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The role of verbal memory in regressions during reading is modulated by the target word's recency in memory

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Abstract During reading, a number of eye movements are made backward, on words that have already been read. Recent evidence suggests that such eye movements, called regressions, are guided by memory. Several studies point to the role of spatial memory, but evidence for the role of verbal memory is more limited. In the present study, we examined the factors that modulate the role of verbal memory in regressions. Participants were required to make regressions on target words located in sentences displayed on one or two lines. Verbal interference was shown to affect regressions, but only when participants executed a regression on a word located in the first part of the sentence, irrespective of the number of lines on which the sentence was displayed. Experiments 2 and 3 showed that the effect of verbal interference on words located in the first part of the sentence disappeared when participants initiated the regression from the middle of the sentence. Our results suggest that verbal memory is recruited to guide regressions, but only for words read a longer time ago.

Keywords Reading · Regression · Short term memory · Verbal memory

During reading in languages like English and French, the eyes move along the lines in a left-to-right manner. Some eye movements are made in the opposite direction, on words that have already been fixated (what is called a *regression*; see, e.g., Frazier & Rayner, 1982). Regressions represent 10 %–15 % of the saccades made during reading and play a key role in reading (Rayner, Pollatsek, Ashby, & Clifton, 2012). Because regressions can be very precise (e.g., Kennedy & Murray, 1987), their execution must be based on a memory representation of the target word. There is abundant evidence that spatial memory plays a key role in guiding regressions, allowing the eyes to land near the location of the target word (e.g., Kennedy & Murray, 1984). Evidence for the role of verbal memory is more controversial, however (see, e.g., Guérard, Saint-Aubin, & Maltais, 2013; Weger & Inhoff, 2007). For instance, Weger and Inhoff showed that verbal memory played a limited role in guiding the initial saccade toward the target word during regressions. In another study, however, we showed the opposite result, where verbal interference decreased the precision of initial regressions (Guérard et al., 2013). The objective of the present study was to pursue this line of research and to examine the conditions under which verbal memory is recruited to guide regressions. We combined verbal interference with a task where participants were required to make regressions on target words located in the first or second part of a sentence that could be displayed on one or two lines.

The role of verbal memory during regressions has first been demonstrated in studies using long texts. For instance, Rawson and Miyake (2002; see also Therriault & Raney, 2009) asked participants to locate information in texts of several pages. They found that verbal, but not visuospatial, abilities correlated with participants' accuracy in locating the target information. They concluded that verbal memory was recruited for guiding regressions and developed the verbally based reconstruction hypothesis according to which target words are located by reconstructing the order of the elements of the text. As was pointed out by Guérard et al. (2013), however, the processes underlying regressions in a long text might differ from those recruited when executing a regression within the same sentence from which it was initiated.

In Weger and Inhoff's (2007) study, immediately after reading a sentence, participants were asked to regress to a target word in the sentence. They displayed sentences on two

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lines. The target word could be located on the first or on the second line of text. In order to investigate the role of verbal memory, they manipulated the number of words read before the regression was initiated—what they called *verbal load*. They showed that verbal load did not decrease the precision of the initial regression but influenced the corrective saccades that were made to reach the target after the initial saccade. They suggested that verbal memory played a limited role in planning the initial saccade during regressions. In a subsequent study, however, Guérard et al. (2013) used a verbal interference task that consisted of repeating irrelevant letters during reading—what is known as *articulatory suppression*. They found that the initial regression accuracy was significantly impaired by articulatory suppression and suggested that verbal memory played a more important role during regressions than was initially suggested by Weger and Inhoff.

The present study

In the present study, we were interested in investigating the factors that modulate the contribution of verbal memory during regressions. We first examined the effect of text arrangement. For instance, Weger and Inhoff (2007) suggested that the contribution of verbal memory might be predominant when the sentence is displayed on a single line because the order of a word in the sentence is correlated with its spatial location; for instance, the last word of the sentence is always in the most rightward location. When displayed on two lines, however, the spatial and verbal positions of a word are not correlated, at least for the part of the sentence that appears on the second line. The contribution of verbal memory might therefore be less important when the text is displayed on two lines, particularly for words located on the second line. The contribution of verbal memory has been found both in studies using sentences displayed on a single line (see, e.g., Guérard et al., 2013) and in studies where the text was displayed over several lines (see, e.g., Rawson & Miyake, 2002). The effect of text arrangement on regressions executed within the same sentence has never been investigated, however. We also examined the role of verbal memory as a function of target location. Indeed, on the basis of the finding that the effect of verbal interference was stronger for the first words of the sentence, the results of Guérard et al. suggest that the role of verbal memory during regressions might be predominant for words located in the first part of the sentence.

Two factors were therefore examined: the number of lines on which the sentence was displayed (one or two) and the part of the sentence where the target word was located (first or second half). The procedure was similar to that used by Guérard et al. (2013) and by Weger and Inhoff (2007). Participants were first asked to read the sentence. The target word was then presented auditorily, and participants had to execute a regression on the target word. On half of the trials, participants had to perform articulatory suppression. This verbal interfering task is traditionally used in studies of memory in order to interfere with the processes involved in verbal retention. Indeed, it is widely assumed that articulatory suppression prevents verbal rehearsal, one of the central mechanisms recruited for retaining verbal materials (see, e.g., Baddeley & Hitch, 1974).

Experiment 1

Method

Participants

Twenty-four French-speaking students (21 females) from Université de Moncton volunteered to take part in the experiment.

Apparatus and materials

The stimuli were displayed on a computer screen with a resolution of 1,024 × 768 pixels. Participants were seated at 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° and 500 Hz). The eye movements were captured by two cameras mounted on a headband that allowed tracking both eyes and head position for head-motion compensation. Only the pupil of the participant's eye for which the most accurate calibration was achieved was tracked. Participants' head was stabilized using a chinrest.

Target words were 48 six-letter nouns with a frequency count ranging between 20 and 80 occurrences per million and an imagery value ranging between 4 and 6 on a maximum of 7 (New, Pallier, Ferrand, & Matos, 2001). Across the four conditions, the mean frequency (M = 39.21, SD = 0.77) and imagery values (M = 5.19, SD = 0.11) were equated. Target words were included in sentences of 10 words, in positions 2, 3, 4, 7, 8, or 9, with eight sentences for each position. Positions 2, 3, and 4 were considered to be in the first part of the sentence, and positions 7, 8, and 9 were considered to be in the second part of the sentence. The other positions were not used in the critical sentences in order to avoid having a target word located at the beginning or end of a line. Forty additional sentences were used as fillers. The target words in the filler sentences were verbs (10), adjectives (6), or function words (24), with 4 target words at each of the 10 possible locations. All sentences contained between 57 and 61 characters, including space and punctuation, and ended with a period. They were presented in black Courier New police font. At a viewing distance of 60 cm, each character sustained 0.5°.

Half of the sentences were displayed on a single line, located at 6° from the top of the screen. The other half were displayed on two lines of five words. In this condition, the first line was presented at the same location as in the single-line condition. The second line was presented below, at 12° from the top of the screen. A black cross was also presented to the right of all sentences, aligned with the top line in the single-line condition and with the bottom line in the two-line condition. The cross was located at 4 and 27 characters from the right of the screen in the single-line and two-line conditions, respectively.

In order to ensure that participants read normally and understood the meaning of the sentences, 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

Participants were tested individually. Before the experiment, participants were asked to fixate alternatively nine calibration dots. Before the presentation of each sentence, participants were asked to fixate a single calibration dot displayed in the center of the computer screen. After recalibration, a cross vertically aligned with the beginning of the sentence was displayed at two characters from the left of the screen. When participants fixated that cross, the experimenter pressed a button to trigger the apparition of the full sentence and the disappearance of the cross. Participants then read the sentence. After reading of the sentence, they were instructed to fixate the cross at its right. A 100-ms fixation on the cross triggered the presentation of the target word through the loudspeakers. Participants were instructed to find the word in the sentence and to fixate it until the sentence disappeared. Three seconds after the onset of the word, the sentence disappeared, and the question was displayed. Participants read the question silently and responded orally by saying yes or no. Their response was recorded by the experimenter, who initiated the next trial.

