

The role of verbal memory in regressions during reading

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Abstract During reading, participants generally move their eyes rightward on the line. A number of eye movements, called *regressions*, are made leftward, to words that have already been fixated. In the present study, we investigated the role of verbal memory during regressions. In Experiment 1, participants were asked to read sentences for comprehension. After reading, they were asked to make a regression to a target word presented auditorily. The results revealed that their regressions were guided by memory, as they differed from those of a control group who did not read the sentences. The role of verbal memory during regressions was then investigated by combining the reading task with articulatory suppression (Exps. 2 and 3). The results showed that articulatory suppression affected the size and the accuracy of the initial regression but had a minimal effect on corrective saccades. This suggests that verbal memory plays an important role in determining the location of the initial saccade during regressions.

Keywords Reading · Memory

Because of the structure of the eye, the acquisition of information during reading is limited to a small area around the fixation point, which prompts readers to constantly move their eyes on the line. Research shows that during reading, the eyes generally move rightward (Rayner & Pollatsek, 1989). However, 10 % to 15 % of these eye movements, called *regressions*, are made in the opposite direction, to words that have already been fixated. It has been suggested that regressions are made in order to reanalyze words that have been incorrectly interpreted (see, e.g., Frazier & Rayner, 1982; Kennedy & Murray, 1984). In these cases,

the eyes are not directed randomly, but aim at a precise word location (Kennedy & Murray, 1987), suggesting that regressions are guided by memory. Some studies have suggested that regressions are mostly guided by a spatial code attached to each word (see, e.g., Kennedy, 1992; Kennedy, Brooks, Flynn, & Prophet, 2003). Although some studies point to a contribution of verbal memory during regressions (see, e.g., Rawson & Miyake, 2002; Weger & Inhoff, 2007), little convincing evidence exists. The objective of the present study was therefore to examine the contribution of verbal memory¹ during regressions through the use of verbal interference.

In order to examine the role of memory during regressions, researchers usually measure the pattern of eye movements. For instance, a precise regression is taken as evidence that the reader remembers the word's location. In Kennedy and Murray's study (1987; see also Kennedy et al., 2003), participants were asked to read a sentence that was followed by a test word presented visually at the end of the line. Their task was to identify whether or not the test word had been presented in the sentence. Kennedy and Murray (1987) found that when participants made an eye movement toward the target word in the sentence, the regression was very accurate and landed on the target word. The researchers argued that such a high level of precision would only be possible if the spatial coordinates of the words were retained in memory during reading. Additional evidence for this theory was provided by Kennedy et al. (2003) using a similar procedure. They showed that if the sentence was shifted slightly to the right before the regression was

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¹ We refer to *verbal* and *spatial* memory for simplicity's sake, but this nomenclature could refer to the existence of separate verbal or spatial stores, such as those postulated by the working memory model (see Baddeley & Hitch, 1974), or to the use of articulation and of the oculomotor system as retention mediums, as proposed by unitary views of memory (see, e.g., Jones, Hughes, & Macken, 2006).

initiated, participants overshot the target word more often than during a condition with no shift, suggesting that regressions are guided by memory for the position of the word relative to the page layout, rather than by the visual configuration of the sentence (see also Inhoff, Weger, & Radach, 2005).

Other studies have investigated the contribution of verbal memory during regressions. For instance, Theriault and Raney (2002) showed that after reading a text, participants were no better than chance at relocating where information was presented relative to the page layout. However, they could remember in which part of the text they had encountered some information (first, second, third, or fourth quarter of the text). In line with this result, Rawson and Miyake (2002) showed that text relocation skills correlated with participants' verbal but not spatial abilities. They suggested a verbally based reconstruction hypothesis according to which relocation relies on verbal memory. For instance, in order to determine the regression landing position, participants would reconstruct the text by retrieving the order of events from the text. Rawson and Miyake therefore suggested that verbal memory plays an important role during reading. These studies, however, were concerned with memory for text passages, and therefore might not explain regressions, which usually land within the same sentence rather than being directed into a preceding sentence (see Rayner & Pollatsek, 1989).

Evidence that verbal memory might be involved during regressions in single-sentence reading was provided by Weger and Inhoff (2007; see also Inhoff & Weger, 2005). In Weger and Inhoff's study, participants were required to read sentences displayed simultaneously on two lines, in which invisible boundaries were inserted. When the eyes crossed a boundary, a word to which participants were required to regress was presented auditorily. Weger and Inhoff manipulated the linguistic load (the number of words read before the regression) and the spatial proximity of the target in order to examine the relative contributions of verbal and spatial memory, respectively. They observed that although the initial regressions made toward the target were not precise, they were selective—that is, they were longer for far targets than for near targets—and that this effect did not interact with linguistic load. The authors concluded that the initial regression was guided mostly by spatial memory. Linguistic load, however, influenced the total number of characters travelled by the eyes before reaching the target—what is called the *cumulative regression size*. On the basis of this finding, Weger and Inhoff suggested that corrective saccades made to reach the target word were guided by verbal memory.

As was argued by Inhoff et al. (2005), in most paradigms the relative influences of spatial and verbal memory on the pattern of eye movements during regressions are very difficult to disentangle. Indeed, most demonstrations in favor of

the existence of a spatial code might also be interpreted in light of a verbal-reconstruction hypothesis (see Rawson & Miyake, 2002), because in most designs the words' spatial locations are highly correlated with their order in the sequence of successive events depicted by the sentence. In the study of Weger and Inhoff (2007), this possibility was partly removed by displaying sentences on two lines. Indeed, such a procedure allowed pitting verbal and spatial manipulations against each other: For instance, regressions made over a short spatial distance were associated with a higher verbal load than were regressions made over a long distance. Their manipulation of verbal load, however, might be explained in terms of spatial memory. Indeed, spatial coding might be influenced by the number of words in memory, just as verbal coding is. To date, there therefore seems to be no satisfying evidence showing the contribution of verbal memory during regressions.

The present study

Our objective was to examine the contribution of verbal memory during regressions using a dual-task procedure in which participants had to do verbal suppression during reading. The procedure used was similar to that developed by Inhoff and Weger (2005, Exp. 4; see also Weger & Inhoff, 2007). In each trial, participants were required to read a sentence, followed by auditory presentation of the target word. Participants were required to move their eyes to the target word in the sentence as precisely as possible. Performance in that condition was first compared with performance in a control condition in which participants had not read the sentence, so as to examine the influence of memory representations on the pattern of eye movements (Exp. 1). In Experiments 2 and 3, verbal suppression was used in combination with the reading task in order to examine the contribution of verbal memory during the execution of regressions.

Weger and Inhoff (2007) suggested that the spatial selectivity of the regression—that is, the extent to which it precisely aims at the target—and of corrective saccades could be affected differently. In order to examine the contribution of verbal memory in regressions, we also assessed spatial selectivity and corrective saccades by measuring the size and the precision of the initial regression and the total distance travelled by the eyes before reaching the target (the cumulative regression size). The cumulative regression size was therefore measured in order to investigate whether verbal memory guides the corrective saccades made to reach the target word after an initial saccade has been made. For instance, if participants do not remember the location of the target word, they should scan more words before reaching the target, leading to longer cumulative regressions.

Experiment 1

In the reading group, participants were first asked to read a sentence, and then to make a regression to a target word presented auditorily. Inhoff and Weger (2005) argued that presenting the target visually could create an additional spatial code that competes with that of the word in the sentence. In order to ensure that the contribution of verbal memory in the present study was not dependent on the unavailability of the target's spatial code, the target was also presented auditorily in our experiments. In the control group, participants were asked to make a regression to a target word in a sentence that they had not read. We assumed that in the latter group, regressions would be guided solely by the visual configuration of the sentence and by general knowledge about typical sentence structures. The specific goal of this experiment was to validate our procedure and to confirm that regressions elicited by our paradigm are guided by memory.

