Long Reading Regressions are Accompanied by a P600-like Brain Potential
Evidence from Simultaneous Recording of Eye Movements and ERPs

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Abstract: About 15% of reading saccades move the eyes backwards in the text. To study the neurophysiological correlates of such regressions, we co-registered gaze position and ERPs of 54 subjects during natural, left-to-right reading. Sentences were grammatically diverse but contained no syntactic violations or local ambiguities. Accompanying the onset of longrange regressions, we observed a late centroparietal positivity, closely resembling the P600 component commonly observed for syntactic violations and garden-path sentences in traditional ERP experiments. This suggests that the P600 indexes individual comprehension difficulty or parsing problems even in the absence of syntactic ambiguity. Co-registration of eye movements and ERPs may help to differentiate between regressions caused by oculomotor overshoot, word identification failures, and syntactic parsing problems.

Please note the dedicated symposium on EM-EEG co-registration on thursday

Introduction

About 10-15% of reading saccades are **regressions** that move the eyes back to earlier parts of the text. Because regressions are difficult to induce experimentally, comparatively little is known about their **determinants**.
In the present study, we investigated the **neurophysiological correlates** of regressive eye movements. Traditional reading experiments with event-related potentials (ERPs) do not allow for such analyses, because sentences are presented **word-by-word** and eye movements are **strictly precluded**. Consequently, readers cannot return to earlier words in the sentence.
We used a recently developed method that allows for **simultaneous recordings** of eye movements and ERPs during **natural, left-to-right reading** [2,3,4] to establish a relationship between regressive saccades and the accompanying brain activity.

Hypotheses

Three (non-exclusive) accounts have been proposed to explain reading regressions [1]: **Visuomotor accounts** assume that regressions mainly compensate for prior saccadic overshoot. **Word identification accounts** hold that regressions are due to incomplete identification of a previously fixated word. **Comprehension accounts** attribute regressions to difficulties in the ongoing sentence comprehension, in particular syntactic parsing problems.
The three functional types of regressions should roughly correspond to short, medium, and long backwards saccades, respectively.
Because **long regressions** are likely to reflect a reader's problem with parsing a particular sentence [5], we hypothesized that they should be associated with a **P600 potential**.
The P600, or *Syntactic Positive Shift*, is a long-lasting centroparietal positivity that begins 200-400 ms and peaks 500-900 ms after presentation of a target word. It is typically regarded as an **index of syntactic reanalysis and repair** because it has been observed for syntactic violations, garden-path sentences, and other syntactically complex sentences.
We expected **no** P600 for **short** (intraword) regressions as these should be primarily determined by low-level visuomotor factors.

Methods

Subjects, Stimuli & Task

We **reanalyzed** data from two co-registration experiments. Gaze and EEG were recorded while subjects read from left to right, moving their eyes freely.

- read single, unrelated German sentences for understanding
- for natural reading flow, sentence presentation was triggered by subject's eye movements
- comprehension questions after 25% (33%) of sentences

EXPERIMENT 1

30 subjects (20 female, 22.6 yrs)

Read *Potsdam Sentence Corpus I*:
- 144 normal sentences
- 5 - 11 words
- Wide range of grammatical structures including, for example, non-canonical (object first) sentences

0.25° per character

EXPERIMENT 2

24 subjects (18 female, 27.0 yrs)

Read *Potsdam Sentence Corpus III*:
- 144 easily comprehensible sentence pairs
- 9 - 12 words
- Frequent grammatical structures
- Originally designed to study word recognition (cloze probability manipulation in 2nd sentence)

0.45° per character

Examples
`Den Ton gab der Künstler seinem Gehilfen` (Exp. 1)
`Den ganzen Tag über konnte man die Raben krächzen hören.` (Exp 1.)
`Er redete nur noch von seiner Glatze und nervte die anderen.` (Exp 2.)

Eye Tracking & EEG Recording

- Tracking from right eye, binocular viewing
- Tracker calibration (13 point) controlled on every trial (0.5° max. allowed error)
- Systems synchronized via TTL pulses

Experiment 1:
- IView-X HiSpeed 240 Hz Tracker
- EEG from 33 electrodes
(SR 250 Hz, bandpass 0.02-30 Hz, average reference)

Experiment 2:
- IView-X HiSpeed 1250 Hz Tracker
- EEG from 64 electrodes
(SR 500 Hz, bandpass DC-100 Hz, average reference)

References

[1] **Vitu, F. (2005).** Visual extraction processes and regressive saccades in reading. In G. Underwood (Ed.), Cognitive processes in eye guidance. Oxford, NY: Oxford University Press. pp. 1-32.