In the articulatory suppression blocks, participants initiated suppression while fixating the left cross, before the sentence was displayed. They stopped suppression when their eyes landed on the right cross. During suppression, participants were asked to repeat aloud the letters A-B-C-D at a rate of two letters per second.

Design and measurement

A repeated measures design with three factors—number of lines (two levels: single line, two lines), target location (two levels: first part, second part), and articulatory suppression (two levels: control, articulatory suppression)—was used. The 88 sentences were divided into four blocks of experimental trials (single-line/control, single-line/articulatory suppression, two-line/control, two-line/articulatory suppression). Each block comprised 10 filler sentences and 12 critical sentences, 2 for each target position (2, 3, 4, 7, 8, and 9)—and therefore, 6 sentences with the target word in the first part (positions 2, 3, and 4) and 6 sentences with the target in the second part (positions 7, 8, and 9). The sentences in each block were presented in the same random order for all participants. Each block began with two practice trials. The four blocks were counterbalanced across participants.

Several measures were collected. We first measured comprehension, as assessed by the questions asked after each sentence. We then computed several measures of eye movements during the reading of the sentence. We first computed first-fixation duration (the duration of the first fixation made during the first pass), gaze duration (the sum of all fixations on the word prior to a saccade to a following or preceding word), total fixation time (the sum of all fixations on the word), and skipping rate (the proportion of words not fixated at all) on the target words. We then measured eye movements on the whole sentence during reading—that is, the number of fixations and of regressions, as well as the time required to read the sentence. These measures were calculated starting from the onset of the first fixation on the sentence until the offset of the last fixation on the sentence. We also measured gaze duration, as well as the proportion of skips on each word. The two latter analyses were restricted to the words that were not at the beginning or end of a line. Therefore, gaze duration and skip rate were calculated for words in positions 2, 3, 4, 7, 8, and 9.

Several measures of regressions are then presented. Two measures of initial regressions were first computed: the initial regression error and the number of part errors. The *initial regression error* corresponds to the number of characters between the middle of the target word and the letter on which the initial regression landed. For instance, in Fig. 3, if the target word was *crayon* and the regression landed on the letter *r* of *acheter*, the regression error was 7 characters (the space after the last word of the first line was considered a character). The measure of *part errors* was the proportion of trials where participants executed a regression on the incorrect part of the sentence; for instance, one part error was credited when the target word was located in the first part of the sentence and the regression landed on the second part of the sentence. This measure was computed in order to examine whether the effect of articulatory suppression on regression accuracy is due to the fact that articulatory suppression produces line errors when the sentence is displayed on two lines. We also computed initial regression error as a function of the word position on the line. Finally, we computed the *total number of saccades*—including the initial regression—in order to assess corrective saccades that were made to reach the target. We considered that the target was reached when the eyes landed on the target word or in the space before or after.

Results

Eye movements in the 48 critical sentences were analyzed with the EyeLink Data Viewer program. Over the 1,152 critical sentences (48 sentences × 24 participants), 1.9 % were removed from the analysis due to large distortion in eye movement recording. Fixations shorter than 80 ms were omitted from the analysis.

Comprehension

The mean percent of correct responses to the comprehension questions in the four conditions was submitted to a 2 (number of lines) × 2 (articulatory suppression) repeated measures analysis of variance (ANOVA). For all analyses, the .05 level of significance was adopted, and the Greenhouse–Geisser correction was applied when the sphericity criterion was not met. The analysis showed that comprehension scores in the single-line (M = 92 %, SD = 4 %) and two-line (M = 94 %, SD = 4 %) conditions did not differ significantly, $F < 1$. As was expected, comprehension was lower in the articulatory suppression condition (M = 90 %, SD = 3 %) than in the control condition (M = 96 %, SD = 6 %), $F(1, 23) = 20.10$, $p < .001$, $\eta^2_p = .47$. The interaction between number of lines and articulatory suppression was not significant, $F < 1$.

Eye movements on the target words during reading

These results are presented in Table 1, and the 2 (number of lines) × 2 (target location) × 2 (articulatory suppression) repeated measures ANOVAs are presented in Table 2. The analyses showed that articulatory suppression increased single, gaze, and total fixation durations. There was also a main effect of target location for total fixation, suggesting that overall, participants fixated the target words in the first part of the sentence for a longer amount of time than in the second part. The analysis on skip rate revealed a significant three-way interaction that is probably due to the higher proportion of skips in the second part of the sentence displayed on two lines in the control condition.

Eye movements on the sentence during reading

All measures are presented in Table 3, and the 2 (number of lines) × 2 (articulatory suppression) repeated measures ANOVAs are presented in Table 4. The analysis showed that the number of lines only affected the total number of fixations on the sentence, with a higher number of fixations on sentences displayed on two lines. Articulatory suppression increased gaze duration and the proportion of skips. For the number of regressions, the interaction between number of lines and articulatory suppression was significant. This interaction was due to the fact that articulatory suppression increased the number of regressions when the sentence was displayed on a single line (p = .013), but not on two lines (p = .90).

Initial regression error and part errors

In the control condition, 25 % (SD = 12 %) and 33 % (SD = 18 %) of initial regressions landed on the target word or in the space before or after, in the single-line and two-line conditions, respectively. These percentages are similar to those reported by Guérard et al. (2013; 28%) with shorter sentences of eight words and suggest that participants remember the location of the target. Examination of Fig. 1 suggests that articulatory suppression increased regression errors and part errors, but only when the target word was located in the first part of the sentence. The 2 (number of lines) × 2 (target location) × 2 (articulatory suppression) repeated measures ANOVAs (Table 5) revealed the same pattern: The main effects of target location and of articulatory suppression were significant, but not the main effect of number of lines. The

Table 1 First-fixation duration, gaze duration, total fixation duration, and skipping rate on target words during reading in Experiment 1 (with standard deviations in parentheses)

	Single Line				Two Lines			
	First Part		Second Part		First Part		Second Part	
	Control	AS	Control	AS	Control	AS	Control	AS
First	228 (37)	256 (54)	227 (46)	244 (42)	220 (47)	249 (62)	226 (50)	239 (45)
Gaze	253 (46)	299 (92)	250 (55)	281 (66)	255 (65)	293 (98)	242 (60)	266 (74)
Total	269 (65)	334 (118)	274 (66)	307 (77)	305 (124)	346 (129)	270 (67)	287 (85)
Skip	.09 (.13)	.07 (.12)	.07 (.11)	.11 (.17)	.06 (.08)	.08 (.13)	.15 (.16)	.07 (.12)

Note. AS = articulatory suppression

Table 2 ANOVAs performed on the first-fixation duration, gaze duration, total fixation duration, and skipping rate on target words during reading in Experiment 1

Source	*df*	*F*	*MSE*	η^2_p
First				
Number of lines (Nb)	1, 23	0.72	1,760.48	.03
Target location (L)	1, 23	0.53	1,758.38	.02
Articulatory suppression (AS)	1, 23	15.99*	1,415.67	.41
Nb × L	1, 23	0.35	845.80	.02
Nb × AS	1, 23	0.01	1,004.67	.00
L × AS	1, 23	1.45	1,534.51	.06
Nb × L × AS	1, 23	0.04	1,864.21	.00
Gaze				
Number of lines (Nb)	1, 23	0.85	2,767.07	.04
Target location (L)	1, 23	3.10	3,688.07	.12
Articulatory suppression (AS)	1, 23	10.21*	5,609.22	.31
Nb × L	1, 23	0.38	2,697.12	.02
Nb × AS	1, 23	0.35	1,762.26	.02
L × AS	1, 23	0.88	3,149.65	.04
Nb × L × AS	1, 23	0.00	3,237.06	.00
Total				
Number of lines (Nb)	1, 23	0.24	6,776.62	.01
Target location (L)	1, 23	5.57*	7,213.07	.20
Articulatory suppression (AS)	1, 23	8.15*	8,828.36	.26
Nb × L	1, 23	3.22	4,752.37	.12
Nb × AS	1, 23	1.01	4,759.57	.04
L × AS	1, 23	1.32	6,776.69	.05
Nb × L × AS	1, 23	0.03	6,137.99	.00
Skip				
Number of lines (Nb)	1, 23	0.03	0.02	.00
Target location (L)	1, 23	2.53	0.01	.10
Articulatory suppression (AS)	1, 23	0.16	0.02	.01
Nb × L	1, 23	2.59	0.01	.10
Nb × AS	1, 23	2.59	0.01	.10
L × AS	1, 23	0.16	0.02	.01
Nb × L × AS	1, 23	5.79*	0.01	.20