Method

Participants

A group of 40 students (20 in the reading group and 20 in the control group) from the Université de Moncton volunteered to take part in the experiment.

Apparatus and materials

The course of the experiment was controlled by a PC computer with a resolution of $1,024 \times 768$ pixels ($28^\circ \times 22^\circ$). Participants were seated 60 cm from the computer screen. Eye movements were recorded with the Research Ltd Eye-Link II system. The system's resolution and sampling rate are $<0.5^\circ$ and 500 Hz. The eye movements were captured by two cameras mounted on a headband that allowed for tracking both eyes and head position for head-motion compensation. In this experiment, only the pupil of the participant's eye for which the most accurate calibration was achieved was tracked.

A total of 80 six-letter target words were selected. The target words were nouns with a frequency ranging between 20 and 80 occurrences per million (New, Pallier, Ferrand, & Matos, 2001). Each target word was included in a sentence containing eight words. Ten of the target words were inserted in each of the eight word positions. In addition to the 80 critical sentences, 40 filler sentences containing eight words were constructed. The target words in the filler sentences were 18 function words, 10 verbs, and 12 adjectives or adverbs that could be presented in any word position in the sentence. All sentences contained from 40 to 45

characters, including space and punctuation, and ended with a period. At a viewing distance of 60 cm, each character subtended 0.6° . A black cross was also presented to the right of all sentences, at nine characters from the right of the screen. In order to promote reading for comprehension, one question was constructed for each sentence. The correct response was "yes" for half of the sentences and "no" for the other half. The questions were presented in blue, centered at the top of the computer screen.

Procedure

The participants were tested individually. The experimental session began with a calibration phase in which participants were asked to alternatively fixate nine calibration dots.

Reading group The procedure used in the reading group is illustrated in the three panels of Fig. 1. Before the presentation of each sentence, participants had to fixate a single calibration dot located nine characters from the left of the screen, vertically aligned with the sentence, in order to ensure eye movement recording accuracy. Participants were then instructed to read the sentence for comprehension. After reading the sentence, they had to fixate the cross to the right of the sentence in order to hear a word through the loudspeakers. The word's onset was triggered by a 100-ms fixation on the cross. After hearing the word, participants were instructed to move their eyes to the word in the sentence as precisely as possible and to fixate it until the sentence disappeared. A total of 3 s after onset of the target word on the screen, the sentence disappeared and the question was presented. Participants verbally answered "yes" or "no" and their answer was recorded by the experimenter, after which the next trial was presented. The 120 trials were split into two blocks of 60 trials separated by a pause. Before participants started the second block, a second calibration phase was done. The experimental session lasted about 50 min.

Control group Before the presentation of each sentence, participants had to fixate a single calibration dot displayed nine characters from the right of the screen and vertically aligned with the sentence. After calibration, the calibration dot disappeared and a black cross was displayed at the same spatial location, along with the sentence. The sentence was located at the exact same location as in the reading group. Participants were instructed to fixate the cross in order to hear a word through the loudspeakers; the auditory onset of the word was triggered by a 100-ms fixation on the cross. After hearing the word, the participants were instructed to find the word in the sentence and to fixate it until the sentence disappeared. This procedure is illustrated by the panels B and C of Fig. 1. A total of 4 s after the onset of the word on the screen, the sentence disappeared and the experimenter initiated the next trial. This 4-s delay was longer than

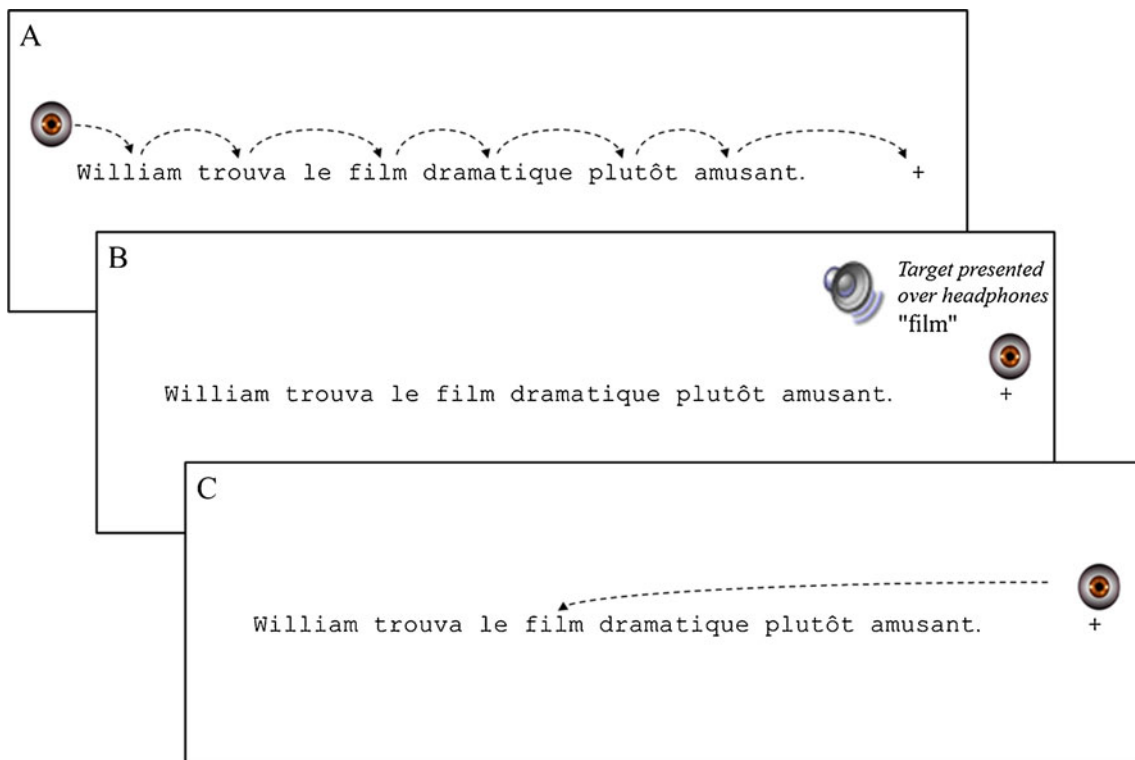


Fig. 1 Illustration of the task performed in the reading group (panels A, B, and C) and control group (panels B and C) of Experiment 1

the delay in the reading group to ensure that participants in the control group—who had not read the sentence—would have enough time to find the target word. The 120 trials were presented within a single block. The experimental session lasted about 25 min.

Design

A mixed design was used with one repeated measures factor, Word Position (eight levels: 1 to 8) and one between-participants factor, Group (two levels: control or reading). The 120 sentences were presented in the same random order for all participants. The experimental trials were preceded by two practice trials.

Results

Eye movements were analyzed with the EyeLink Data Viewer program, which displays the participant's eye movements superimposed on the text presented during the experiment. Eye movements were analyzed for the 80 critical sentences only. Over the 3,200 critical sentences (80 sentences \times 40 participants), 1.8 % were removed from the analysis due to large distortions in the eye movement recording or because participants executed a regression on the sentence before hearing the target word. In the reading group, the percentage of correct responses to the comprehension questions was 89 % ($SD = 4$ %).

Several measures were computed. First, we analyzed fixation durations and skip rates during reading of the sentence in the reading group. Then, four measures of regressions were analyzed.