[2] **Dimigen, O., Hohlfeld, A., Sommer, W.; Jacobs, A., Engbert, R. & Kliegl, W. (2005).** Measuring ERPs during left-to-right reading, Poster presented at the IX International Conference on Cognitive Neuroscience, Havana, Cuba

[3] **Dimigen, O., Sommer, W., Hohlfeld, A., Jacobs, Engbert, R., Kliegl, R. (2006).** Concurrent recording of EEG and gaze position: Measuring effects of word predictability during left-to-right reading of normal sentences. *Journal of Cognitive Neuroscience*, Supplement 224

[4] **Dimigen, O., Schild, U., Hohlfeld, A., Berg, P. & Sommer, W. (manuscript under review).** Auditory Language Comprehension During Saccadic Eye Movements: An Investigation With Event-Related Brain Potentials

[5] **Frazier & Rayner (1982).** Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. Cognitive Psychology, 14, pp. 178-210

[6] **Engbert & Kliegl (2003).** Microsaccades uncover the orientation of visual attention. Vision Research, 43, pp. 1035-1045

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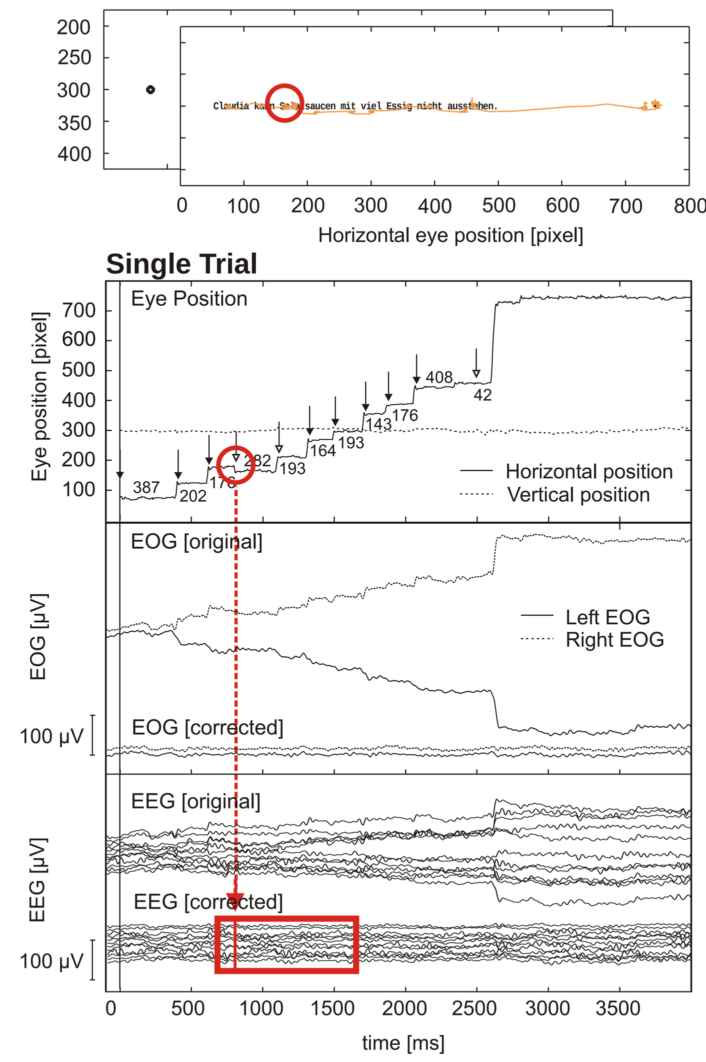
The Co-Registration Technique

Co-registration setup

- **62,767** reading fixations detected [6]
- Fixations occured in the first 800 ms after sentence onset and were discarded to avoid overlap with ERPs evoked by the sentence onset [3,4]. Sentence-final fixations were also not used.
- For each of **38,177** remaining fixations, EEG segments were cut time-locked to **fixation** and the outgoing **saccade** (100 ms baseline)
- Segments were **averaged** according to the direction and amplitude of the (outgoing) saccade

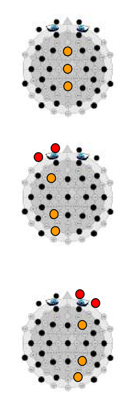


Co-registration data for one sentence. An intra-word regression is highlighted.