* $p < .05$

interaction between number of lines and target location was significant. Paired samples *t*-tests showed that initial regression error ($p = .18$) and part errors ($p = .29$) did not differ between the first and second parts of the sentence when it was displayed on two lines. When the sentence was displayed on a single line, however, regression error and part errors were higher in the first part than in the second part (*p*s < .001). Most important, the interaction between target location and articulatory suppression was significant. Paired samples *t*-tests showed that the effect of articulatory suppression on regression error was significant for the first part of the sentence ($p < .001$), but not for the second part ($p = .60$). Similarly, the effect of articulatory suppression on part errors was significant for the first part of the sentence ($p < .01$), but not for the second part ($p = .63$).

Initial regression error as a function of target position on the line

In order to have a sufficient number of observations for each position, we pooled the single- and two-line conditions together. Figure 2 shows regression error for words in positions 2, 3, and 4 in each part. Therefore, words in positions 2, 3, and 4 of the second part were the sixth, seventh, and eighth words of the sentence. As can be seen in Fig. 2, the effect of articulatory suppression was present for the three word positions in the first part and absent for the three word positions in the second part. A 2 (target location: first part, second part) × 2 (articulatory suppression) × 3 (position: 2, 3, 4) repeated measures ANOVA confirmed that regression error was higher for words in the first part than in the second part, $F(1, 23) = 25.89$, $p < .001$, $\eta^2_p = .53$, and higher under articulatory suppression than in the control condition, $F(1, 23) = 17.87$, $p < .001$, $\eta^2_p = .44$. The main effect of position was also significant, $F(2, 46) = 26.27$, $p < .001$, $\eta^2_p = .53$. The interactions between target location and articulatory suppression, $F(1, 23) = 11.85$, $p < .01$, $\eta^2_p = .34$, and between target location and position, $F(2, 46) = 5.78$, $p < .01$, $\eta^2_p = .20$, were also significant. The latter interaction was due to the fact that regression accuracy decreased as a function of position to a lesser extent for words in the first part, $F(2, 46) = 17.68$, $p < .001$, $\eta^2_p = .44$, than for words in the second part, $F(2, 46) = 14.58$, $p < .001$, $\eta^2_p = .39$. No other interactions were significant.

Total number of saccades

As is shown in the bottom panel of Fig. 1, articulatory suppression seemed to impair corrective saccades, but only when the target word was located in the first part of the sentence. The 2 (number of lines) × 2 (target location) × 2 (articulatory suppression) repeated measures ANOVA (Table 5) showed that there were more saccades to reach the target when the sentence was displayed on a single line than when it was displayed on two lines but that the location of the target word had no influence. Articulatory suppression increased the number of saccades. As is shown by the significant interaction between target location and articulatory suppression, suppression increased the number of corrective saccades when the target word was located in the first part of the sentence ($p = .001$), but not when the target word was located in the second part ($p = .45$). The interaction between number of lines and target location was also significant, suggesting that there were more saccades when the target word was located in the first part in the single-line condition ($p < .001$), but not when the sentence was displayed on two lines ($p = .03$).

Table 3 Average reading time, number of fixations and of regressions on the sentence, gaze duration, and skip rate during reading in Experiment 1 (with standard deviations in parentheses)

	Single Line		Two Lines	
	Control	AS	Control	AS
Reading time	2,498 (524)	2,768 (880)	2,733 (804)	2,829 (972)
Number of fixations	10.10 (1.55)	10.31 (2.38)	11.01 (2.32)	10.55 (2.31)
Number of regressions	1.10 (0.60)	1.59 (0.93)	1.61 (0.90)	1.64 (0.96)
Gaze duration	254 (40)	277 (59)	246 (44)	270 (60)
Skip rate	.31 (.09)	.35 (.07)	.28 (.10)	.34 (.11)

Note. AS = articulatory suppression

Discussion

Our results showed that articulatory suppression slightly impaired comprehension and increased fixation durations during reading. These findings replicate what we had previously observed (see Guérard et al., 2013). The number of lines on which the sentences were displayed affected regression accuracy. Indeed, when the sentences were displayed on two lines, regressions were as accurate when performed on the first and second parts of the sentence. On a single line, however, regressions made to target words located in the first part were less accurate and were followed by more corrective saccades than for target words located in the second part of the sentence. Therefore, the arrangement of the text seemed to influence the processes underlying regressions. The most important finding is that suppression affected regression accuracy, but only when the target word was located in the first part of the sentence. This effect was observed irrespective of whether the sentence was displayed on a single line or on two lines, which suggests that the arrangement of the text does not modulate the role of verbal memory during regressions.

Table 4 ANOVAs performed on the average reading time and number of fixations and regressions on the sentence, as well as on gaze duration and skip rate during reading in Experiment 1

Source	*df*	*F*	*MSE*	η^2_p
Reading time				
Number of lines (Nb)	1, 23	3.56	147,244.62	.13
Articulatory suppression (AS)	1, 23	1.56	514,024.51	.06
Nb × AS	1, 23	1.13	162,374.75	.05
Number of fixations				
Number of lines (Nb)	1, 23	6.32*	1.23	.22
Articulatory suppression (AS)	1, 23	0.10	3.61	.00
Nb × AS	1, 23	3.00	0.90	.12
Number of regressions				
Number of lines (Nb)	1, 23	3.74	0.48	.14
Articulatory suppression (AS)	1, 23	2.11	0.77	.08
Nb × AS	1, 23	5.50*	0.23	.19
Gaze duration				
Number of lines (Nb)	1, 23	1.82	748.24	.07
Articulatory suppression (AS)	1, 23	8.90*	1,469.77	.28
Nb × AS	1, 23	0.01	463.28	.00
Skip rate				
Number of lines (Nb)	1, 23	2.90	0.00	.11
Articulatory suppression (AS)	1, 23	11.70*	0.00	.34
Nb × AS	1, 23	0.80	0.00	.03

* $p < .05$

Experiment 2

The results of Experiment 1 showed that articulatory suppression only impaired regressions made to words located in the first part of the sentence. One possibility is that the involvement of verbal memory during regressions depends on the order of the target word in the sentence; that is, only the first words of a sentence would be retrieved through verbal memory. This possibility is in line with models defining verbal memory capacity as a definite number of items (see, e.g., Cowan, 1993). Once this capacity is reached, another system or code would need to be used. Another possibility is that the involvement of verbal memory depends on the number of words that have been read after the target word; that is, verbal memory would only be recruited to retrieve the location of words that have been read a long time ago, such as when regressing to a word located at the beginning of the sentence after the whole sentence has been read. In other words, readers would not use a verbal code to guide their regressions to the most recently read items, presumably because they have access to another, more efficient source of information.

