interaction between display condition and sentence type was significant (both ts < 0.96; see Fig. 3). The lack of an effect of display condition on initial reading time suggests that subjects did not adopt a strategy different from their normal one when reading with a trailing mask.

Regressions into the subject noun

We calculated the probability of making a regression into a word as the proportion of trials on which there was at least one regression from a later part of the sentence back to that word. To assess whether subjects returned to the subject noun in order to repair an initial misinterpretation, we compared the degree to which they went back to reread the subject noun across display conditions and sentence types. There was a significant effect of sentence type; regressions into the subject noun were significantly more likely in ambiguous sentences than in unambiguous sentences (b = 0.69, z = 2.05, p = .04). There was also a significant effect of display condition; regressions into the subject noun were significantly less likely in the trailing-mask condition than during normal reading (b = −3.10, z = 7.94, p < .001). The interaction between sentence type and display condition was not significant (p > .11; see Fig. 4). These data suggest that readers were able to take into account the display condition and resisted making regressions when they were rendered useless (i.e., in the trailing-mask condition). Additionally, as in prior work (e.g., Christianson et al., 2001; Frazier & Rayner, 1982), ambiguous

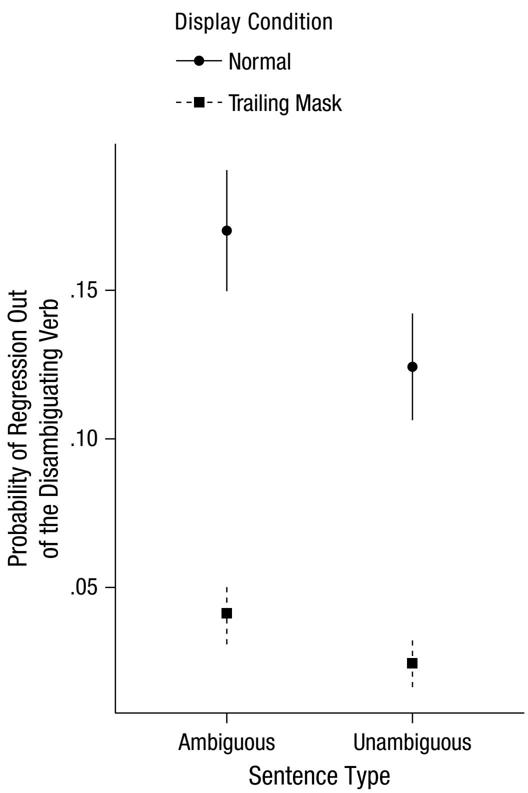

Fig. 5. Probability of making a regression out of the disambiguating verb as a function of sentence type and display condition. Error bars represent ±1 *SEM*.

garden-path sentences led to more regressions than did unambiguous sentences (because of the structural ambiguity designed into the sentences), and in our study, this difference was unaffected by display condition.

Regressions out of the disambiguating verb

To assess whether the regressions into the subject noun were related to detecting the structural ambiguity, we also analyzed the probability of making a regression out of the disambiguating verb (i.e., making an eye movement backward from that verb). The main effect of sentence type was not significant ($p > .17$); subjects were equally likely to make regressions from the disambiguating verb when reading the ambiguous and the unambiguous sentences. There was a significant effect of display condition ($b = -3.27$, $z = 7.33$, $p < .001$); regressions were less likely in the trailing-mask condition than in the normal-reading condition, a pattern paralleling the finding for regressions into the subject noun. There was also a significant interaction between sentence type and display condition ($b = -1.65$, $z = 2.20$, $p = .03$); the effect of sentence type (more regressions in ambiguous sentences than in unambiguous sentences) was smaller in the trailing-mask condition than in the normal-reading condition (see Fig. 5). These data suggest that, although subjects were sensitive to ambiguity in the sentences (i.e., they made regressions more often in ambiguous sentences than in unambiguous sentences when reading normally), they were able to suppress this tendency to reread when they knew that regressions would be useless (i.e., in the trailing-mask condition).

The effects of rereading on comprehension accuracy

To assess the degree to which regressions supported reading comprehension, we compared comprehension accuracy across three trial types: (a) normal-reading trials in which the subject made a regression out of the disambiguating verb, (b) normal-reading trials in which the subject did not make a regression out of this region, and (c) trailing-mask trials in which the subject did not make a regression out of this region. We used the contr.sdif function in the MASS package in R to test for successive differences in comprehension accuracy between these trial types. That is, the first contrast tested for a difference in comprehension between trials in which subjects voluntarily did and did not make a regression during normal reading. The second contrast tested for a difference in comprehension between trials in which the reader did not make a regression but for potentially different reasons—either because the reading system determined that a regression was not necessary (i.e., in normal reading) or because a regression was useless and inhibited (i.e., in the trailing-mask condition). To test whether the ability to make regressions had a different effect on comprehension of ambiguous compared with unambiguous sentences, we entered these contrasts, crossed with sentence type (centered) as fixed effects and random effects, using the maximal random-effects structure.