Eye movements during reading

We calculated first-fixation durations (the durations of the first fixation made during the first pass), gaze durations (the sums of all fixations on the word prior to a saccade to a following or preceding word), total fixation times (the sums of all fixations on the word), and skipping rates (the proportions of words not fixated at all, neither during the first pass nor after a regression) on the target words in the reading group (see Table 1).

Repeated measures analyses of variance (ANOVAs) with Word Position (eight levels: 1 to 8) as a factor were carried out on each of these measures. For all analyses, the .05 level of significance was adopted, and the Greenhouse–Geisser correction was applied when the sphericity assumption was not met. The analysis showed that first-fixation durations, $F(7, 133) = 1.68, p = .17, \eta_p^2 = .08$, gaze durations, $F(7, 133) = 2.33, p = .06, \eta_p^2 = .11$, and skip rates, $F(7, 133) = 2.13, p = .09, \eta_p^2 = .10$, did not vary across word positions. The main effect of word position was significant for total fixation durations, $F(7, 133) = 3.64, p = .01, \eta_p^2 = .16$. As is shown in Table 1, this effect was due

Table 1 First-fixation durations, gaze durations, total fixation durations, skip rates, and regression latencies for target and function words in Experiment 1 during reading for the reading group

	Word Position								Mean	
	1	2	3	4	5	6	7	8	Target	Function
First	229 (79)	209 (51)	238 (58)	238 (32)	223 (80)	241 (42)	242 (57)	241 (44)	233 (44)	163 (48)
Gaze	323 (125)	288 (108)	271 (74)	295 (86)	270 (104)	292 (64)	312 (69)	314 (95)	295 (75)	174 (53)
Total	368 (110)	359 (115)	298 (77)	331 (92)	312 (109)	329 (79)	370 (99)	360 (142)	342 (86)	250 (51)
Skip	.13 (.17)	.08 (.10)	.03 (.06)	.09 (.11)	.12 (.13)	.07 (.09)	.06 (.10)	.06 (.08)	.08 (.06)	.48 (.14)
Regression latencies	493 (134)	483 (128)	457 (119)	469 (130)	494 (132)	507 (127)	498 (118)	516 (134)		

Standard deviations are indicated in parentheses

to the fact that fixation durations for words in the middle of the sentence were shorter than those for words at the beginning or end of the sentence.

In order to examine whether eye movements are characteristics of normal reading, we compared fixation durations and skip rates for the target words with those for function words. We selected 30 function words containing two or three characters from 30 different trials. Equal numbers of function words were selected from Word Positions 2 to 7. The different measures were pooled across word positions (see Table 1). Repeated measures ANOVAs with Word Function (two levels: target or function) as a factor were carried out on each of these measures. The analysis indicated that skip rates were much higher for function words than for target nouns, $F(1, 19) = 167.08, p < .001, \eta_p^2 = .90$. Moreover, first-fixation durations, $F(1, 19) = 56.27, p < .001, \eta_p^2 = .75$, gaze durations, $F(1, 19) = 121.73, p < .001, \eta_p^2 = .87$, and total fixation durations, $F(1, 19) = 60.60, p < .001, \eta_p^2 = .76$, were longer for fixated target nouns than for fixated function words.

Measures of regressions

In the reading group, 28 % ($SD = 23$ %) of all initial regressions reached the target, as compared to 7 % ($SD = 11$ %) among the control group, a difference that was significant, $F(1, 38) = 68.29, p < .001, \eta_p^2 = .64$. The mean number of saccades executed to reach the target was also lower in the reading group ($M = 2.7, SD = 0.8$) than in the control group ($M = 3.5, SD = 1.1$), $F(1, 38) = 32.47, p < .001, \eta_p^2 = .46$. Four measures of regressions were computed:

1. *Initial regression size*, which corresponded to the number of characters travelled by the eyes during the first saccade made after hearing the word; regressions shorter than two characters were not considered.
2. *Initial regression error*, which consisted of the number of characters between the middle of the target word and the

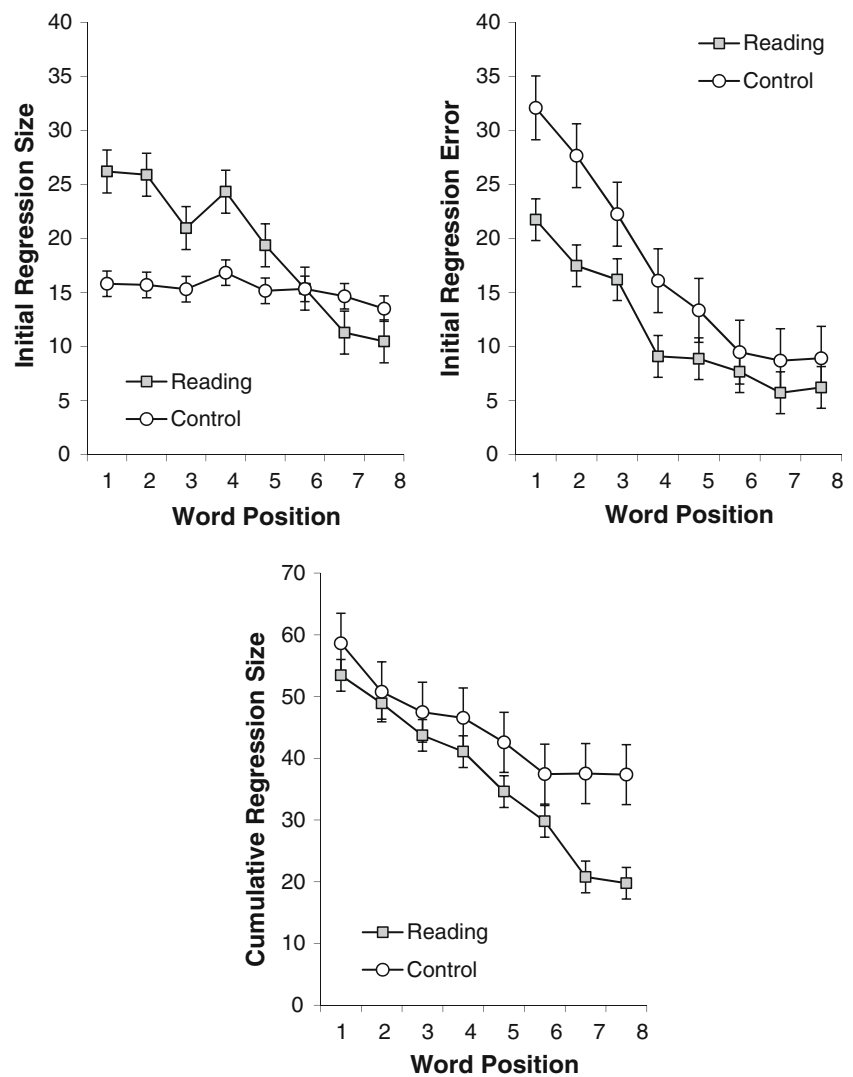
landing of the initial saccade; the initial regression error was therefore a measure of the accuracy of the regression.

3. *Cumulative regression size*, which corresponded to the total number of characters travelled by the eyes before fixating the target word; the target word was considered fixated when the eyes landed on the target word or on the space before or after.
4. *Regression latencies*, which were the times that elapsed between the presentation of the target word and the initiation of the regression.