In order to test these two hypotheses, in Experiment 2, we used the two-line condition of Experiment 1. Regressions in the critical sentences were always initiated from the line where the target word was located. When the target word was located on the first line, participants executed the regression after having read the first half of the sentence. Therefore, the regression in the first-line condition was initiated from the

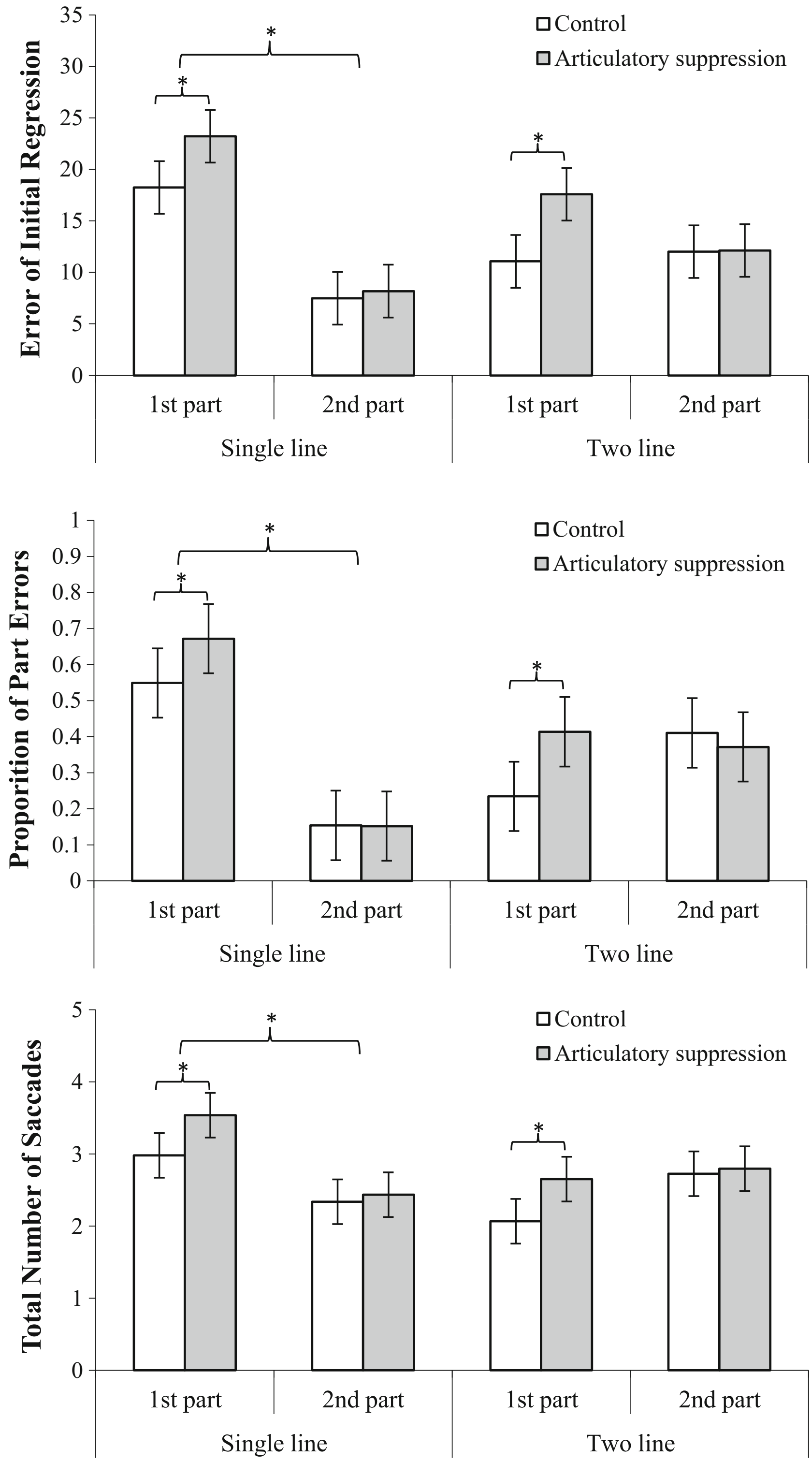

Fig. 1 Initial regression error (top), proportion of part errors (middle), and total number of saccades (bottom) as a function of number of lines, target location, and articulatory suppression in Experiment 1. Errors bars represent 95 % confidence intervals

end of the first line. When the target word was located on the second line, participants executed the regression after having read the whole sentence: The regression was initiated from the end of the second line. Therefore, irrespective of whether the target word was located in the first or in the second half of the sentence, the target word was always one of the five most recently read words. If verbal memory is recruited to retrieve words located in the first part of the sentence—irrespective of

Table 5 ANOVAs performed on the initial regression error, part errors, and total number of saccades in Experiment 1

Source	*df*	*F*	*MSE*	η^2_p
Initial regression error				
Number of lines (Nb)	1, 23	1.60	35.11	.07
Target location (L)	1, 23	26.11*	105.58	.53
Articulatory suppression (AS)	1, 23	19.22*	23.62	.46
Nb × L	1, 23	42.51*	31.94	.65
Nb × AS	1, 23	0.12	23.33	.01
L × AS	1, 23	12.31*	27.72	.35
Nb × L × AS	1, 23	0.33	41.40	.01
Part errors				
Number of lines (Nb)	1, 23	0.83	0.34	.04
Target location (L)	1, 23	11.21*	0.16	.33
Articulatory suppression (AS)	1, 23	4.97*	0.04	.18
Nb × L	1, 23	72.71*	0.05	.76
Nb × AS	1, 23	0.03	0.04	.00
L × AS	1, 23	8.08*	0.04	.26
Nb × L × AS	1, 23	0.75	0.04	.03
Total number of saccades				
Number of lines (Nb)	1, 23	8.96*	0.37	.28
Target location (L)	1, 23	3.11	0.86	.12
Articulatory suppression (AS)	1, 23	14.61*	0.35	.39
Nb × L	1, 23	19.44*	0.92	.48
Nb × AS	1, 23	0.00	0.75	.00
L × AS	1, 23	5.91*	0.48	.20
Nb × L × AS	1, 23	0.02	0.43	.00

* $p < .05$

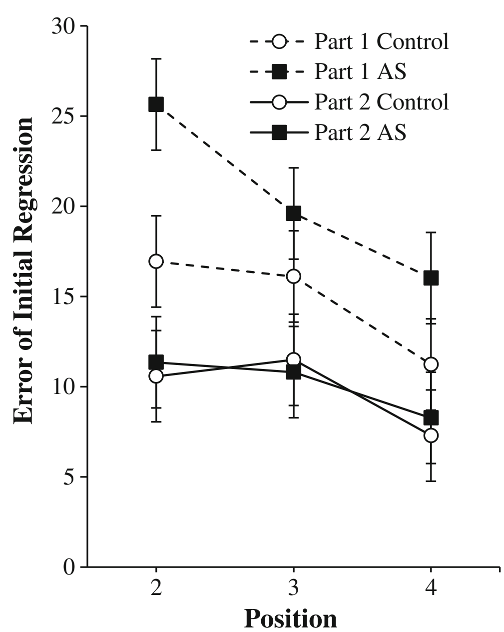

Fig. 2 Initial regression error as a function of target location and articulatory suppression for target words in positions 2, 3, and 4 of each part in Experiment 1. Errors bars represent 95 % confidence intervals

the number of words read after the target word—Experiment 2 should replicate the detrimental effect of articulatory suppression when the target word is located in the first part of the sentence. If verbal memory is recruited to retrieve the location of words read a longer time ago, the effect of articulatory suppression for target words on the first line should be abolished in Experiment 2, because the target words located on first line have just been read when the regression is initiated.

Method

Participants

Twenty-four French-speaking students (11 females) from Université de Moncton volunteered to take part in the experiment. None of the participants took part in the previous experiment.

Apparatus and materials

Eye movements were recorded with the Research Ltd Eye Link 1000 system (the system's resolution and sampling rate are <0.5° and 2000 Hz). The eye movements were captured by a camera located at the bottom of the computer screen. Only the pupil of the participant's eye for which the most accurate calibration was achieved was tracked. Participants' head was stabilized using a chinrest.

All sentences were displayed on two lines of five words, as in the two-line condition of Experiment 1. The 48 target words and critical sentences were the same as in Experiment 1. Three types of filler sentences were constructed. The target words in the filler sentences were verbs (2), adjectives or nouns (12), or function words (22). Twenty-four filler sentences contained the target word in the first part of the sentence, which could be located at any of the five first possible positions (positions 1, 2, 3, 4, or 5). In half of these filler sentences, participants initiated the regression from the bottom line. In the other half, participants initiated the regression from the top line. Twelve additional filler sentences were constructed with the target word located in the second half of the sentence.