Ocular Correction & Control of Overlap

EEG recordings during normal vision are highly susceptible to signal distortion [2,3]. **Ocular EEG artifacts** were corrected with *Surrogate Multiple Source Correction* (MSEC, Berg & Scherg, 1994; Ille et al., 2003). For each subject, eye calibration data and 3-D electrode locations were recorded. Source waveforms for artifact topographies were estimated in presence of a static fixed-dipole model of brain activity, thereby reducing the erroneous subtraction of spatially correlated brain activity. MSEC yields satisfying results, especially for horizontal saccades [2,3,4].

Differential overlap. During normal vision, fixation-locked potentials are massively overlapped by potentials elicited by successive fixations (e.g. *lambda waves*). Naturally, the degree of overlap varies with systematic differences in fixation behavior. This may produce apparent condition differences.
We used a simulation method that utilizes the temporal distribution of adjacent fixations to estimate the maximum impact of differential overlap on the ERP average.

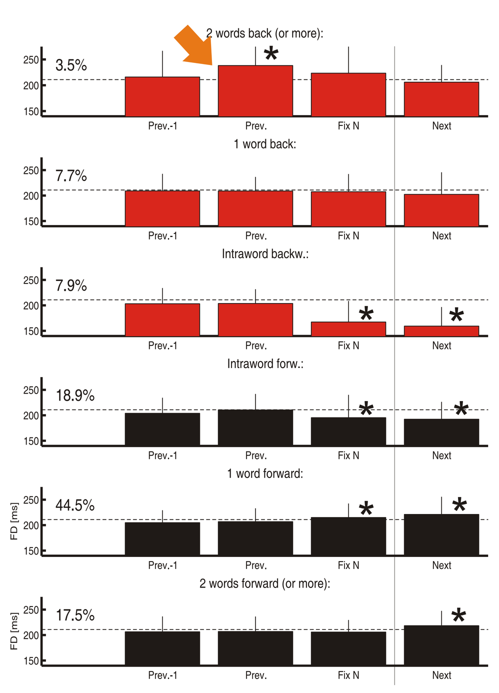


		Correlation with ET	
		Before	After
Midline	Fz	0.09 (0.04)	0.06 (0.04)
	Cz	-0.02 (0.04)	0.00 (0.03)
	Pz	-0.02 (0.05)	0.00 (0.04)
Left head	Hori. EOG	-0.97 (0.02)	-0.08 (0.04)
	Vert. EOG	-0.66 (0.08)	0.06 (0.07)
	F3	-0.47 (0.05)	0.03 (0.04)
	P3	-0.20 (0.05)	-0.02 (0.05)
	O1	-0.08 (0.04)	-0.01 (0.05)
Right head	Hori. EOG	0.97 (0.01)	0.01 (0.07)
	Vert. EOG	0.66 (0.09)	0.04 (0.07)
	F4	0.54 (0.07)	0.05 (0.03)
	P4	0.14 (0.05)	0.03 (0.04)
	O2	0.06 (0.03)	0.04 (0.04)

Correlation between selected EEG and horizontal eye track before/after correction. Non-significant correlations (grey) indicate the absence of residual artifact

Results: Fixation durations

EXPERIMENT 1



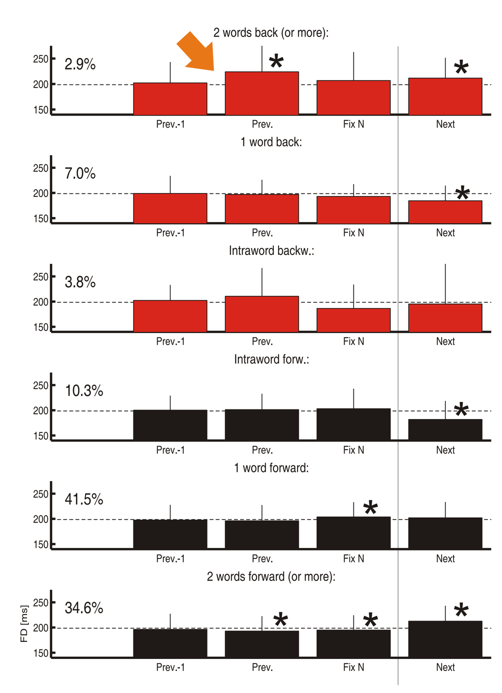
19.1% regressions

Mean **fixation durations** (FD) for fixations followed by backwards or forwards saccades of different amplitude (Fixation *N*). FDs for neighboring fixations are also given.