Initial regression size The initial regression size was computed for each word position in the two groups. Inspection of Fig. 2 suggests that the initial regression size did not vary as a function of word position in the control group, but did decrease as a function of word position in the reading group. A 2 (group) \times 8 (word position) mixed ANOVA indicated that the initial regression size was not significantly different between the two groups, $F(1, 38) = 3.53, p = .068, \eta_p^2 = .09$, but did vary as a function of word position, $F(7, 266) = 36.18, p < .001, \eta_p^2 = .49$. Importantly, the interaction between word position and group was significant, $F(7, 266) = 21.91, p < .001, \eta_p^2 = .37$. Simple main effect analyses with $\alpha = .015 (.15 / 10)$ revealed that the initial regression size varied as a function of word position in the reading group, $F(7, 133) = 38.43, p < .001, \eta_p^2 = .67$, but not in the control group, $F(7, 133) = 2.53, p = .018, \eta_p^2 = .12$.

Initial regression error As is suggested by Fig. 2, a 2 (group) \times 8 (word position) mixed ANOVA indicated that regression error was higher in the control group than in the reading group, $F(1, 38) = 45.13, p < .001, \eta_p^2 = .54$, and decreased as a function of word position, $F(7, 266) = 70.93, p < .001, \eta_p^2 = .65$. The interaction between group and word position was also significant, $F(7, 266) = 3.46, p = .05, \eta_p^2 = .08$, due to the fact that the difference between the two groups decreased as a function of word position. Paired-samples *t* tests with $\alpha = .015 (.15/10)$ confirmed that initial regression error was significantly

Fig. 2 Initial regression size (top left panel), initial regression error (top right panel), and cumulative regression size (bottom panel) in the reading and control groups, as a function of word position in Experiment 1. Errors bars represent 95 % confidence intervals calculated separately for each group



higher in the control group than in the reading group for words located in Positions 1, ($p = .001$), 2 ($p < .001$), 3 ($p = .006$), 4 ($p < .001$), and 5 ($p < .001$), but not for words in Positions 6 ($p = .12$), 7 ($p = .07$), and 8 ($p = .16$).

Cumulative regression size As is shown in Fig. 2, cumulative regression size decreased linearly as a function of word position in both groups, but it seemed to be higher in the control group than in the reading group. A 2 (group) \times 8 (word position) mixed ANOVA confirmed that cumulative regression size was higher in the control group than in the reading group, $F(1, 38) = 10.97, p = .002, \eta_p^2 = .22$, and decreased as a function of word position, $F(7, 266) = 50.03, p < .001, \eta_p^2 = .57$. The interaction between group and word position was also significant, $F(7, 266) = 4.33, p = .008, \eta_p^2 = .10$, suggesting that the difference between the two groups increased as a function of word position. Paired-

samples t tests with $\alpha = .015$ (.15/10) confirmed that cumulative regression size was significantly longer in the control group than in the reading group for words located in Positions 7 ($p = .001$) and 8 ($p = .006$).

Regression latencies It was not possible to analyze regression latencies in the control group because in many trials, participants initiated the regression before the target word was heard. Indeed, in 44 % of all trials, the regression was initiated within 200 ms following the onset of the target word—as compared to 6 % of all trials in the reading group. Therefore, regression latencies were analyzed in the reading group only. Regression latencies shorter than 200 ms were removed from the analysis (6 % of all trials), as well as those that were shorter or longer than three standard deviations from the participant’s mean (0.8 % of all trials). The regression latencies are presented in Table 1. A repeated measures ANOVA with Word Position (eight levels: 1 to 8) as a factor

showed that the effect of word position was significant, $F(7, 133) = 6.32, p < .001, \eta_p^2 = .25$. Post hoc comparisons showed that this effect was due to the lower regression latencies for words in Positions 3 and 4 than for words in the other positions. Regression latencies for words in Positions 1, 2, 5, 6, 7, and 8 did not differ.

Discussion

Experiment 1 served to establish our procedure. Importantly, eye movements while reading the sentences were typical of eye movements observed during normal reading. For instance, fixation durations were shorter and skip rates were much higher for function words than for content words (see, e.g., Carpenter & Just, 1983; Chamberland, Saint-Aubin, & Légère, *in press*; Gautier, O'Regan, & Le Gargasson, 2000; O'Regan, 1979). Our task therefore seems to engage normal reading processes.

In line with previous studies, Experiment 1 suggested that after reading a sentence, regressions are guided by memory representations of the sentence (see, e.g., Inhoff & Weger, 2005). Indeed, the pattern of eye movements during regressions in the reading group was strikingly different from that observed in the control group, who had not read the sentence. In the reading group, the size of the initial regression increased as a function of target eccentricity. Regressions were therefore spatially selective, with words farther away targeted by longer regressions. However, regression accuracy for the first words of the sentences was relatively low, ranging from 22 to 16 characters from Word Positions 1 to 3. In line with Inhoff and Weger, this suggests that although regressions were spatially selective, they were imprecise. Cumulative regression size also differed between the two groups, mostly for the last words of the sentence. This suggests that in the reading group, participants' memory for the word location allowed them to direct corrective saccades more efficiently toward the target word, reducing the cumulative regression size as compared to the control group.

Experiment 2

To examine the contribution of verbal memory during regressions, in Experiments 2 and 3 we used articulatory suppression: During the reading of the sentences, participants had to articulate irrelevant items. Indeed, several studies have demonstrated that verbal memory is greatly disrupted by articulatory suppression (see, e.g., Baddeley, Lewis, & Vallar, 1984; Guérard & Tremblay, 2008). On half of the trials, participants had to perform articulatory suppression during the reading of the sentence, whereas in the

other half, they read the sentence quietly, following the procedure used in Experiment 1.

Method

Participants

A group of 20 students from the Université de Moncton volunteered to take part in the experiment in exchange for a small honorarium.

Apparatus and materials

In order for the experiment to last a reasonable amount of time despite the addition of an articulatory suppression condition, the sentences were shortened from eight to seven words, and the target words were positioned in four rather than eight critical positions. A new set of 80 six-letter target words with a frequency ranging from 20 to 80 occurrences per million was selected. Each target word was included in a sentence containing seven words and a total of 42 or 43 characters. The target words were inserted in the first, third, fifth, or seventh position in the sentence. There were 20 trials for each word position, for a total of 80 experimental trials. Forty filler sentences containing seven words were also constructed. The target words in the filler sentences were 20 function words, 10 verbs, and 10 adjectives/adverbs that could be presented in any word position in the sentence.

Procedure

The procedure was the same that had been used by the reading group of Experiment 1, except that before the presentation of each sentence, participants had to fixate a single calibration dot located in the middle of the screen in order to ensure eye movement recording accuracy. After recalibration, a cross vertically aligned with the sentence was displayed nine characters from the left of the screen. A 500-ms fixation on that cross triggered the appearance of the sentence. After reading the sentence, participants were required to fixate a cross presented to the right of the sentence, as in Experiment 1. A 100-ms fixation on that cross triggered the presentation of the critical word through the loudspeaker. Participants were instructed to move their eyes as precisely as possible to the location of the target word. A total of 3 s after the onset of the target word on screen, the sentence disappeared and the question was presented. Participants verbally answered "yes" or "no."

In the control condition, participants were asked to read the sentences in silence. In the suppression condition, they had to repeatedly say the letters "A B C D" at a pace of two letters per second while reading. Articulatory suppression

was initiated before recalibration and ended upon hearing the target word.

Design

The analysis featured two repeated measures factors, Suppression (two levels: articulatory suppression or no suppression) and Word Position (four levels: 1, 3, 5, or 7). The 120 sentences were split into two blocks, each containing ten sentences per word position and 20 filler sentences. One block was performed in the control condition, and one block in the articulatory suppression condition. The order of the two blocks was counterbalanced across participants. Each set of sentences was used equally often in the articulatory suppression and no-suppression blocks.