Procedure

The procedure is presented in Fig. 3. On each trial, the first part of the sentence was presented, along with a cross located at 27 characters from the left of the screen, vertically aligned with the top line. Participants were instructed to read the first part of the sentence and to fixate the cross at its right. When the regression was initiated from the top line, a 100-ms fixation on this cross triggered the presentation of the target word through the loudspeakers. Participants were instructed to find the word in the sentence and to fixate it until the sentence disappeared. When the regression was initiated from the bottom line, a 100-ms fixation on the cross triggered the apparition of the second part of the sentence. Participants were instructed to read the second part and to fixate the right cross aligned with the bottom line. A 100-ms fixation on this cross triggered the presentation of the target word. Participants were instructed to find the target word and to fixate it. In both conditions, the sentence disappeared 3 s after the onset of the target word, and the question was displayed. Participants read the question and responded orally by saying yes or no. Their response was recorded by the experimenter who initiated the next trial. The rest of the procedure was as in Experiment 1.

Design

A repeated measures design with two factors, target location (two levels; first part, second part) and articulatory suppression (two levels; control, articulatory suppression), was used. The 84 sentences were divided into two blocks of experimental trials (control and articulatory suppression). Each block comprised 24 critical sentences: 12 with the target in the first part and 12 with the target in the second part. For the 12 critical sentences with the target located in the first part, the regression was always initiated from the top line. Each block also contained 18 filler sentences. The 18 filler sentences consisted of 12 sentences with the target word in the first part (6 in which participants initiated the regression from the top line and 6 in which participants initiated the regression from the bottom line) and 6 sentences with the target word in the second part (in which participants initiated the regression from the bottom line). The sentences in each block were presented in the same random order for all participants. Each block began with three practice trials. The two blocks were counterbalanced across participants.

Results

Over the 1,152 critical sentences (48 sentences × 24 participants), 1.1 % were removed from the analysis due to large distortion in eye movement recording.

Comprehension

A 2 (target location) × 2 (articulatory suppression) repeated measures ANOVA was performed on the percent of correct responses for the comprehension questions. As was expected, the analysis showed that when participants read only the first part of the sentences (M = 50 %, SD = 7 %), comprehension was at chance level, which is much lower than when they read the two parts (M = 79 %, SD = 9 %), $F(1, 23) = 388.26$, $p < .001$, $\eta^2_p = .94$. The effect of articulatory suppression was also significant, $F(1, 23) = 6.43$, $p < .05$, $\eta^2_p = .22$, as well as the interaction between target location and articulatory suppression, $F(1, 23) = 5.66$, $p < .05$, $\eta^2_p = .20$. This interaction was due to the fact that articulatory suppression affected comprehension when the target was located in the second part of the sentence ($p = .008$) and, therefore, participants read the full sentence, but not when the target was located in the first part of the sentence ($p = .41$) and participants read only the first part.

Eye movements on the target words during reading

The mean fixation durations and skip rates on the target words are presented in Table 6, and the 2 (target location) × 2 (articulatory suppression) repeated measures ANOVAs are presented in Table 7. The analyses showed that articulatory suppression increased single, gaze, and total fixation durations. Fixation durations were also longer, and skip rate was lower for words located in the first part of the sentence, as compared with words located in the second part. This effect was also observed in Experiment 1. Measures of eye movements on the whole sentence during reading were not computed in Experiment 2, because for half of the trials, only the first part of the sentence was presented, and for the second half, the two parts were presented sequentially rather than simultaneously, with a fixation on the right cross after having read the first part.

Initial regression error

In the control condition, 46 % (SD = 17 %) and 41 % (SD = 20 %) of initial regressions landed on the target in the first part and second part conditions, respectively. Inspection of Fig. 4 suggests that articulatory suppression had no effect on the precision of regressions. A 2 (target location) × 2 (articulatory suppression) repeated measures ANOVA confirmed that the main effect of articulatory suppression was not significant, $F < 1$, nor was the interaction between target location and articulatory suppression, $F(1, 23) = 1.78$, $p = .20$, $\eta^2_p = .07$. Regression error was higher when the regression was made in the second part of the sentence, as compared with the first part, $F(1, 23) = 14.82$, $p < .01$, $\eta^2_p = .39$. Part errors were not possible when the regression was initiated from the first line. When the regression was initiated from the second line, the number of part errors was low and did not differ between the control (M = .06, SD = .06) and suppression (M = .08, SD = .09) conditions, $F < 1$.

Initial regression error as a function of target position on the line

A 2 (target location: first part, second part) × 2 (articulatory suppression) × 3 (position: 2, 3, 4) repeated measures ANOVA showed that regression error was higher when target

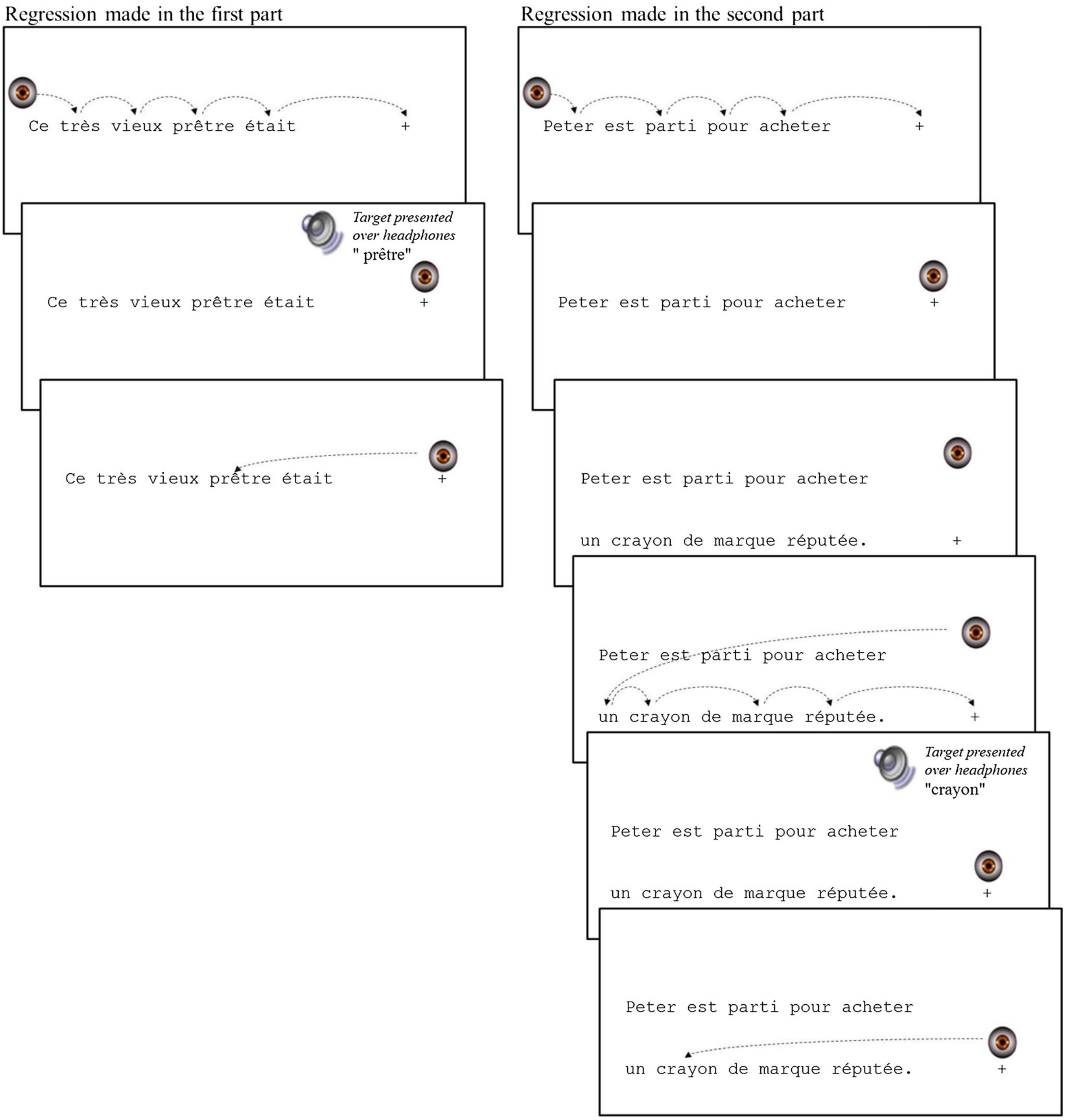

Fig. 3 Illustration of the task performed in the first part (left) and second part (right) conditions of Experiment 2

words were located in the second part than when they were located in the first part, $F(1, 23) = 15.39$, $p < .01$, $\eta^2_p = .40$ (see Fig. 5). The main effect of word position was also significant, $F(2, 46) = 80.74$, $p < .001$, $\eta^2_p = .78$. The main effect of articulatory suppression was not significant, $F < 1$. The interactions between target location and position was significant, $F(2, 46) = 6.82$, $p < .01$, $\eta^2_p = .23$. The latter interaction was due to the fact that regression accuracy decreased as a function of position to a lesser extent for target words in the first part, $F(2, 46) = 17.68$, $p < .001$, $\eta^2_p = .44$, than for target words in the second part, $F(2, 46) = 14.58$, $p < .001$, $\eta^2_p = .39$. No other interactions were significant.