FDs that differ significantly from the mean FD (horizontal line) are highlighted (*).

- Regression rates and FDs were higher in Exp. 1 which involved syntactically more complex sentences.
- Longer FDs were observed two fixations prior to long regressions (orange arrows).

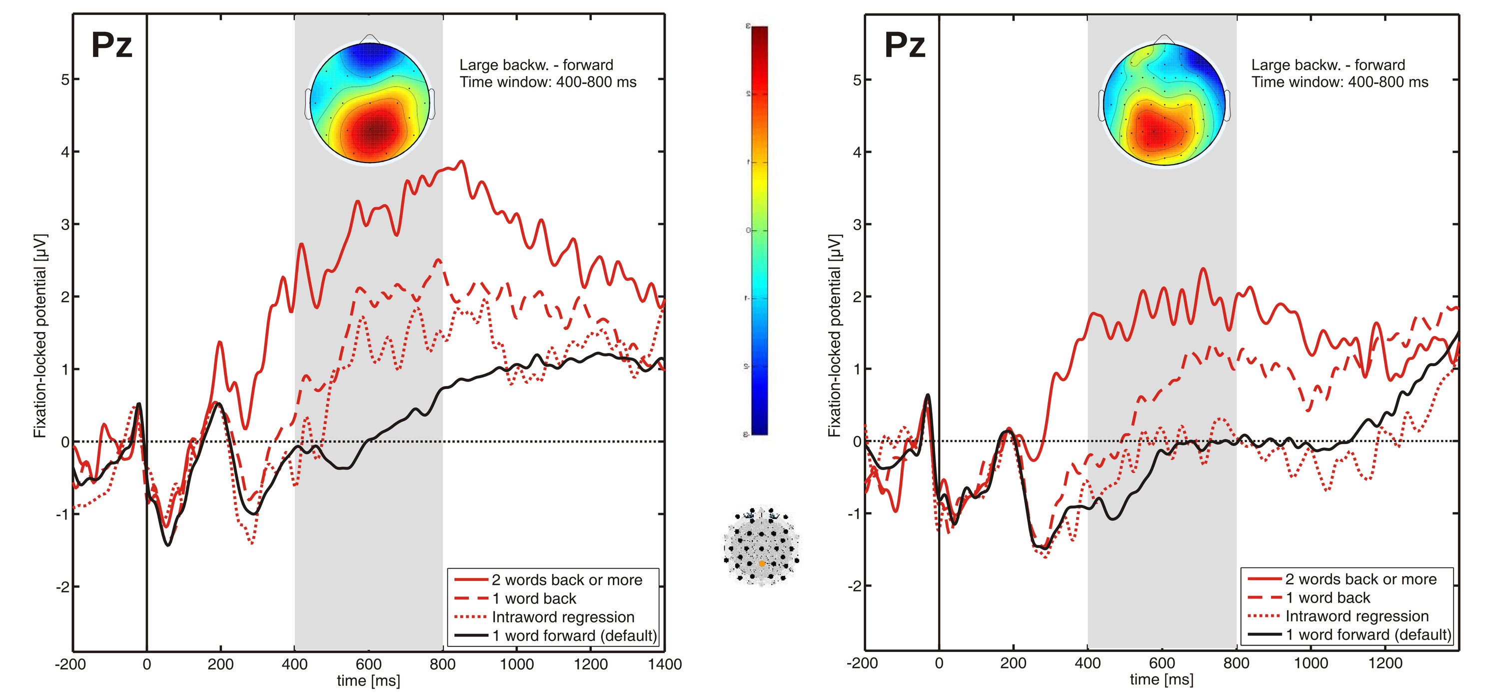
EXPERIMENT 2



13.7% regressions

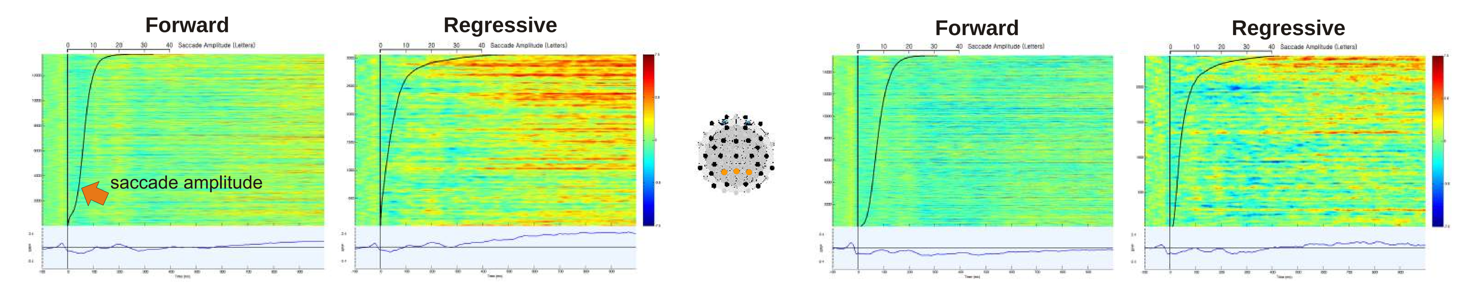
Results: Regression-locked potentials

EXPERIMENT 1 – Potsdam Sentence Corpus I (N=30)
EXPERIMENT 2 – Potsdam Sentence Corpus III (N=24)



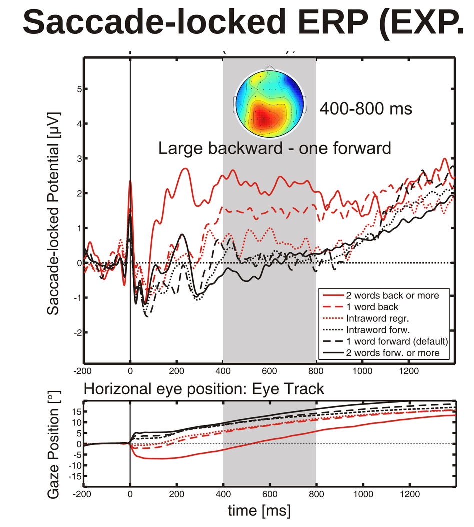
Grand average fixation-locked ERP at electrode Pz. The ERP is time-locked to fixation onset on a word *N* when followed either by a forward saccade (to next word) or a short (one word), medium (one word) or long (two words or more) regression. Topographical maps show the voltage difference between long regressions and forward saccades in the expected P600 time window.

Fixation-locked single epochs, sorted by outgoing saccade direction and amplitude



Above. **ERPimages.** Every horizontal line depicts one fixation-locked EEG segment. Amplitude is color-coded, **red** indicates **positive** voltages. Epochs were **sorted** by the amplitude of the outgoing saccade. The figure shows that long regressive saccades, in particular, but not forward saccades, are followed by a sustained positivity at centroparietal electrodes.

Saccade-locked ERP (EXP. 2)



Right. **Grand-average saccade-locked ERP**. For long regressions, the P600-like modulation began approx. 100 ms after saccade onset.

Summary & Conclusions