Results

Over the 1,600 critical sentences (80 sentences \times 20 participants), 0.7 % were removed from the analysis due to large distortions in the eye movement recording or because participants executed a regression on the sentence before hearing the target word. Articulatory suppression ($M = 88\%$, $SD = 6\%$) slightly impaired comprehension as compared to the no-suppression condition ($M = 91\%$, $SD = 5\%$), $F(1, 19) = 5.07$, $p = .036$, $\eta_p^2 = .21$. For all analyses, Block Order was entered as a factor. These analyses are reported only when the main effect of block order was significant or when it interacted with another factor.

Eye movements during reading

First-fixation durations, gaze durations, total fixation times, and skipping rates on the target words in both conditions are shown in Table 2. For each measure, a 2 (suppression) \times 4 (word position) repeated measures ANOVA was performed. For the measures of first-fixation, gaze, and total durations, the same pattern was observed: The duration was longer under articulatory suppression than in the no-suppression condition [$F(1, 19) = 10.79$, $p = .004$, $\eta_p^2 = .36$; $F(1, 19) = 5.02$, $p = .04$, $\eta_p^2 = .21$; and $F(1, 19) = 8.46$, $p = .009$, $\eta_p^2 = .31$, respectively]. Although the main effect of word position was not significant, $F_s < 1.86$, the interaction between suppression and word position was [$F(3, 57) = 3.60$, $p = .002$, $\eta_p^2 = .16$; $F(3, 57) = 5.02$, $p = .04$, $\eta_p^2 = .21$; and $F(3, 57) = 3.44$, $p = .02$, $\eta_p^2 = .15$, respectively]. Paired-samples t tests with $\alpha = .025$ (.15/6) showed that the first fixation was longer in the articulatory suppression condition for Word Positions 1 ($p = .004$) and 3 ($p = .014$). For gaze and total durations, this interaction was due to the fact that the

durations were longer in the articulatory suppression condition for Word Position 1 only [$p_s = .012$ and $.002$, respectively]. For skip rate, the main effects of suppression, $F < 1$, and word position, $F(1, 19) = 1.48$, $p = .23$, $\eta_p^2 = .01$, were not significant, nor was their interaction, $F < 1$.

Measures of regressions

In the no-suppression condition, 37 % ($SD = 12\%$) of all initial regressions reached the target, as compared to 29 % ($SD = 11\%$) in the articulatory suppression condition. This difference was significant, $F(1, 19) = 10.58$, $p = .004$, $\eta_p^2 = .36$. The mean numbers of saccades executed to reach the target also differed between the two conditions, $F(1, 19) = 19.52$, $p < .001$, $\eta_p^2 = .51$, with 2.3 saccades in the no-suppression condition ($SD = 0.3$) and 2.6 in the articulatory suppression condition ($SD = 0.4$).

Initial regression size As is shown in Fig. 3, the initial regression was longer in the no-suppression condition than under articulatory suppression. A repeated measures ANOVA confirmed that the main effects of suppression, $F(1, 19) = 5.49$, $p = .03$, $\eta_p^2 = .22$, and of word position, $F(3, 57) = 47.69$, $p < .001$, $\eta_p^2 = .72$, were significant. The interaction between suppression and word position was also significant, $F(3, 57) = 7.93$, $p < .001$, $\eta_p^2 = .29$. Paired-samples t tests with $\alpha = .025$ (.15/6) indicated that the effect of suppression was significant for Word Position 1 ($p < .001$), but not for Positions 3 ($p = .27$), 5 ($p = .15$), and 7 ($p = .05$). Although the main effect of block order was not significant, there was a significant triple interaction including Block Order as a factor. The three-way interaction was due to the fact that the interaction between suppression and word position was enhanced when participants started with the articulatory suppression condition. One possibility is that participants who began with the no-suppression condition suffered less from articulatory suppression because they had time to become familiar with the task before the articulatory suppression block. However, initial regression size was the only measure to be influenced by block order. Therefore, this interaction will not be discussed further.

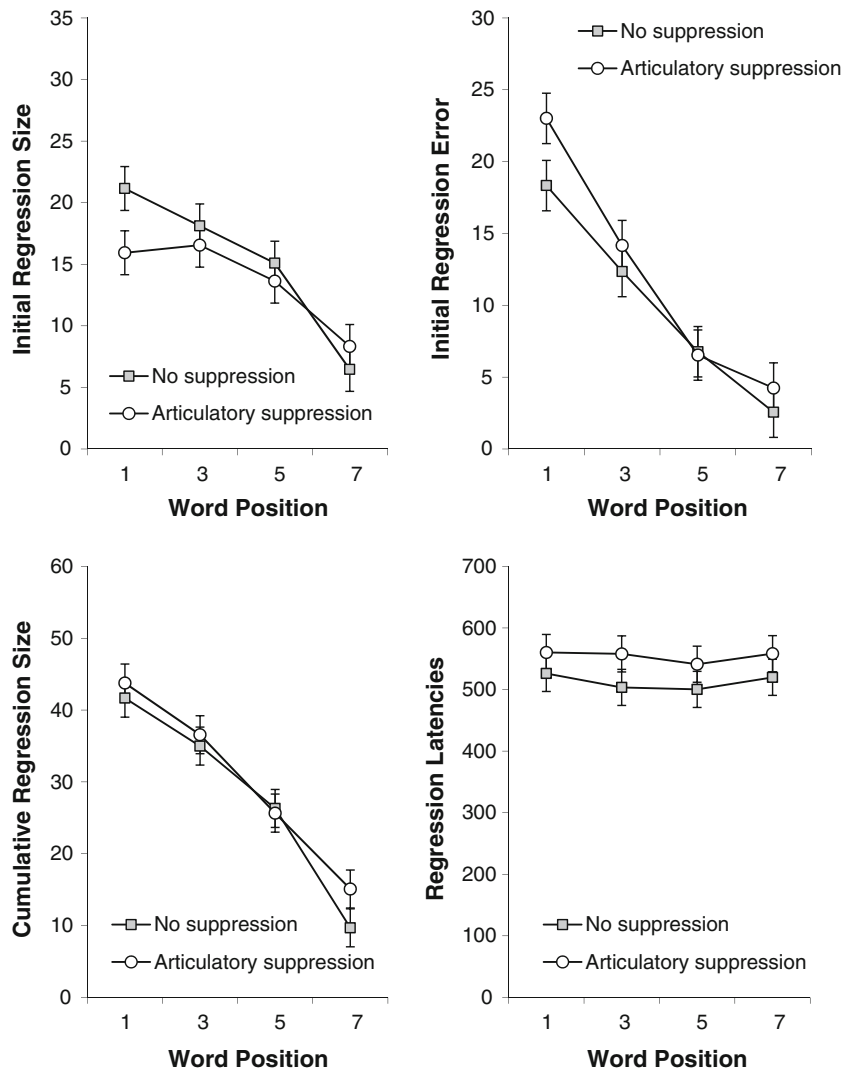
Initial regression error Inspection of Fig. 3 suggests that regression error was higher in the articulatory suppression condition. This was confirmed by repeated measures ANOVAs showing that regression error was higher in the articulatory suppression condition than in the no-suppression condition, $F(1, 19) = 11.15$, $p = .003$, $\eta_p^2 = .37$, and decreased as a function of word position, $F(3, 57) = 102.23$, $p < .001$, $\eta_p^2 = .84$. The interaction between suppression and word position was