Total number of saccades

As is shown in the bottom panel of Fig. 4, corrective saccades were not influenced by articulatory suppression. A 2 (target location) × 2 (articulatory suppression) repeated measures

Table 6 First-fixation duration, gaze duration, total fixation duration, and skipping rate on target words during reading in Experiments 2 and 3 (with standard deviations in parentheses)

	First Part		Second Part	
	Control	AS	Control	AS
Experiment 2				
First	209 (39)	250 (66)	181 (45)	205 (54)
Gaze	257 (63)	302 (97)	202 (57)	237 (73)
Total	307 (92)	408 (121)	264 (81)	330 (114)
Skip	.03 (.05)	.04 (.06)	.08 (.09)	.08 (.12)
Experiment 3				
First	223 (41)	247 (44)	203 (42)	209 (54)
Gaze	314 (142)	317 (90)	257 (81)	262 (70)
Total	417 (202)	501 (182)	352 (142)	411 (153)
Skip	.05 (.07)	.05 (.07)	.08 (.12)	.07 (.12)

Note. AS = articulatory suppression

Table 7 ANOVAs performed on the first-fixation duration, gaze duration, total fixation duration, and skipping rate on target words during reading in Experiments 2 and 3

Source	*df*	*F*	*MSE*	η^2_p
Experiment 2				
First				
Target location (L)	1, 23	43.40*	742.64	.65
Articulatory suppression (AS)	1, 23	18.86*	1,344.20	.45
L × AS	1, 23	1.58	903.86	.06
Gaze				
Target location (L)	1, 23	37.83*	2,262.13	.62
Articulatory suppression (AS)	1, 23	12.97*	2,959.55	.36
L × AS	1, 23	0.55	1,390.94	.02
Total				
Target location (L)	1, 23	29.22*	3,006.21	.56
Articulatory suppression (AS)	1, 23	23.16*	7,265.63	.50
L × AS	1, 23	2.60	2,801.57	.10
Skip				
Target location (L)	1, 23	13.63*	0.00	.37
Articulatory suppression (AS)	1, 23	0.06	0.01	.00
L × AS	1, 23	0.00	0.00	.00
Experiment 3				
First				
Target location (L)	1, 23	17.37*	1,166.93	.43
Articulatory suppression (AS)	1, 23	3.63	1,612.25	.14
L × AS	1, 23	1.95	1,020.28	.08
Gaze				
Target location (L)	1, 23	16.93*	4,498.07	.42
Articulatory suppression (AS)	1, 23	0.11	4,751.79	.01
L × AS	1, 23	0.03	2,195.06	.00
Total				
Target location (L)	1, 23	29.13*	5,042.33	.56
Articulatory suppression (AS)	1, 23	5.74*	21,549.13	.20
L × AS	1, 23	0.71	5,427.13	.03
Skip				
Target location (L)	1, 23	2.49	0.01	.10
Articulatory suppression (AS)	1, 23	0.14	0.01	.01
L × AS	1, 23	0.24	0.00	.01

* $p < .05$

ANOVA confirmed that neither the main effect of articulatory suppression, $F < 1$, nor the interaction between target location and articulatory suppression, $F(1, 23) = 2.29$, $p = .14$, $\eta^2_p = .09$, was significant. There were more corrective saccades when the target word was located in the second part, as compared with the first part, $F(1, 23) = 4.72$, $p < .05$, $\eta^2_p = .17$.

Discussion

Comprehension on trials where the sentence was fully displayed was lower (79 %) than comprehension in Experiment 1 (94 %). One possible explanation is that because several trials displayed only half of the sentence in Experiment 2—in which case, the meaning is almost impossible to extract—participants paid less attention to the meaning of the sentences during reading. Importantly, Experiment 2 showed that the effect of articulatory suppression observed for target words located in the first part of the sentence in Experiment 1 was abolished in Experiment 2. This suggests that verbal memory is predominantly recruited for words that have been read a longer time ago.

Experiment 3

The objective of Experiment 3 was to replicate the effect of articulatory suppression on regressions made in the first part of the sentence in Experiment 1 and the null effect in Experiment 2 within a single experiment. Indeed, since Experiment 2 yielded a null effect, replicating this finding along with the key finding of Experiment 1 seems warranted. We employed the procedure used in Experiment 2, in which all trials were displayed on two lines. We included additional critical trials where the regression was launched from the bottom line and the target word was located in the first part. Therefore, the effect of articulatory suppression was assessed in three conditions: (1) The regression was launched from the second line with the target word in the first part, (2) the regression was launched from the second line with the target word in the second part, and (3) the regression was launched from the first line with the target word in the first part. In line with the two previous experiments, articulatory suppression should impair regression accuracy when it is initiated from the second line to

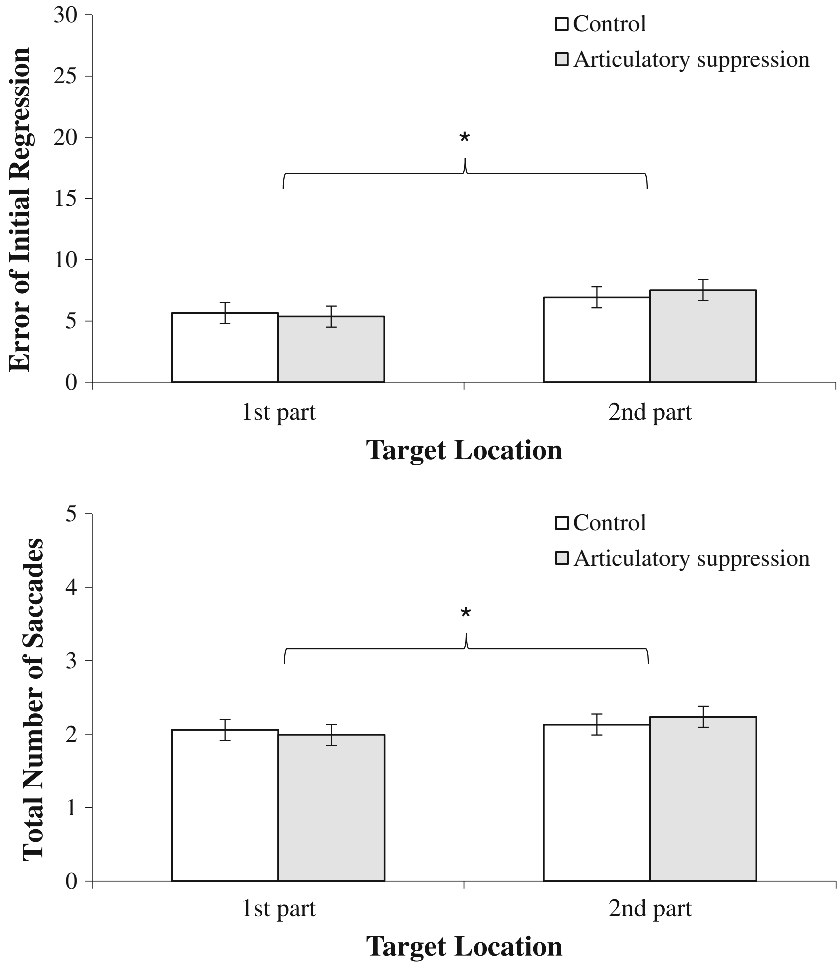

Fig. 4 Initial regression error (top) and total number of saccades (bottom) as a function of target location and articulatory suppression in Experiment 2. Errors bars represent 95 % confidence intervals

a target word in the first part, but not in the two other conditions.