The analysis revealed that comprehension was not significantly different between cases in which subjects made a regression (M = 84% averaged across both sentence types) or did not make a regression (M = 78%; $p > .98$) during normal reading. This suggests that when readers make a regression, they do so to improve failed comprehension and that regression improves their understanding to be equivalent to its level in cases in which they do not need to reread. In contrast, comprehension was significantly poorer when subjects did not make a regression in the trailing-mask condition (M = 71%), compared with when they chose not to make a regression during normal reading ($b = -0.75$, $z = 4.03$, $p < .001$). Neither the

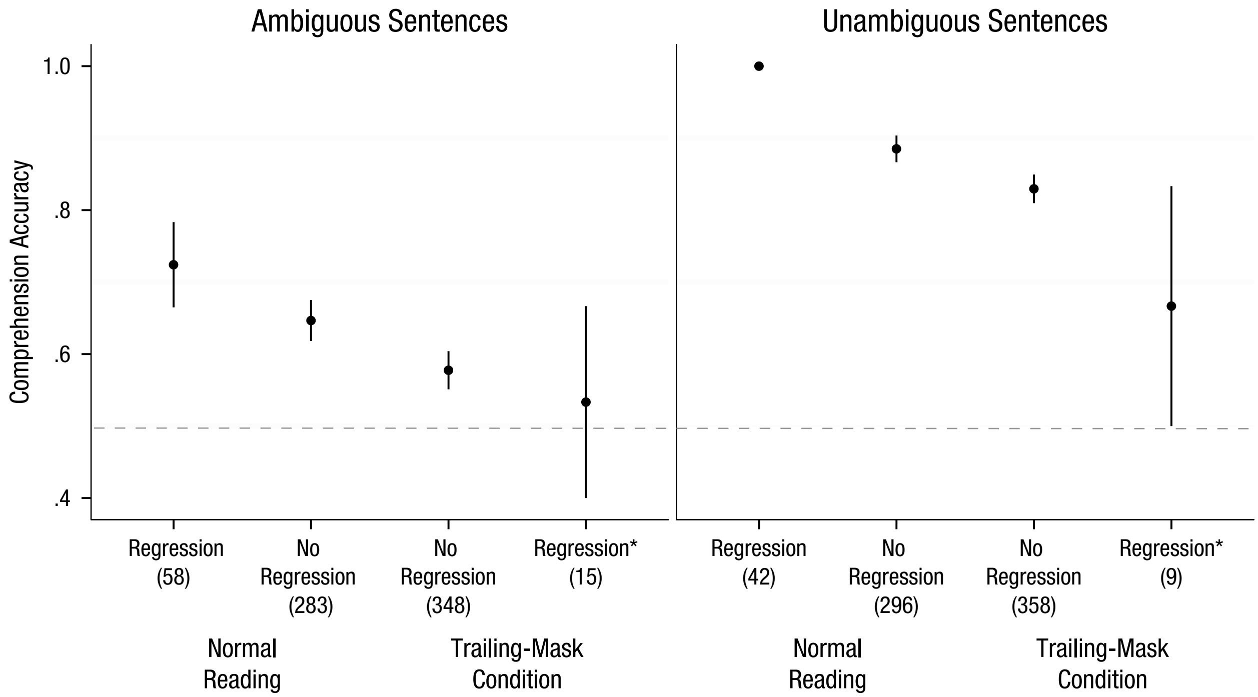

Fig. 6. Comprehension accuracy as a function of display condition and whether or not the subject made a regression out of the disambiguating verb. Results are shown separately for ambiguous sentences (left) and unambiguous sentences (right). The number of observations contributing to each data point is presented in parentheses below the *x*-axis. Error bars represent ±1 *SEM*. The dotted line represents chance performance (.5). The conditions labeled "Regression*" constitute cases in which readers made a regression in the trailing-mask paradigm, so that they looked at a string of *x*s.

main effect of sentence type nor any of its interactions were significant (all $ps > .26$). Thus, it appears that the relationship between regressions and comprehension was relatively stable and did not depend on sentences that generally cause comprehension difficulties (i.e., ambiguous garden-path sentences).