Table 2 First-fixation durations, gaze durations, total fixation durations, and skip rates for the target words in the no-suppression and articulatory suppression conditions of Experiments 2 and 3

	No Suppression				Articulatory Suppression			
	1	3	5	7	1	3	5	7
Experiment 2								
First	213 (44)	214 (26)	224 (36)	246 (52)	268 (94)	245 (59)	246 (41)	251 (48)
Gaze	254 (62)	250 (41)	264 (50)	277 (66)	341 (162)	287 (86)	289 (70)	278 (60)
Total	295 (64)	307 (77)	326 (79)	328 (91)	407 (165)	359 (111)	372 (103)	347 (98)
Skip	.03 (.06)	.03 (.07)	.04 (.08)	.04 (.06)	.02 (.07)	.03 (.07)	.07 (.13)	.04 (.07)
Experiment 3								
First	256 (68)	242 (56)	245 (45)	280 (66)	298 (92)	265 (62)	264 (50)	283 (88)
Gaze	316 (101)	328 (113)	323 (73)	357 (114)	444 (226)	348 (123)	344 (90)	332 (139)
Total	388 (159)	429 (171)	413 (106)	399 (122)	538 (242)	480 (160)	447 (125)	393 (148)
Skip	.00 (.00)	.02 (.06)	.01 (.03)	.04 (.06)	.02 (.04)	.01 (.03)	.01 (.03)	.08 (.12)

Standard deviations are indicated in parentheses

Fig. 3 Initial regression size and error, cumulative regression size, and regression latencies as a function of word position in the articulatory suppression and no-suppression conditions in Experiment 2. Errors bars represent 95 % confidence intervals



also significant, $F(3, 57) = 4.64, p = .006, \eta_p^2 = .19$. Paired-samples t tests with $\alpha = .025$ (.15 / 6) confirmed that articulatory suppression increased the initial regression error for the first word position ($p = .001$) and had no effect on Positions 3 ($p = .16$), 5 ($p = .71$), and 7 ($p = .05$).

Cumulative regression size Figure 3 suggests that cumulative regression size did not differ between the no-suppression ($M = 28.1$ characters, $SD = 3.4$) and articulatory suppression ($M = 30.2$, $SD = 3.8$) conditions. A repeated measures ANOVA, however, revealed that the main effect of suppression was significant, $F(1, 19) = 6.55, p = .019, \eta_p^2 = .26$. There was also a significant main effect of word position, $F(3, 57) = 173.68, p < .001, \eta_p^2 = .90$, but the interaction between suppression and word position was not significant, $F(3, 57) = 1.83, p = .15, \eta_p^2 = .09$.

Regression latencies Regression latencies are also presented in Fig. 3. A repeated measures ANOVA showed that the main effects of suppression, $F(1, 19) = 3.57, p = .07, \eta_p^2 = .16$, and word position, $F(3, 57) = 1.94, p = .14, \eta_p^2 = .09$, were not significant. In the same line, the interaction between suppression and word position was not significant, $F < 1$.

Discussion

Experiment 2 replicated the results of Experiment 1 by showing that the initial regression size and error and the cumulative regression size increased as the word was located farther from the launching position. Articulatory suppression appeared to slightly affect comprehension and to increase fixation durations on the first target word. In line with Weger and Inhoff's (2007) results, Experiment 2 also showed that articulatory suppression affected the pattern of eye movements during regressions. More specifically, suppression reduced the size of the initial saccade, as well as its accuracy. It also slightly impaired corrective saccades.

Experiment 3

In Experiments 1 and 2, our results suggested that participants relied on memory in order to retrieve the location of the target word. It is not clear, however, whether the availability of the sentence during regressions influenced our pattern of interference. For instance, in the articulatory suppression condition, participants may have opted for a strategy in which they did not try to remember the words' locations because they knew that the sentence would be displayed: During the regression, they only searched for

the target word. Moreover, it is also possible that articulatory suppression did not alter the precision of the words' location representations, but only the strategies used during the regression. For instance, because of the difficulty of the task under articulatory suppression, participants may have opted for a more conservative strategy in which they made shorter regressions coupled with more corrective saccades. In order to test these possibilities in Experiment 3, we replicated Experiment 2 using a slightly different procedure. Indeed, rather than displaying the original sentence on the screen during regressions, the sentence was replaced by a series of Xs, which allowed us to compute the accuracy of the word's location in memory and to remove the contribution of online sentence processing during regressions.

Method

Participants

A group of 16 students from the Université de Moncton volunteered to take part in the experiment in exchange for a small honorarium.

Apparatus and materials

The apparatus and materials were the same as in Experiment 2.

Procedure and design

The procedure and design were the same as those used in Experiment 2, except that at the onset of the critical word through the loudspeaker, the sentence was replaced by a series of Xs: All punctuation marks were removed, and a series of capital Xs corresponding to the length of the original sentence was displayed. All spaces between words were also replaced by Xs. Participants were instructed to move their eyes as precisely as possible to the location of the target word.

Results

Over the 1,280 critical sentences (80 sentences \times 16 participants), 2.9 % were removed from the analysis due to large distortions in the eye movement recording or because participants executed a regression in the sentence before hearing the target word. Articulatory suppression ($M = 88\%$, $SD = 6\%$) slightly impaired comprehension as compared to the no-suppression condition ($M = 92\%$, $SD = 4\%$), $F(1, 15) = 5.53, p = .033, \eta_p^2 = .27$.

As in Experiment 1, we first analyzed fixation durations on the target words. In addition to the measures of regression used in Experiments 1 and 2, the precision of the retrieved location—called the last-fixation error—was computed in Experiment 3. The last-fixation error corresponded to the distance between the final fixation before the series of Xs disappeared and the two middle letters of the target word. For instance, if the last fixation was positioned on the X corresponding to the first letter or last letter of the target word, the last-fixation error was two characters. For all analyses, Block Order was entered as a factor. These analyses are reported only when the main effect of block order was significant or when it interacted with another factor.

Eye movements during reading

The eye movement data are presented in Table 2. For each measure, a 2 (suppression) \times 4 (word position) repeated measures ANOVA was performed. For the measures of first fixations, neither the main effects of suppression and word position nor their interaction was significant, $F_s < 3.24$. For gaze and total durations, although the main effects of suppression and word position did not reach significance, $F_s < 3.91$, their interaction was significant [$F(3, 45) = 5.84, p = .01, \eta_p^2 = .28$, and $F(3, 45) = 4.49, p = .008, \eta_p^2 = .23$, for gaze and total durations, respectively]. Paired-samples t tests showed that this interaction was due to the fact that the difference between the two suppression conditions was significant for Word Position 1 only ($p = .01$). For total duration, block order interacted with suppression, $F(1, 14) = 5.81, p = .03, \eta_p^2 = .29$. This interaction was due to the fact that suppression increased the total fixation duration when participants started with the suppression block, $F < 1$, but not when they started with the control block ($p = .006$). For the proportions of skips, the main effect of suppression and the interaction between suppression and word position were not significant, $F_s < 1.41$. The main effect of word position was significant, $F(3, 45) = 7.49, p < .001, \eta_p^2 = .33$, because, as is suggested in Table 2, it was higher for words at the ends of sentences.

Measures of regressions

In the no-suppression condition, 36 % ($SD = 12$ %) of all regressions reached the target, as compared to 30 % ($SD = 13$ %) in the articulatory suppression condition. This difference was significant, $F(1, 15) = 5.31, p = .04, \eta_p^2 = .26$.