Method

Participants

Twenty-four French-speaking students (15 females) from Université de Moncton volunteered to take part in the experiment. The mean age of participants was 19.7 years (SD = 3.1). None of the participants took part in the previous experiments.

Apparatus and materials

All sentences were displayed on two lines of five words as in Experiment 2. Fifty-four critical sentences were used in this experiment, 18 in each of the three conditions. On 18 trials, the regression was initiated from the second line, and the target word was located in the first part. On 18 trials, the regression was initiated from the second line, and the target word was located in the second part. On the last 18 trials, the regression was initiated from the first line, and the target word was located in the first part. In each condition, the target word was equally often at positions 2, 3, and 4 on the line. There were 36 filler sentences, 12 in each condition. The target words in the filler sentences were verbs (7), adjectives or nouns (10), or function words (19) and could be located at any position in the sentence.

Procedure and design

The procedure is the same as that used in Experiment 2. The 90 sentences were divided into two blocks of experimental trials (control and articulatory suppression). Each block comprised 18 filler sentences and 27 critical sentences: 9 with the regression initiated from the second line with the target in the first part (second line to first part), 9 with the regression initiated from the second line with the target in the second part (second line to second part), and 9 with the regression initiated from the first line with the target in the first part (first line to first part). A repeated measures design with two factors, condition (three levels: second line to first part, second line to second part, first line to first part) and articulatory suppression (two levels: control, articulatory suppression), was used.

Results

Over the 1,196 critical sentences (54 sentences × 24 participants), 5.5 % were removed from the analysis due to large distortion in eye movement recording.

Comprehension

A 2 (number of lines) × 2 (articulatory suppression) repeated measures ANOVA showed that when participants read only the first part of the sentences (M = 67 %, SD = 8 %), comprehension was lower than when they read the two parts (M = 85 %, SD = 9 %), $F(1, 23) = 120.57$, $p < .001$, $\eta^2_p = .84$. The effect of articulatory suppression was also significant, $F(1, 23) = 7.95$, $p < .05$, $\eta^2_p = .26$. The interaction between number of lines and articulatory suppression was not significant, $F(1, 23) = 1.29$, $p = .27$, $\eta^2_p = .05$.

Eye movements on the target words during reading

The mean fixation durations and skip rates are presented in Table 6 and the 2 (target location) × 2 (articulatory suppression) repeated measures ANOVAs are presented in Table 7.

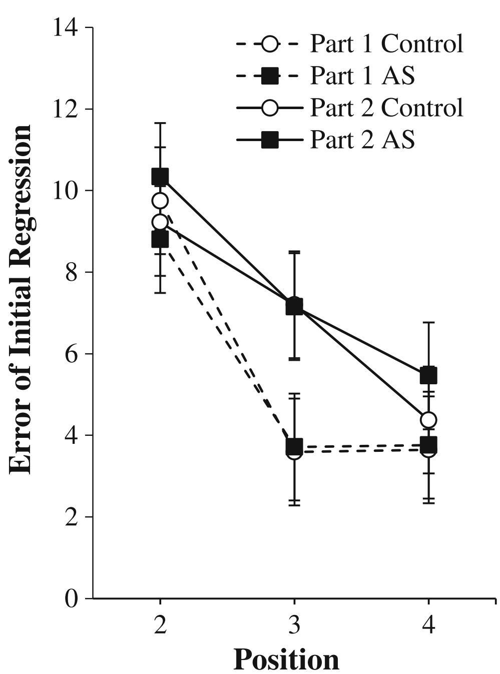

Fig. 5 Initial regression error as a function of target location and articulatory suppression for target words in positions 2, 3, and 4 of each part in Experiment 2. Errors bars represent 95 % confidence intervals

As in the previous experiments, the analyses showed that fixation duration was shorter for target words located in the second part of the sentence than for target words located in the first part. Total fixation duration was also longer under articulatory suppression. Skip rates were not affected by articulatory suppression and target location.

Initial regression error

In the control condition, 28 % (SD = 18 %), 30 % (SD = 16 %), and 44 % (SD = 12 %) of initial regressions landed on the target in the second line to first part, second line to second part, and first line to first part conditions, respectively. Inspection of Fig. 6 suggests that articulatory suppression reduced the precision of regressions when they were launched from the second line to a target in the first part, but not when they were executed on the same line from which they were launched. A 3 (condition) × 2 (articulatory suppression) repeated measures ANOVA confirmed that the main effects of condition, $F(2, 46) = 52.03$, $p < .001$, $\eta^2_p = .69$, and of articulatory suppression, $F(1, 23) = 15.40$, $p < .01$, $\eta^2_p = .40$, were significant. Pairwise comparisons showed that regression error was higher when the regression was launched from the second line to a target word in the first part than in the two other conditions (ps < .001). Regression error was also higher when the regression was launched from the second line to a target word in the second part than when it was launched from the first line to a target word in the first part ($p < .001$). Importantly, the interaction between condition and articulatory suppression was significant, $F(2, 46) = 9.50$, $p < .001$, $\eta^2_p = .29$. Paired sample t-tests showed that the effect of articulatory suppression was significant when the regression was initiated from the second line to a target in the first part ($p = .001$), but not when the regression was initiated from the second line to a target in the second part ($p = .85$) or from the first line to a target word in the first part ($p = .42$). Because there were only two observations for each position in the control and articulatory suppression conditions, we did not assess regression accuracy as a function of target position.

Total number of saccades

In line with the analysis of initial regression, corrective saccades appeared to increase under articulatory suppression only when participants initiated the regression from the second line to a word in the first part (see bottom panel of Fig. 6). A 3 (condition) × 2 (articulatory suppression) repeated measures ANOVA showed that the main effects of condition, $F(2, 46) = 27.91$, $p < .001$, $\eta^2_p = .55$, and of articulatory suppression, $F(1, 23) = 11.72$, $p < .01$, $\eta^2_p = .34$, were significant. Pairwise comparisons showed that regression error was higher when the regression was launched from the second line to a target word in the first part than in the other two conditions