In two experiments the EEG was recorded during left-to-right reading. We assumed that long - but not short - regressions would index a reader's problem with ongoing sentence comprehension. We therefore hypothesized that long regressions should be accompanied by a **P600 potential**, an ERP correlate of **syntactic reanalysis.**

- In both experiments, long regressions were accompanied by a long-lasting **centroparietal positivity** that resembled the P600 in its **scalp topography.**
- The effect was found despite the **absence** of **syntactic violations** and **structural ambiguities** in the sentences. However, simultaneous eye tracking presumably allowed us to identify **individual cases** of comprehension breakdown.
- The effect's **latency** - beginning ~100 ms after saccade onset - is **compatible** with traditional P600 findings if one assumes that comprehension problems typically arose on the fixation preceding the regression or - as FDs suggest - **one more** fixation before that.
- We can **rule out** that the effects were merely due to residual ocular artifacts. We can largely exclude significant modulations through baseline effects and differential overlap.
- A **smaller** and delayed **P600-like effect** was also found for short regressions. This could mean that some proportion of short regressions is due to higher-level comprehension problems. Alternatively, it could indicate that late positivities also appear for word identification problems.

In summary, the present analyses established a **direct relationship** between oculomotor and neurophysiological correlates of comprehension difficulty. Future application of the co-registration technique - with dedicated sentence materials - may help to **clarify the cognitive processes** that underlie regressive saccades as well as the P600.

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