Initial regression size As is shown in Fig. 4, the initial regression seemed to be longer in the no-suppression condition than under articulatory suppression for the words in

Positions 1 and 3. A repeated measures ANOVA indicated that the main effects of suppression, $F(1, 15) = 15.09, p = .001, \eta_p^2 = .50$, and word position, $F(3, 45) = 37.66, p < .001, \eta_p^2 = .72$, were significant. The analysis also revealed a significant interaction between suppression and word position, $F(3, 45) = 4.18, p = .01, \eta_p^2 = .22$. Paired-samples t tests with $\alpha = .025$ (.15/6) indicated that the effect of suppression was significant for Word Position 1 ($p < .001$), but not for Positions 3 ($p = .039$), 5 ($p = .60$), and 7 ($p = .60$).

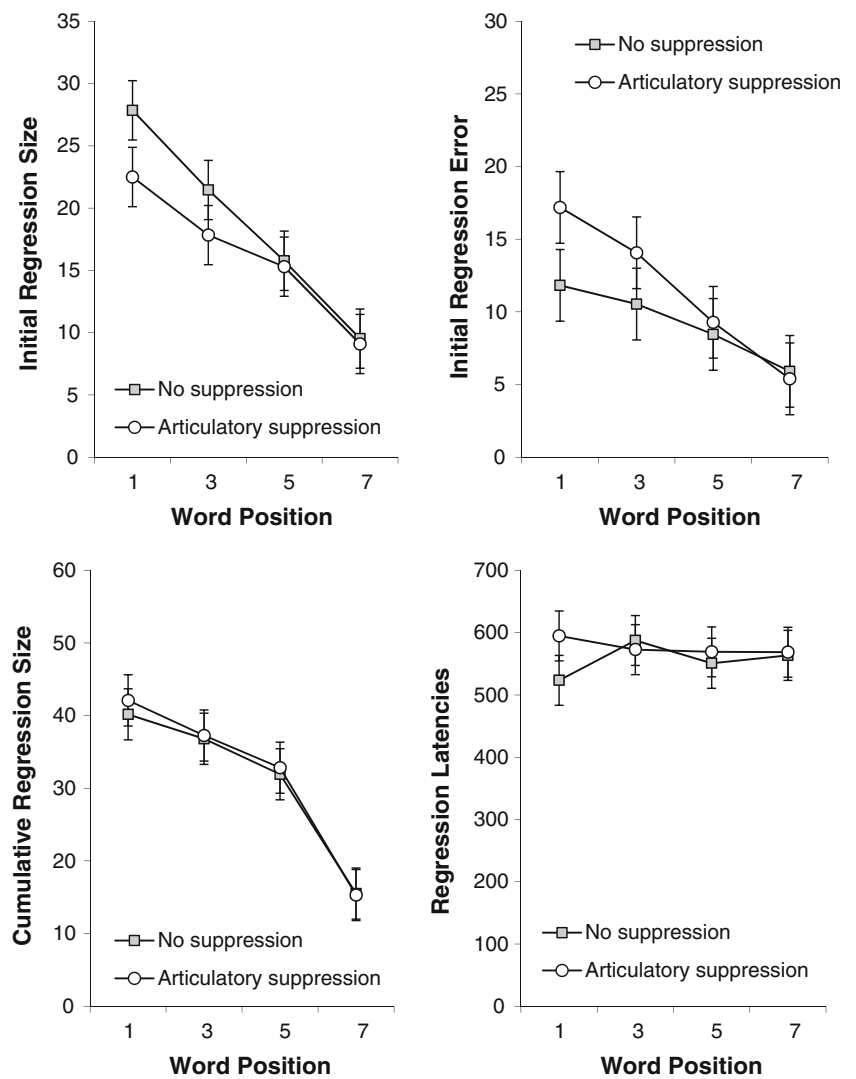
Initial regression error Figure 4 suggests that the regression error was higher in the articulatory suppression condition than in the no-suppression condition. This was confirmed by a repeated measures ANOVA showing that regression error was higher in the articulatory suppression than in the no-suppression condition, $F(1, 15) = 20.10, p < .001, \eta_p^2 = .57$, and decreased as a function of word position, $F(3, 45) = 10.31, p = .001, \eta_p^2 = .41$. The interaction between suppression and word position was also significant, $F(3, 45) = 7.05, p = .001, \eta_p^2 = .32$. Paired-samples t tests with $\alpha = .025$ (.15/6) confirmed that articulatory suppression increased the initial regression error for Word Position 1 ($p = .001$) and had no effect on Positions 3 ($p = .05$), 5 ($p = .07$), and 7 ($p = .46$).

Cumulative regression size A repeated measures ANOVA revealed a significant main effect of word position, $F(3, 45) = 47.50, p < .001, \eta_p^2 = .76$, but neither the main effect of suppression nor the interaction between suppression and word position was significant, $F_s < 1$ (see Fig. 4).

Regression latencies Regression latencies are also presented in Fig. 4. A repeated measures ANOVA showed that neither the main effects of word position and suppression nor their interaction was significant, $F_s < 1$. However, the three-way interaction including Block Order as a factor was significant, $F(3, 42) = 3.63, p = .02, \eta_p^2 = .21$. Simple main effects showed that this was due to the Suppression \times Word Position interaction, which was significant in the group who started with the control block, $F(3, 21) = 3.57, p = .03, \eta_p^2 = .34$, but not in the group who started with the suppression block, $F(3, 21) = 1.07, p = .38, \eta_p^2 = .13$. Paired-samples t tests in the former group, however, revealed no significant difference.

Last-fixation error As is shown in Fig. 5, last-fixation errors were lower in the no-suppression condition ($M = 2.47, SD = 0.80$) than under articulatory suppression ($M = 3.98, SD = 1.40$). This was confirmed by a repeated measures ANOVA

Fig. 4 Initial regression size and error, cumulative regression size, and regression latencies as a function of word position in the articulatory suppression and no-suppression conditions in Experiment 3. Errors bars represent 95 % confidence intervals



showing that the main effects of suppression, $F(1, 15) = 19.90, p < .001, \eta_p^2 = .57$, and word position, $F(3, 45) = 1.92, p < .001, \eta_p^2 = .44$, were significant. The interaction between suppression and word position was not significant, $F(3, 45) = 2.03, p = .15, \eta_p^2 = .12$. The effect of word position confirms that the last fixation was less accurate for words in the middle of the sentence. In order to examine whether this effect was related to the number of saccades executed to reach the target, we analyzed the number of saccades executed before the final fixation, pooled between conditions. The mean numbers of saccades executed to reach words located in Positions 1, 3, 5, and 7 were 2.2, 2.4, 2.7, and 1.5, respectively. A repeated measures ANOVA with Word Position as a factor showed that the main effect of word position was significant. Post hoc comparisons indicated that this effect was due to the lower number of saccades

executed to reach the word in Position 7 as compared to the three other positions, which did not differ.

Discussion

In line with the results of Experiment 2, the initial regression size and error and the cumulative regression size decreased as a function of word position. The measure of last-fixation accuracy also indicated that participants remembered the locations of the words better at the beginning or end of the sentence than in the middle positions.