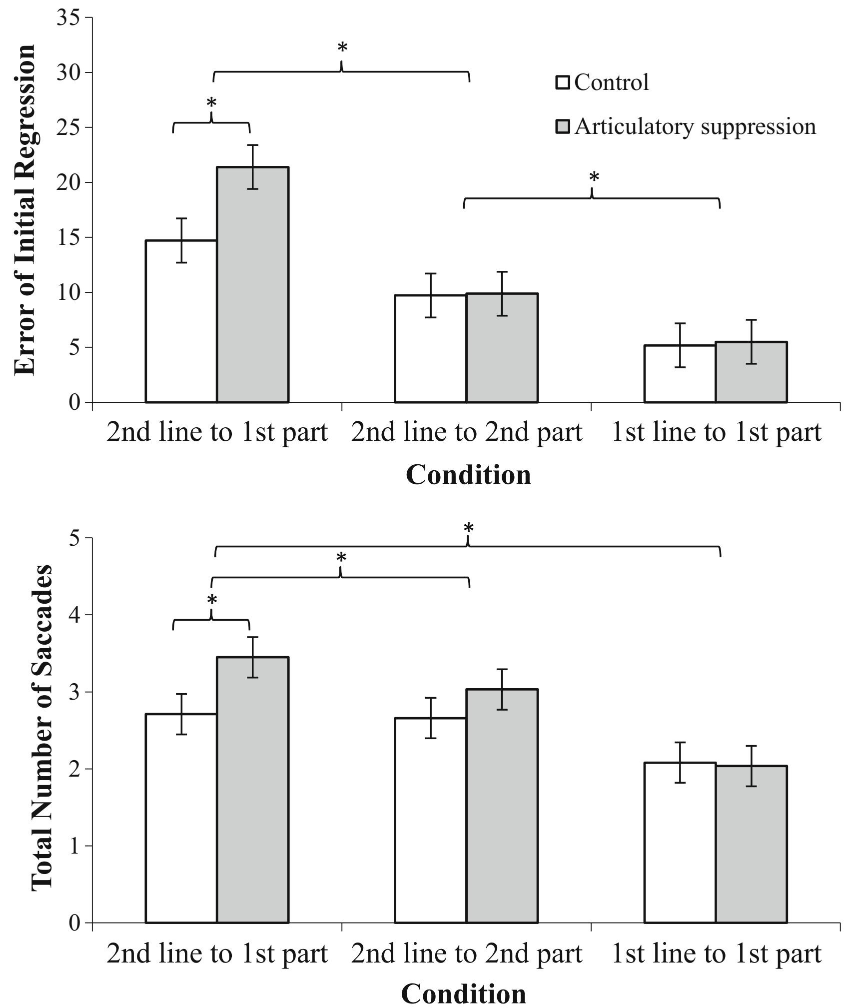

Fig. 6 Initial regression error (top) and total number of saccades (bottom) as a function of condition and articulatory suppression in Experiment 3. Errors bars represent 95 % confidence intervals

(*p*s < .001) but did not differ between the two latter conditions ($p = .64$). The interaction between condition and articulatory suppression was also significant, $F(2, 46) = 4.79$, $p < .05$, $\eta^2_p = .17$. Paired sample *t*-tests showed that the effect of articulatory suppression was significant when the regression was initiated from the second line to a target in the first part ($p < .001$), but not when the regression was initiated from the second line to a target in the second part ($p = .14$) or from the first line to a target word in the first part ($p = .62$).

Discussion

Comprehension in Experiment 3 when the full sentences were displayed (85 %) was slightly better than in Experiment 2 (79 %), but still lower than in Experiment 1 (94 %). This might be explained by the fact that the proportion of trials where only the first half of the sentence was presented (33 %) was lower than in Experiment 2 (43 %) but higher than in Experiment 1 (0 %). Importantly, Experiment 3 replicated the two key findings of Experiments 1 and 2. As in Experiment 1, when participants were asked to regress to a target word in the first part of the sentence after having read the whole sentence, articulatory suppression impaired regression accuracy. As in Experiment 2, when the regression was made on a target word that had just been read, articulatory suppression had no effect.

General discussion

The objective of the present experiments was to examine the factors that modulate the contribution of verbal memory during regressions. In Experiment 1, we showed that the role of verbal memory was not influenced by text arrangement: Whether the sentence was displayed on one or two lines did not modulate the effect of articulatory suppression. Articulatory suppression, however, was found to affect regressions made on the first part of the sentence. This effect was abolished in Experiment 2 when regressions on the first part of the sentence were initiated from the middle of the sentence, just after the first words had been read. In Experiment 3, we replicated these results and showed that articulatory suppression decreased regression accuracy when the regression was launched from the second line to a word on the first line, but not when the regression was directed on a target word that had just been read.

The role of verbal memory in regressions

In line with our previous results (see Guérard et al., 2013), the present study showed that verbal memory is involved in guiding regressions during reading. This finding is consistent with the verbally based reconstruction hypothesis (Rawson & Miyake, 2002) stating that in order to execute a regression, participants locate the target word by reconstructing the order of the elements within a sentence. Our results also indicate that verbal memory plays a less important role when the regression has to be executed on a word that has just been read. In this case, other processes could come into play. A likely candidate is spatial memory, which has been shown to play a crucial role during regressions in a great number of studies (Inhoff & Weger, 2005; Kennedy, 1992; Kennedy, Brooks, Flynn, & Prophet, 2003; Kennedy & Murray, 1984; Weger & Inhoff, 2007). For instance, if each word is tagged to a spatial code (see, e.g., Kennedy, 1992), this code could be retrieved more directly and efficiently for recently read words, and therefore, spatial memory may be preferred over verbal memory (see, e.g., Inhoff, Weger, & Radach, 2005). The number of words that can be retrieved through their spatial tag might be limited, however (see, e.g., Fischer, 1999), so that when words have been read a longer time ago, verbal memory is preferred.

The reasons why another type of code than verbal memory would be privileged for the most recently read words remain to be investigated. One possibility, however, is that if, as stated by the verbally based reconstruction hypothesis (Rawson & Miyake, 2002), retrieval of the target location is based on the reconstruction of the elements of the sentence, the involvement of verbal memory is a lengthy process. If reconstruction involves retrieving the words of the sentence from the first to the last, the last words are certainly more difficult, or would take longer to retrieve, than the first words. Therefore, when words are located at the end of the sentence, verbal memory might be less efficient than other processes. The finding that regressions to the first words of the sentence rely to a lesser extent on verbal memory when they are initiated from the middle of the sentence points to the idea that the most recently read words are simply easier to access using another type of memory code.

Another possible interpretation of our results, is that the effect of articulatory suppression on regression accuracy depends on saccade size. Indeed, Experiments 1 and 3 showed that articulatory suppression impaired regressions in the condition where regression size is the highest (when the target word is located in the first part). When this confound is removed by having participants execute a saccade on the first part from the first line, the effect of articulatory suppression is abolished. We do not think equating saccade size is responsible for the abolition of the effect of articulatory suppression on regression accuracy, however. Indeed, if the effect of articulatory suppression increased as a function of regression size, the effect of articulatory suppression would be much larger when regressions are made to the first part when the sentence is displayed on a single line—where target words are the farthest from the regression launching site—than when it is displayed on two lines, which was not the case.

The idea that the retrieval of words read a longer time ago relies on verbal memory can explain the apparent discrepancies observed in the literature. For instance, studies using longer texts have shown an important role of verbal memory in locating target information (e.g., Rawson & Miyake, 2002; Therriault & Raney, 2009). In line with the present results, the retrieval of target words in long texts might preferentially recruit verbal memory. Its contribution might be more difficult to observe when paradigms using a single sentence are used and when most regressions are executed on words that have just been read, such as in Weger and Inhoff's (2007) study.

The effect of text arrangement on regression accuracy

Although our results showed that the involvement of verbal memory is not modulated by text arrangement, the number of lines on which the text was displayed nevertheless influenced regression accuracy. For instance, in Experiment 1, we showed that regressions were less precise when executed on the first part of the sentence than when executed on the second part, but only when the text was displayed on a single line. This suggests that the accuracy of regressions executed to words at the beginning of a sentence is influenced by the number of words on the line. One possibility is that on a single line, participants use a strategy where they first land in the second part of the sentence and regress backward until they reach the target word. Consistent with this idea, Experiment 1 showed that when the sentence is displayed on a single line, the proportion of part errors was very high for target words located in the first part. This indicates that regressions landed in the second part before reaching the target in the first part. When the sentence is displayed on two lines, participants might first retrieve the line where the target word is located (leading to the same proportion of part errors for words located in the first and second parts) and then aim at the target word.

When the length of the saccade was equated between regressions executed on the first and second lines in Experiments 2 and 3, regressions were less accurate when executed in the second part, as compared with the first part, of the sentence. Therefore, the number of words in memory when executing the regression has an effect on regression accuracy. This result is difficult to interpret, since it is not clear what processes are called upon for retrieving the location of the last words of the sentence. One possibility, however, is that spatial memory plays a role and that, as the number of words read increases, the precision of the spatial tag decreases, leading to a general cost in performance (see Fischer, 1999). Another possibility is that the processes underlying regressions made in the second part of the sentence are less precise than those underlying regressions made in the first part, leading to less accurate regressions.

Conclusion

In sum, our results replicate previous findings showing that verbal memory is recruited to guide regressions (see, e.g., Guérard et al., 2013). The present study advances existing knowledge by showing that verbal memory would be recruited to a lesser extent to retrieve words that have just been read but would be critical when the word to which the regression is made has been read a longer time ago. Together with other studies, our results suggest that more than one type of memory code can be used to retrieve the location of a target word during regressions and that the privileged code might depend on several factors, such as the number of words that has been read after the target word has been fixated.

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