The data are summarized in Figure 6. Note that the figure also shows results for trials in which subjects made a regression in the trailing-mask condition, fixating on strings of *x*s (see the right-most data point in each panel). We did not include these trials (24 out of 1,409, less than 2% of the data) in the analysis because their rarity would lead to low power (note the size of the error bars in the figure). However, we point readers toward the pattern these data points reveal. Presumably, they represent times at which readers could not help making a regression despite knowing that a regression would not provide them additional information about the text. The fact that these points (despite high variability) indicate the lowest comprehension accuracy suggests that when subjects made regressions, they were searching for information that would support their understanding of the text. When they had access to this information again (i.e., in normal reading), their comprehension of the sentences was quite high (84%), but when whey they did not have access to this information again, their comprehension was dramatically lower (i.e., in the trailing-mask condition; 56%). We must emphasize, though, that this interpretation is only a speculative explanation of the qualitative pattern because the rarity of regressions in the trailing-mask condition prohibited a systematic statistical investigation.

Discussion

The results of our experiment are quite straightforward and demonstrate that readers' control over their eye movements is important for their comprehension. First, the main effect of display condition on comprehension accuracy suggests that conditions in which readers cannot go back to reread words (i.e., in the trailing-mask paradigm and in the RSVP method generally) lead to poorer understanding of the text (Masson, 1983). Second, the fact that display condition did not affect the duration of gaze on the subject noun suggests that our manipulation did not dramatically affect the initial reading process. Third, the fact that subjects were much less likely to make a regression in the trailing-mask condition than in the normal-reading condition suggests that readers do have control over their eye movement behavior and adapt to conditions such as the trailing-mask manipulation. Finally, and most important, our data showing the relationship between regressions and reading comprehension are the most compelling evidence suggesting that reading without the ability to reread parts of the text, when necessary, decreases comprehension accuracy. The fact that this finding did not differ between ambiguous and unambiguous sentences suggests that this is a global effect, not confined to generally difficult language.

In summary, our data call into question how successful apps like Spritz will be in allowing users to read and, crucially, understand text via RSVP presentation. Although RSVP might be fine for reading short, simple sentences in which readers would not typically make regressions, given that readers normally make regressions 10% to 15% of the time (Rayner, 1998, 2009), removing this ability will have drastic negative consequences for the understanding of sentences.

Obviously, the ability to make regressions is not the only thing that differentiates normal reading from the RSVP method. These other differences also suggest that reading will be less effective with RSVP. For example, many studies have demonstrated that readers access information from words before fixating them (i.e., *parafoveal processing*) and that this information is used to facilitate processing once the words are directly fixated (i.e., *parafoveal preview*; see Schotter, Angele, & Rayner, 2012, for a review). Because words are presented one at a time in RSVP, this ability is also eliminated. Together, the numerous studies showing the benefit of parafoveal preview and the present study showing the benefit of the opportunity to make regressions call into question the viability of reading and understanding reasonably long and important passages of text via the RSVP method (e.g., Spritz). Furthermore, the current findings elucidate the utility of eye movements to the reading process. During our investigation into the motivation for and hype surrounding RSVP methods, we have read several comments suggesting that people generally think of regressions as a "problem" that needs to be "gotten rid of." In contrast, our data suggest that, although regressions (and saccades in general) add a small amount of time to the reading process, the benefits they provide for understanding far outweigh the costs.

Author Contributions

R. Tran developed the study concept. E. R. Schotter and R. Tran developed the study design under the supervision of K. Rayner. R. Tran developed and programmed the paradigm under the supervision of E. R. Schotter. Testing and data collection were performed by R. Tran and research assistants. E. R. Schotter and R. Tran performed the data analysis and interpretation. E. R. Schotter drafted the manuscript, and R. Tran and K. Rayner provided critical revisions. All the authors approved the final version of the manuscript for submission.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Notes

1. The technique was first introduced by Forster (1970) and widely used by Potter and her colleagues (e.g., Potter, Kroll, & Harris, 1980; for a recent example, see Potter, Nieuwenstein, & Strohminger, 2008). Research with the RSVP paradigm has demonstrated that people understand single sentences presented at a rate of 12 words per second. However, it is also known that when the text is more than a single sentence, comprehension in the RSVP paradigm falls apart (Masson, 1983).
2. In addition, we included a manipulation of sentence length, in which we deleted the text (e.g., "that was clear and cold") intervening between the subject noun (e.g., *water*) and the disambiguating verb (e.g., *overflowed*). This variable did not have a significant interaction with any of the others, so we collapsed across it in the analyses in order to focus on the theoretically interesting effects.

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