Experiment 3 also replicated the results of Experiment 2 by showing that the initial regression size and the initial regression error were affected by articulatory suppression. The final fixation was also less precise under articulatory suppression. Contrary to Experiment 2, however, cumulative regression size was not affected. It is important to note,

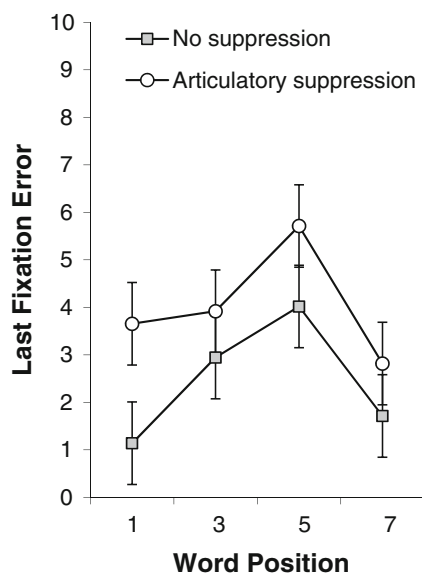


Fig. 5 Last-fixation errors as a function of word position in the articulatory suppression and no-suppression conditions in Experiment 3. Error bars represent 95 % confidence intervals

however, that in Experiment 2, articulatory suppression increased cumulative regression sizes by only two characters. Combined, the two experiments suggest that corrective saccades are not significantly impaired by articulatory suppression. Finally, suppression had a small effect on comprehension. The effect of suppression on comprehension in Experiments 2 and 3 was in line with the results of Baddeley, Eldridge, and Lewis (1981; see also Farmer, Berman, & Fletcher, 1986), who showed that articulatory suppression reduced participants' ability to detect semantic errors in sentences.

General discussion

The objective of this series of experiments was to investigate the role of verbal memory during regressions. Experiment 1 showed that regressions made after reading the sentence (reading group) differed greatly from those based solely on the visual configuration of the sentence (control group): In the reading group, the initial regression size increased as the word was located farther from the launching site, and the cumulative regression size was shorter than for the control group. The initial regression was also more accurate in the reading than in the control group. These results suggest that both the initial regression and the corrective saccades made to reach the target were based on memory (see Inhoff & Weger, 2005; Weger & Inhoff, 2007). Moreover, in line with the results of Inhoff and Weger, our results showed that although the initial regression is spatially selective, it is not precise.

In order to examine the role of verbal memory during regressions, we combined the reading task with articulatory suppression (Exps. 2 and 3). Articulatory suppression affected the length of the initial regression, its accuracy, and the accuracy of the last fixation, but had only a limited effect on corrective saccades. It seems, therefore, that verbal memory is primarily used to guide the initial saccade during a regression. It is important to note that articulatory suppression also had an impact on fixation durations during reading, but only for the first word location. This suggests that beginning the reading task was more challenging under suppression, but after the first one or two words of the sentence, participants could read at their normal speed even under suppression.

Finally, our results showed that the accuracy of the final fixation followed an inverse U-shaped curve: Participants were more precise in relocating words at the beginnings and ends of sentences than words in the middle. Fischer (1999) also reported a similar pattern by showing that the time required to locate a word in a sentence was faster for the first and last words of the sentence than for words in the middle positions. He argued that such evidence of recency and primacy effects indicates that recall is based on the retrieval of the words' spatial location from memory. However, plenty of studies have shown that primacy and recency effects are characteristics of both verbal (Neath, Surprenant, & LeCompte, 1998; Rundus, 1971) and spatial (Jones, Farrand, Stuart, & Morris, 1995; Parmentier & Jones, 2000; Smyth, 1996) short-term recall. Therefore, we believe that this pattern is not indicative of the nature of the representations guiding regressions—that is, whether they are spatial or verbal. It does suggest, however, that regressions recruit memory processes also involved during typical short-term memory tasks.

The effect of articulatory suppression on regressions can be interpreted in light of the verbally based reconstruction hypothesis (see Rawson & Miyake, 2002). For instance, upon hearing the target word, participants might have reconstructed the sentence by retrieving the order of the concepts presented there. This process might have allowed them to approximately locate the target word. Such an interpretation is therefore consistent with the finding that, although regressions were spatially selective, they were rather imprecise. Articulatory suppression might have disrupted the encoding of the words' order, resulting in more errors during reconstruction. In line with this idea, Baddeley et al. (1981) suggested that articulatory suppression prevented subvocalization, a process that would allow participants to translate written text into an articulatory code. According to Baddeley et al. (1981), such a code would be particularly useful to encode the order of the words, but would not be implicated in understanding the meaning of the sentences.

In order to examine how the locations of target words were retrieved before a regression, we measured regression latencies. For instance, if participants must reconstruct the sentence in order to relocate the target words, words located at the beginning of the sentence should be retrieved faster than words located at the end of the sentence (Rawson & Miyake, 2002). Regression latencies should therefore increase as a function of word position. The patterns of response latencies in our three experiments do not show such a linear trend. The experimental paradigm used in the present experiment might not be optimal, however, to interpret saccade latencies, as this measure can be influenced by several factors that were not controlled in our experiments. For instance, long saccades take longer to initiate than do short saccades (see, e.g., Yang et al., 2006). Therefore, even if words located at the beginning of the sentence might have been retrieved faster, regression latencies are likely to increase for these words because long saccades take more time to initiate. In order to examine saccade latencies for words at the beginning versus the end of the sentence, the absolute distances would have to be equated between word locations.

The processes underlying eye movement planning and execution might have influenced other measures than saccade latencies in our task. For instance, one possibility is that words at the beginnings of sentences were undershot, followed by a higher number of corrective saccades that brought the target word into the fovea, as compared to words at the end of the sentence. Note, however, that the numbers of corrective saccades did not differ between Word Positions 1, 3, and 5 in Experiment 3. Another possibility is that regressions for words located at the beginning of the sentence are less precise than for words located at the end because long saccades are less accurate than short saccades (see, e.g., Abrams, Meyer, & Kornblum, 1989). Clearly, more work needs to be done in order to understand how regressions are affected by word position and saccade programming.

The fact that initial regressions were still very selective under articulatory suppression suggests that the locations of the words within a sentence could be retained by other processes than subvocalization. One possibility is that spatial memory is very critical during regressions, an idea that has been supported by numerous studies. For instance, previous research has provided evidence of a spatial code when participants must relocate information from a long text (see Le Bigot, Passerault, & Olive, 2009; Zechmeister, McKillip, Pasko, & Bessalec, 1975), although this finding has not been reported consistently (see Theriault & Raney, 2002). Christie and Just (1976) suggested that spatial knowledge could be used to organize the text and as an index to address its content. Other studies have shown that shifting the sentence relative to the page layout affected regression accuracy, which suggests that word position is

encoded relative to external landmarks, such as the page layout (see, e.g., Kennedy et al., 2003).

Another possibility is that semantic or linguistic knowledge is also used to guide regressions. Indeed, some studies have suggested that articulatory suppression would disrupt phonological and not semantic maintenance (see, e.g., Shivde & Anderson, 2011). It is, therefore, possible that semantic or linguistic knowledge contributed to regressions in our task. Semantic and linguistic knowledge might also be responsible for guiding corrective saccades. In effect, although Experiment 1 showed that corrective saccades were guided by memory, our results showed that verbal interference affected corrective saccades only very slightly in Experiment 2, and not at all in Experiment 3. One possibility is that after the first saccade has been initiated, semantic and linguistic knowledge is used to direct the eyes toward the target. This hypothesis is in line with the conclusion of Weger and Inhoff (2007) that linguistic knowledge might play an important role during corrective saccades, as suggested by their effect of verbal load on the cumulative regression size.

Overall, our results show that verbal memory plays an important role in regressions during reading. More specifically, verbal memory seems to be involved in guiding the initial saccade toward the target word. This conclusion supports the verbally based reconstruction hypothesis (Rawson & Miyake, 2002), suggesting that in order to retrieve the location of a word, participants recall the succession of events depicted by the sentence.

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